THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

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April, 1965

IP-700

This is a Transcript of the Ninth Ann Arbor
Industry-Education Symposium That Was
Held on Thursday, April 9, 1964.

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OPENING REMARKS

R. E. Carroll

Director, Industry Program

Well, good morning gentlemen. Welcome to the Ninth Ann Arbor Industry-Education Symposium. We are very pleased to have with us Stephen S. Attwood, Dean of the College of Engineering, who will open the program with a few words of welcome. Dean Attwood.

Stephen S. Attwood

Dean, College of Engineering

I'm very glad, indeed, to extend the welcome of the College of Engineering and the University to you gentlemen who have risen very early to get here, looking so bright-eyed at an hour like this - it is more than I can do. This is a general meeting of the Industry Program, a meeting that has been built around the topic which was felt would be of rather broad interest to the people from various professions and interests, and we have other conferences that are specially arranged on more limited topics, that is, limited in the sense that they may be of more special interest to particular groups. Which I think, points up one of the facts that the College of Engineering is not only trying to teach its 4100 students - undergraduate and graduate - but we also feel that we have professional responsibilities and we do the best we know how to reach out into the state, into the engineering professions, and to Industry, in an effort to be of whatever service we can possibly be to them. On the other hand, industries are very good in supporting our activities and we appreciate that side of the picture too.

We like to think of it as a two-way street where each is giving something of value to the other in understanding and support. Some of the other things we are doing aside from this particular kind of an operation is our program on continuing education for men in industry who have been away from school for some time and feel the need for strengthening their continuing interest in professional matters. We have such operations going on in Midland, Flint, Detroit, and Dearborn, and members of our staffs from Industrial Engineering, Mechanical Engineering, Electrical Engineering and Chemical Engineering take part variously in these different programs.

The work these people have to do is certainly not easy - to come out after hours in general and carry on rather intensive study courses. This requires a great deal of persistence as well as energy, and - no doubt - some help from some wives. And most of these people, at least a good many of them are working for Masters' degrees. As soon as they qualify we are very happy indeed to give them that extra recognition for the hard work they have effectively accomplished.

Through the Institute of Science and Technology one of our professors is heading up what I'll just call for short "The Industry Relations Group" that was set up to work in various special areas in an effort to find out what can be done to help that industry, if we can help it, or if we can suggest who else might help it - so as to, generally speaking, improve the effectiveness of the industry as well as the state's economy. And then I want to mention the Summer Conferences. I'm sure you all picked up folders on them. I know Ray Carroll is a rather shy fellow but I'm sure he wouldn't miss this opportunity to flood you with literature on them. Now this is a very successful operation in which it is quite different in its objectives. Here we gather together, not only our own staff but probably a hundred lecturers from outside, some coming from industry, some coming from government laboratories. Our objectives here are to put on short intensive courses of one or two weeks length in which we strive to present the very latest information that this collective group of instructors and lecturers can bring forth. In other words, we are trying to reach out in that particular group - that particular operation, as far as we can into the future. This year we will have thirty-one courses spread over the summer, and we expect at least seventeen hundred people to come from all parts of the country and Canada. This is a program of increasing interest and industries seem to be very happy to send the appropriate people back to take part in these summer conferences.

Within the last two years, two of the largest rooms in the Engineering buildings have been refurnished with new lights and air conditioning, painted in pastel colors, and have had some good seats installed. I think the people who were lucky enough to have intensive courses in those two locations were very pleased. We use the rooms for other services during the year. The creation of those two special rooms was so successful that we are now finishing out two more that will be ready for operation this summer. So, if we should have a real broiler we will at least cool off some people.

Well, all I want to indicate here was that we try to do much more than just teach freshman courses or even at a higher level. We like to feel that we are a part of a big, important and proud profession, and we want to do our part in carrying on relations with all areas of that profession, whether it is inside or outside of the University.

I think that's the main point that I want to make. I regret that I cannot be with you today as much as I would like. I'll wind up with an old saw that I'm not master of my fate or captain of my soul, but my secretary is. And what she says goes, and she says, "You come back and get some work done." So I'll try to join you for lunch but I will be with you only part of the day. It was a pleasure indeed to have a chance to welcome you and it is a pleasure to have you here. Thank you so much.

When it comes time for words of welcome you're often reminded of the last meeting you went to and how you are welcomed there, or several meetings back, and sometime last winter I went to a meeting down in the State of Georgia. The Dean of the Engineering College gave words of welcome and he included the Yankees. He said that so and so is welcome and so and so is welcome and even the Yankees are welcome - and he said, "This reminds me of when I was a boy." He said, "My father ran a hardware store and in the summertime when I wasn't in school I helped out. One afternoon my Dad came over to me and said, 'Son, when those damn Yankees come in I want you to treat them better. Don't treat them so rudely.' He said, 'The way I figure, those Yankees are worth something. I figure they're worth at least one bale of cotton - and - they're twice as easy to pick'."

But, we are awfully glad you are here today and I would like to say just a couple of things about the mechanism of the meeting before we get started. We have all these microphones out here because we found that with a small group of men interested in a subject, we often get some very good questions and discussions. The discussion will be open after each paper and if you wish at the end of the last talk in the afternoon there will be time for asking questions of any of the speakers if you have forgotten to ask them or hadn't thought to ask them right after their talk. We're taping the meeting, including the discussion. All of this will be put in the record of our meeting which will go into a bound volume. Each person in attendance will receive a copy in due course although this may be quite a few months if the printers aren't any faster than they have been this last year.

If you do have a question or something to add after one of the papers we ask that you look at the microphone closest to you rather than at the speaker. This speaker will hear you but the microphone may not. We have to keep the gain control set down somewhat in order to prevent feedback, as you know.

The first speaker of the morning is chairman of our Mechanical Engineering Department, Gordon J. Van Wylen. He received his Master's degree from the University of Michigan, his Doctor of Science degree from M.I.T. He was appointed Assistant Professor here in 1951, full Professor in 1957, and Department Head in 1958. I won't attempt to give you his total background or that of any of the other speakers but here are a few salient points that I'm sure will be of interest. In the summer in 1955, he did research work in the Cryogenic Engineering Laboratory at the National Bureau of Standards in Boulder, Colorado. His publications include such subjects as The Specific Heat of Gases, Pumping Cryogenic Liquids, Pressurized Discharge of Liquid Nitrogen from Uninsulated Tanks; and he has a very well-known book, now, on Thermodynamics, published by John Wiley and Sons.

He has participated in a number of research projects involving graduate students and other members of the staff, dealing with problems of low temperature equilibrium conditions. I'm very pleased at this time to introduce the first speaker of the morning, Professor Gordon J. Van Wylen.

CRYOGENIC ENGINEERING TODAY

Gordon J. Van Wylen

Chairman, Mechanical Engineering Department

CRYOGENIC ENGINEERING TODAY

Within the past decade the terms cryogenics and cryogenic engineering have come into wide usage and both are well understood technical terms. The increased usage of these terms of course only reflects the tremendous increase in the use of cryogenics and the research and development activity in this field that has occurred in the past ten to fifteen years. There has been a corresponding increase in technical literature and professional meetings devoted to this field. For example, not only has the annual Cryogenic Engineering Conference been a well attended and successful professional meeting, but both ASME and AIChE have organized meetings dealing with cryogenics, and recently the ASME has organized a division dealing with Cryogenic Engineering. Several colleges of engineering have organized short summer courses or conferences on Cryogenic Engineering, and a number of engineering schools now offer a course in Cryogenic Engineering.

One of the striking things about cryogenics and cryogenic engineering is the continual interaction between basic research and applied technology. For example, the development of the Collins Helium Cryostat in the late 1940's made it possible for many laboratories to do basic research at liquid helium temperatures. From this basic research has come the understanding of the physical phenomena and the discovery of new data and new information that has led to such developments as the superconducting magnet. Many similar examples could no doubt be cited, and many more will be forthcoming in the near future.

At the summer conference on cryogenic engineering which was held at the University of Michigan in 1962 it became apparent to us that there is a considerable difference in the interests of those who are concerned with the production of cryogenic fluids and producing refrigeration at cryogenic temperatures and those who study various phenomena at cryogenic temperature and have relatively little concern as to how these temperatures are produced. Yet any review of cryogenic engineering today must necessarily concern both aspects of this field, and both aspects are covered in these notes. Cognizance should also be given to the fact that a number of problems, such as materials, insulation, and instrumentation are common to both the producer and user of cryogenic liquids and refrigeration at cryogenic temperatures.

1.1 The Range of Cryogenic Temperatures

Cryogenics refers, broadly speaking, to extremely low temperatures. While no specific temperature can be logically assigned for the upper temperature limit for the field of cryogenics, let us accept the arbitrarily established value of 150K (-190F). Thus we will not be concerned with refrigeration and phenomena associated with solid and liquid carbon dioxide.

Now at first glance it might appear that the range of temperatures from 0K to 150K is a rather narrow temperature range to serve as the distinguishing characteristic of a particular field of technology. However, if we think in terms of ten-fold changes in temperature we get a more accurate picture of the significance of this range of temperatures.

To illustrate this point, let us consider 300K as our reference temperature. A ten-fold increase in temperature takes us to 3000K, and covers essentially all the processes involved in combustion and industrial technology. Another ten-fold increase brings us to 30,000K , and embraces the newly developing field of plasmas.

On the other hand, a ten-fold decrease in temperature from our 300K reference temperature brings us to 30K. This range embraces the entire field of commercial refrigeration, liquid and solid CO_2 technology, liquefaction of natural gas, the liquefaction and separation of air, and the use of liquid oxygen and liquid nitrogen.

Another ten-fold decrease in temperature gives a temperature of 3K, and embraces the liquefaction of hydrogen and helium, and all the related technology.

However, in the field of cryogenics the next ten-fold decrease in temperature, which brings us to 0.3K, has been investigated for several decades, and commercial equipment is available to produce refrigeration in this range. The temperatures in this range can be produced by pumping a vacuum over liquid helium and by the helium-3 refrigerator. It also includes the upper range of temperature produced by adiabatic demagnetization.

This however is by no means the lower limit of the range of temperatures that have been reached. At this time the lowest temperature which has been reached is one millionth of a degree Kelvin, and involves the technique of nuclear magnetic cooling, which is described in a later section.

This matter of achieving low temperatures would appear to be more dramatic if we used a logarithmic scale of temperature, rather than our present scale. Such a scale was proposed at one time by Lord Kelvin.

From a realistic point of view we may say that our present scale of temperature is defined from the familiar Carnot cycle, which is shown in Figure 1, in accordance with the relations,

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

and

$$T_H - T_L = 180 \quad \text{(for the Fahrenheit scale)}$$

and

$$T_H - T_L = 100 \quad \text{(for the Centigrade scale)*}$$

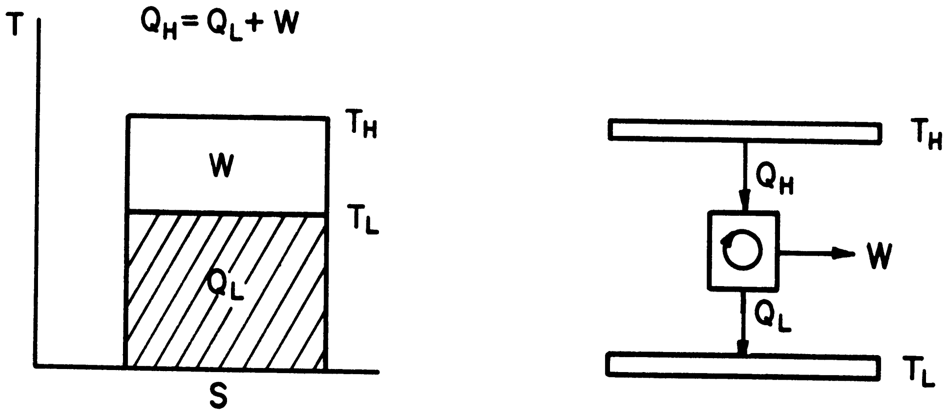

Figure 1. Carnot Cycle.

*The following conversion formulas for various temperature scales are given.

$$°F = °C \times 9/5 + 32 = °R - 460 = °K \times 9/5 - 460$$
$$°C = (°F - 32)5/9 = °R \times 5/9 - 273 = °K - 273$$
$$°R = °K \times 9/5 = °F + 460 \qquad °K = °R \times 5/9 = °C + 273$$

But suppose we had chosen the relation

$$\log_{10} \left(\frac{Q_H}{Q_L}\right) = "T_H" - "T_L"$$

where "T" designates the proposed scale of temperatures. It follows that the proposed scale would be related to our present scale by the relation

$$\log_{10}T_H - \log_{10}T_L = "T_H" - "T_L"$$

or

$$"T" = \log_{10}T + C$$

where C is a constant which determines the level of temperature which will correspond to zero on the proposed scale. Suppose we let C = 0 . We would then have the following temperature scale.

T	"T" x 100
10,000K	400
1,000K	300
300K	247.7
100K	200
10K	100
1K	0
.1K	-100
.01K	-200
.001K	-300
.0001K	-400
.000001K	-600

Note that in this case an increase in temperature from ambient (300K) to 10,000K would be only 152.3 degrees, whereas a decrease from ambient to 1°K would be 247.7 degrees. A further decrease from 1°K to 0.001K would be 300 degrees. This scale would certainly serve to portray more accurately the significance of accomplishments in the field of cryogenics. But since this is not our accepted scale of temperature, we accept the challenges of cryogenics for what they are and not for the apparent drama which the logarithmic temperature scale would offer.

2.1 A Brief Historical Survey of Cryogenics

In order to gain a better insight into where we are in cryogenic engineering today, a brief historical survey of some of the major developments and discoveries in cryogenics is presented. To do this effectively a few terms should be defined, and these are done with the aid of a temperature-entropy diagram shown in Figure 2.

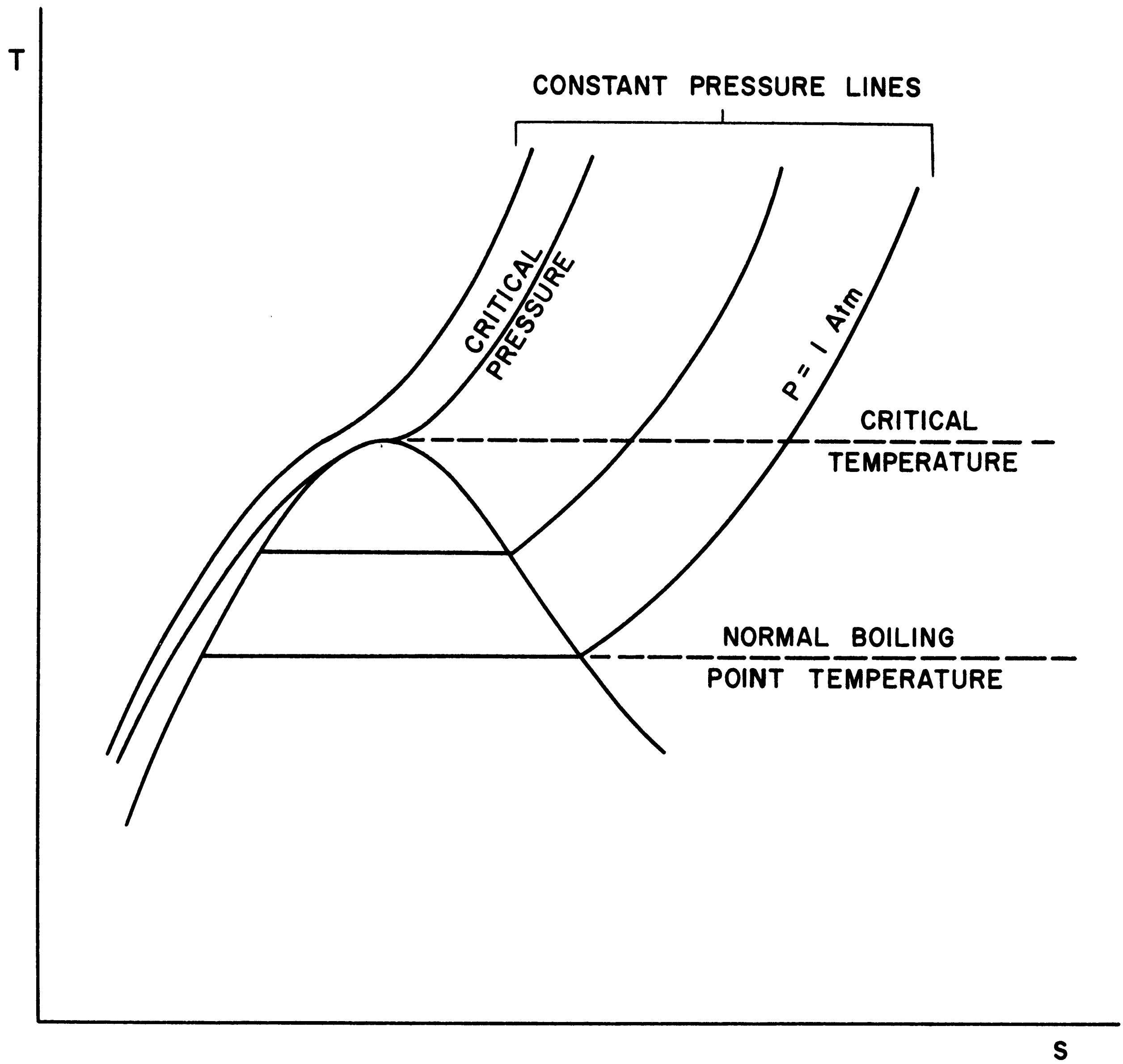

Figure 2. Typical Temperature-Entropy Diagram for a Pure Substance.

We usually think of a fluid as a liquid phase at a temperature below the critical temperature. Thus in the case of a substance whose critical temperature is below the ambient temperature, refrigeration is necessary to produce the liquid. From Figure 2 it is also evident that at temperatures above the critical temperature it is impossible to produce a liquid by simply increasing the pressure.

Thus a study of cryogenic substances leads us to a consideration of the critical temperature and normal boiling points (i.e., at a pressure of one atmosphere) of various substances. Table 1 lists the critical pressure, critical temperature, and normal boiling points of all the elements that can become a cryogenic fluid.

TABLE 1

Substance	Critical Temp. °K	Critical Pressure (atm)	Normal Boiling Pt. °K	Fusion Temp. °K
Oxygen	154.8	50.1	90.19	54.40
Fluorine	118.0	38.0	85.24	55.20
Nitrogen	126.2	33.5	77.34	63.15
Neon	44.5	26.9	27.1	24.57
Hydrogen (Normal)	33.3	12.8	20.39	13.96
Helium	5.3	2.26	4.216	

It is significant to note that less than 100 years has elapsed since the first of these cryogenic fluids was liquefied. The major reason why these substances were not liquefied before that time was that the concept of critical phenomena was not well understood until about 1863. From Figure 2 it is evident that if one had no concept of the critical point, it would be very difficult to develop a technique for liquefying a cryogenic fluid. However, once these principles were clarified and understood, many investigators began working on the problem of liquefying these various gases. As has often happened in the history of science, two independent investigators made an important breakthrough at about the same time, for in December, 1877, Cailletet of France, and

Pictet of Switzerland, both succeeded in liquefying oxygen. The latter's work was particularly significant since he used the cascade principle, which has been used in so many applications since that time. This principle involves a different working fluid in various temperature ranges, and the substance to be liquefied is cooled successively by the various fluids.*

The liquefaction of hydrogen did not occur until the development of the counter-flow heat exchanger, in conjunction with a Joule-Thomson valve, which was developed by Linde and first successfully operated in 1895. Three years later, in 1898, Dewar used this principle to liquefy hydrogen.

About this time Kamerlingh Onnes began the development of the most famous low temperature laboratory in the world, namely the laboratory at Leiden in the Netherlands, which is now referred to as the Kamerlingh Onnes Laboratory. Onnes proceeded to develop a laboratory where substantial quantities of cryogenic fluids would be available. A hydrogen liquefier was built which first produced liquid hydrogen in 1906. It was two years later in 1908, in this laboratory that helium was first liquefied and this represented the last of those gases which were at one time called the "permanent gases" to be liquefied.

Thus we see that from about 1863 to 1908 the major emphasis was on liquefying gases. Closely associated with this was the development of technology that involved the design of cascade systems, heat exchangers, and expansion valves. Furthermore, once these liquefied cryogenic fluids were available, they were used in many different investigations at cryogenic temperatures, and this leads to a consideration of the discovery of several interesting phenomena that occur at cryogenic temperatures.

Soon after Kamerlingh Onnes liquefied helium he undertook to measure electrical resistivities down to liquid helium temperatures. In 1911 he measured the electrical resistance of mercury and found that at about 4K the electrical resistance decreased very abruptly to a value so low that he could detect no resistance whatsoever. This phenomena has been called "superconductivity" and the temperature at

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*M. and B. Ruhemann give an excellent summary of the historical developments in the field of cryogenics in Low Temperature Physics, Cambridge University Press, London, 1937.

which a metal becomes superconducting is called the "transition temperature". Since that time many carefully executed experiments have been performed in an effort to determine whether the electrical resistance is approximately zero or whether it is exactly zero. It has been established that the electrical resistivity, if any, is less than 10^{-20} ohm cm, which means that for both practical and theoretical purposes it can be considered zero.

The discovery of the influence of a magnetic field on the transition temperature was another important step in the understanding of superconductivity and its potential application. Curves for various metals are shown in Figure 3, where it is noted that the transition temperature decreases under the influence of a magnetic field, and above a certain critical field strength the material does not become superconducting even at temperatures as low as 0.7K. Table 2 shows a transition temperature for a number of metals and alloys.

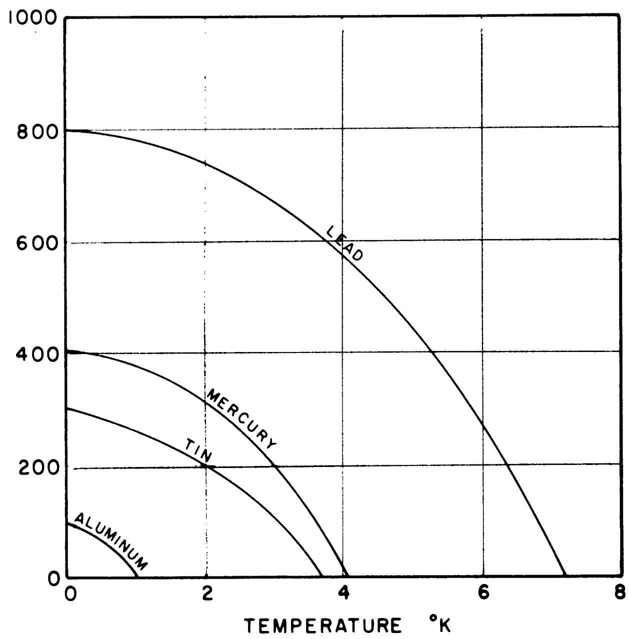


Figure 3. Critical Magnetic-Temperature Curve for Certain Elements.

More recently however it has been discovered that the influence of the magnetic field in the transition temperature can be greatly influenced by the mechanical properties of the material and is quite different for alloys than pure metals, and this has opened up the entire field of superconducting magnets, which is the subject of a subsequent paper in this series.

TABLE 2

Element of Alloy	Transition Temperature
Technetium	11.2
Niobium	8.7
Lead	7.2
Lanthanum	5.4
Vanadium	4.89
Tantalum	4.38
Mercury	4.17
Tin	3.73
Indium	3.4
Thallium	2.39
Rhenium	1.70
Thorium	1.37
Aluminum	1.2
Gallium	1.10
Zinc	0.9
Uranium	0.8, 1.1
Osmium	0.71
Cadmium	0.56
Zirconium	0.55
Ruthenium	0.47
Titanium	0.39
Hafnium	0.37
Nb_3Sn	18.0
V_3Si	17.0
V_3Ga	16.8
NbN	15.0
MoN	12.0
Nb_3Au	11.6
MoC	9.76
$MoGa_2$	9.5
NbC	6.0
V_3Ge	6.0
V_3Sn	6.0

In addition to the superconducting magnetic current, research and development is underway in a number of other areas such as the cryotron, a switch for use in computer devices; superconductor motors; and superconducting bearings. Here is another example of the interaction between fundamental studies and applied technology.

One other phenomenon of significance in the superconducting state is the Meissner effect, which was observed by Meissner and Ochsenfeld in 1933. This is the fact that a material expels the magnetic field when it becomes superconducting, and a superconductor has zero magnetic induction was well as zero electrical resistivity. A superconducting material which is below the transition temperature but has a magnetic field of sufficient strength to restore the normal resistivity expels the magnetic flux when it passes the threshold curve shown in Figure 3, as the magnetic field is reduced in constant temperature. These phenomena are shown schematically in Figure 4.

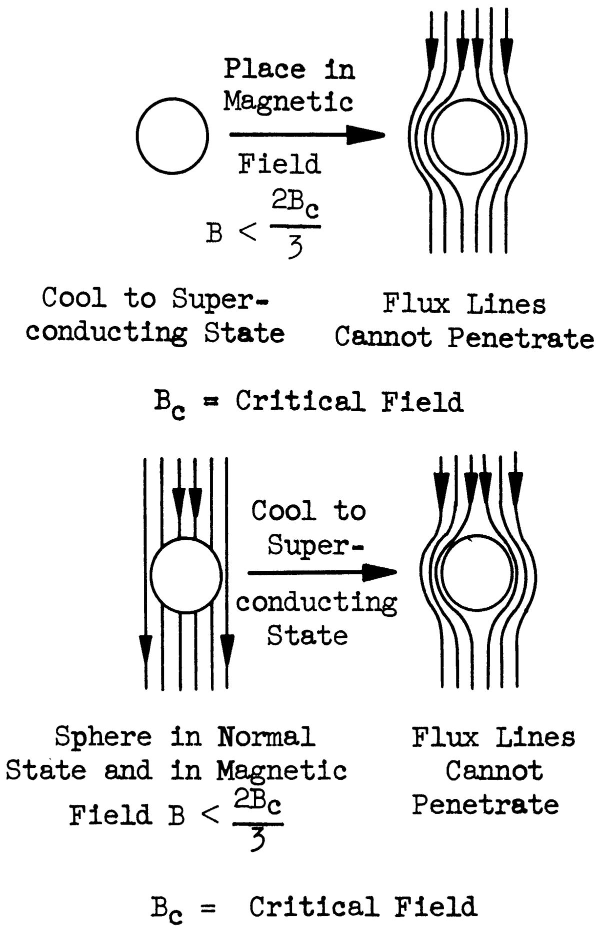


Figure 4. Graphic Description of the Meissner Effect.

In a historical survey of cryogenic engineering one cannot neglect a reference to the properties of helium 2, even though at the present writing this lies primarily in the area of basic research. When helium is cooled below 2.2K a phase transition occurs, and the fluid existing below 2.2K has some very unusual properties. The existance of this fluid, which is known as helium 2, has been known since 1932 when Keesom and his co-workers made careful measurements of the specific heat versus temperature curve for liquid helium. They were particularly interested in the region around 2.2K, since some years earlier they had observed a discontinuity in the dielectric constant at this temperature. The result of their work on specific heat is shown in Figure 5. Once again a sharp discontunity was noted at 2.2K. This transition point was referred to as the lambda point since the appearance of the specific heat versus temperature curve was similar to the Greek letter λ .

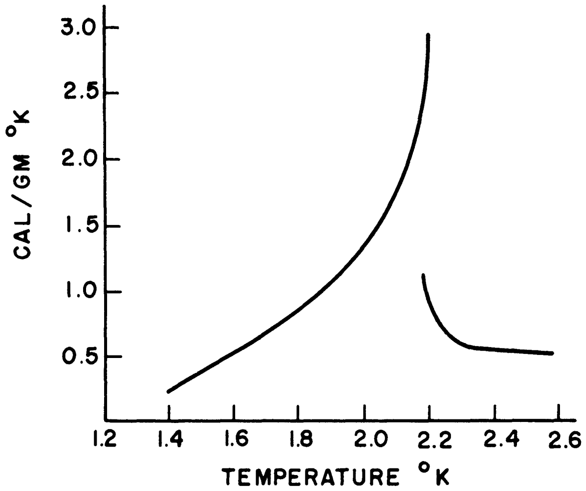


Figure 5. Specific Heat-Temperature Curve for Helium in the Region of the λ Point.

In 1938 the so called fountain effect was discovered by Allen and Jones at Cambridge University. This is shown schematically in Figure 6. Figure 6a shows the difference in liquid level which results when a small amount of electrical energy is supplied as indicated. Figure 6b shows the more dramatic fountain effect which occurs when radiant energy shines on the emery powder. Fountains as high as 30 cm have been observed.

Another interesting phenomenon of helium II was observed when two different techniques were used to measure the viscosity of liquid helium. These two techniques are Poiseuille's method and the oscillating disc method. Normally the results obtained by these two methods are in very good agreement. However, when these two methods were used with helium II, radically different results were obtained. With Poiseuille's method the viscosity was very low, and in fact it approached zero. With the oscillating disc method it was at least a million times greater.

The so called mechano-caloric effect should also be noted here. This is shown schematically in Figure 7. The experiment consists in first immersing the Dewar in a helium 2 bath, allowing fluid to enter the Dewar, and then raising the Dewar and allowing the fluid to flow out. The temperature of the helium during the inflow process and outflow process are compared with the temperature which occurs when there is no flow. It was found that when liquid flows into the vessel there is a decrease in temperature of 10^{-2}K and when it flows out there is an increase in temperature of 10^{-2}K.

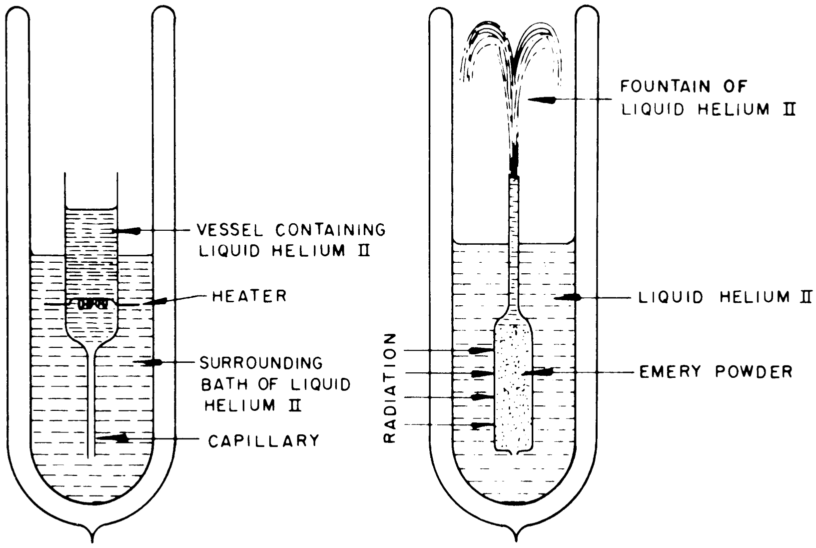


Figure 6. Fountain Effect in Helium 2.

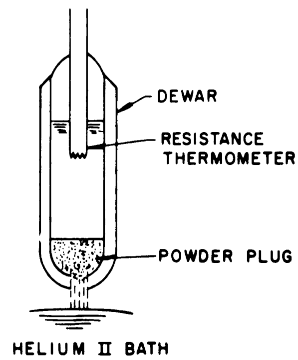


Figure 7. Mechana-Caloric Effect in Helium 2.

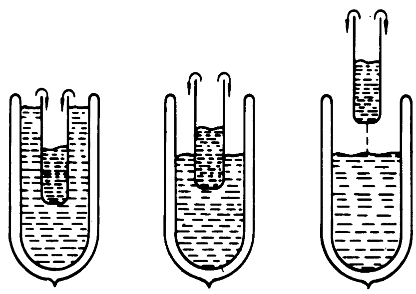


Figure 8. Creeping Film Phenomena in Helium 2.

Figure 8 shows the mobile film phenomenon in helium 2, which was discovered by Onnes in 1915. All vessels which contain helium 2 tend to seek the same level.

Many investigators, both theoretical and experimental have been conducted and are currently in progress that are related to the phenomena of liquid helium 2. The potential technical applications of helium 2 are very limited at present, but, as in the case of many other phenomena that have been observed at cryogenic temperatures, these developments can occur very rapidly when the appropriate situation develops.

What have been some of the major developments in cryogenic engineering of the past decade? A consideration of these developments will also help us to understand where we are today.

The first of these which we cite here is the development of large capacity liquefaction plants to produce liquid oxygen, liquid nitrogen, and liquid hydrogen. These have been developed under the impetus of our missile and space programs. Typical of these is the hydrogen liquefaction plant at West Palm Beach, Florida, which is described in further detail in a subsequent paper.

Closely related is the development of ground handling equipment. The pumping of cryogenic fluids is on excellent example of such equipment. During the summer of 1955 I worked at the NBS Cryogenic Engineering Laboratory, and was involved in a project that involved the pumping of liquid hydrogen. So far as we know, that was the first time that liquid hydrogen had been pumped with a centrifugal pump. Yet today the pumping of liquid hydrogen is a relatively standard operation. The storage, piping, and pumping of cryogenic fluids, with related problems of the development of valves, seals, and expansion joints has involved a major development by cryogenic engineers.

The development of insulating materials is a particularly striking study. Figure 9 shows the typical storage vessel for liquid nitrogen. The insulation consisted essentially of a vacuum space. However, there is considerable transfer of heat by radiation in such a vessel. When it came to the storage of liquid hydrogen, until about 1957 the usual procedure was to use a nitrogen shield as shown in Figure 10. Thus the radiant heat transfer to the liquid hydrogen was decreased. The same procedure was used in the storage of liquid helium.

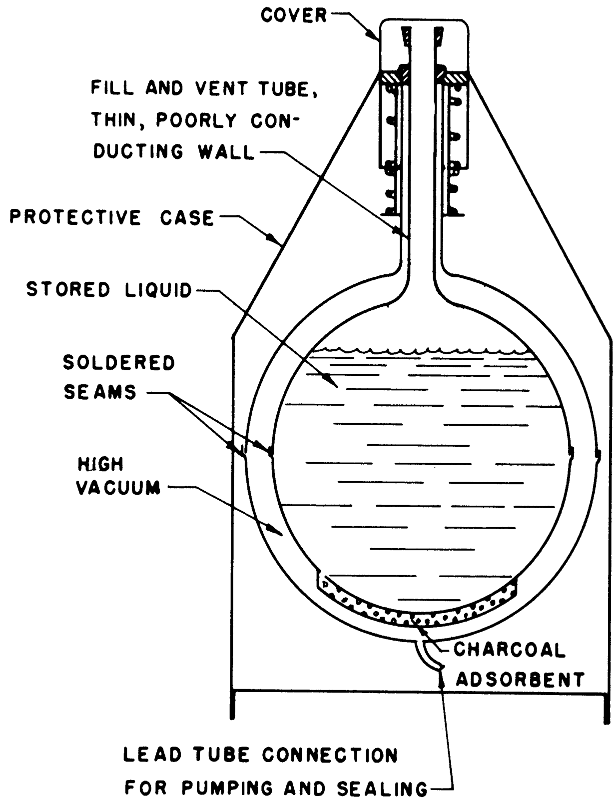


Figure 9. Typical Storage Vessel for Liquid Nitrogen.

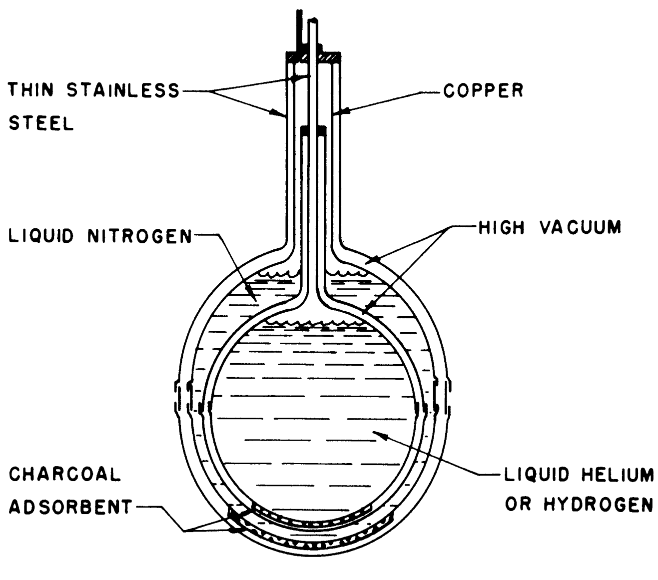


Figure 10. Schematic Arrangement of a Nitrogen Shielded Dewar.

The major problem to be overcome in the development of an improved insulation was the reduction of the radiant heat transfer. The next step in improving insulation was the development of vacuum powder insulation. In this case the vacuum space was filled with a powder, such as Santorel or perlite, which was in a measure opaque to radiation. With the use of these insulations a substantial improvement over simple vacuum insulation was achieved.

The next step was the development of multilayer insulation; which proved to be better than vacuum powder insulation by a factor of about 10. In this insulation the vacuum space is filled with many layers of a very thin radiation shield, with each layer separated by a very thin spacer, which is designed to have high contact resistance. It is the development of this superinsulation which has made possible the dramatic transportation of liquid hydrogen from one part of the country to another by semi-trailer and railroad tank car. One company has recently announced that it is now using 13,200 gallon semi-trailers. In the transportation of liquid hydrogen, which weighs only 0.6 pounds per gallon, the problem is to utilize the maximum allowable volume. In these 13,200 gallon semi-trailers, which are limited to a diameter of 8 feet and a length of 40 feet, only a one inch annular space is required for the multilayer insulation. Yet the evaporation loss is less than 0.4% of capacity per day.

There are a number of various other interesting developments in cryogenic engineering today, some of which are reported in subsequent papers in this series. Certainly cryogenic engineering is an area of challenge and promise. At the University of Michigan we believe we have a sound educational program which will prepare students for this field, and an active research program which will contribute to our knowledge in this area as well as to advance technilogical developments. We are anxious to work in close cooperation with industry in this program, and to have the exchange of information which is mutually profitable, and look forward to continued association with you.

DISCUSSION

R. E. Carroll:

Are you ready for some questions, Gordon?

Question:

What is the approximate thickness of that superinsulation layer in the trailer?

G. Van Wylen
Answer:

One inch, according to the press release.

S. H. Autler
Question:

Do you believe it?

G. Van Wylen
Answer:

I think so.

R. E. Carroll:
Question:

While someone else is thinking of the wording of his question, let me ask one. Has there been any transfer in the technology of insulation at cryogenic temperatures to insulation at more normal temperatures, has some of this leaked through let's say, so it has been beneficial in other areas that you know of?

G. Van Wylen
Answer:

I know of one application. We were going on a picnic last summer and my wife had a hot dish that she wanted transported so I said, "I've got an idea. You don't mind if I use your aluminum foil, do you?" And so I took newspaper and I put some aluminum foil on top of it, another layer of newspaper - I guess I had eight or ten of these and my wife lost quite a bit of aluminum foil. I didn't have a vacuum jacket to put around it so I simply wrapped up this hot dish in it and she was really amazed about three hours later how warm this dish was. So, that's a real practical application. I'm not really aware of any applications at temperatures above room temperature at the present time, because of the radiation problem. As you know, it is related to the fourth power of the absolute temperatures and it is particularly suited for these low temperatures. Professor Clark can tell you more about this in his talk this afternoon.

R. E. Carroll:

Who's next?

Question:

I would like to know what is the present status of superinsulation versus vacuum insulation for liquid helium?

G. Van Wylen
Answer:

You mean just regular vacuum insulation?

Question:

Nitrogen plus vacuum.

G. Van Wylen
Answer:

Oh, nitrogen plus vacuum.

Question:

Say, one or two inch superinsulation.

G. Van Wylen
Answer:

In the laboratory if you want to see the experiment you will use the liquid. Superinsulation is not the answer for they haven't yet made it transparent. So then, if you have a nitrogen shield in glass, then you can observe what you are looking at; this is certainly the advantage of it. But, as an insulator, I think superinsulation is better than liquid nitrogen shielding, by a significant factor.

Question:

Would you say a one-inch layer?

G. Van Wylen
Answer:

Now you are asking me for an opinion but I think the answer is yes. Mr. Lady do you have any opinion on that?

E. R. Lady:

No, I don't want to comment on that.

G. Van Wylen:

Though I'm not quite sure, I'll venture the opinion that the development of superinsulation is such that it would be better than nitrogen shielding.

E. R. Lady:

I would like to make a comment. It shows how one development can lead to another. Now we have this huge tank, 15,000 gallons, one inch of insulation. How do we support this tank? Because now probably the major heat leak is through its supports and we have to have something strong and yet non-conducting which traverses a distance of one inch, unless we deliberately design the support so that it is a lot longer, and thus minimize the heat leak. Linde hasn't told us how they do this and this is probably one of their real breakthroughs. It's not just the application of the insulation but the support. I've designed such trailers and we've had six to eight inches to play with. This is vacuum powder insulation, this has made the support problem much easier. So now here we have solved one problem but there is another problem. I'm very interested to see what this is.

Question:

It could be that in a small laboratory device, because of the ratio of surface area to volume, that the benefit of superinsulation would be much less than in a large tank, and perhaps a nitrogen shielded vessel with vacuum insulation would have a lower heat leak than a superinsulated device.

G. Van Wylen
Answer:

Yes, I agree. And of course, in so many laboratory experiments there are many other considerations: the ease of putting this thing together, you've got liquid nitrogen available and its easier to simply build a jacket around the liquid hydrogen perhaps than to go to the trouble of getting superinsulation.

Question:

I would like to ask about the safety of using liquid hydrogen in your laboratories. It makes me shudder just to think of it, and I understand that some Universities don't allow it. Do you use it here at Michigan?

G. Van Wylen
Answer:

Yes, we do.

Question:

For example, I heard a lecturer just yesterday who said that they didn't allow the experiments with hydrogen at M.I.T. Do they use it on the campus? The implication was that they were not allowed to use liquid hydrogen.

G. Van Wylen
Answer:

Well, I don't know about M.I.T. I was a little gun shy of this at first, but we had a room in which we put a very well-designed ventilation system, and we followed certain procedures and precautions which are well established now in using liquid hydrogen. If you follow these, people who use it use it about like they use gasoline. In other words they take the same kind of precautions that you would use in handling gasoline. This last year is the first time I personally have used it here. We have followed the safety precautions very carefully and have adequate warning devices, etc. I saw Mr. Sonntag here, "Dick, do you have anything you want to say about this?"

R. E. Sonntag:

No, I might say something about it later.

G. Van Wylen:

All right. Mr. Sonntag will be speaking this afternoon and we'll be interested. Mr. Lady, do you want to add anything at this point?

E. R. Lady:

Well, I understand things got a little hairy a few months ago in another department where they had liquid hydrogen and the vent line froze up due to either moisture or perhaps even nitrogen from the air freezing out. So the vent line was plugged up, they couldn't relieve the pressure, the pressure was gradually building. What do you do, do you run or do you try to solve the problem? They managed to solve the problem by carefully heating the line and melting out the plug before the pressure got to the bursting pressure. We still have problems. We have to be very careful with it.

Question:

What is the accident record so far in the laboratory use of hydrogen? Have there been any or many serious incidences?

E. R. Lady
Answer:

As far as I know, the one in Purdue is the only one I know of where they did have an explosion at night. I don't know if anyone was hurt or not.

G. Van Wylen:

I understand there was a major explosion on the West Coast in the last number of months too. Does anybody know about this?

Question:

The University of Chicago has used it for tens of years with no danger at all, as I understand.

G. Van Wylen
Answer:

I think it is one of the things that one has to really go into with his eyes open and there are really quite well established procedures for the amount of ventilation one needs. For example, the air is taken off the top of the room and not at the bottom. These kinds of considerations are important.

Question:

Van, what is the critical temperature of this hydrogen-oxygen mixture, it's fairly high, isn't it, the critical temperature at which it goes, it's about 900 degrees, isn't it?

G. Van Wylen
Answer:

No. If you get the right mixture, of course any little spark will trigger it off. If you get the right concentration, almost anything can start the reaction.

Question:

It burns awful fast doesn't it?

G. Van Wylen
Answer:

Yes, it does. It's important to have explosion blowout panels and this sort of thing to get rid of the pressure.

R. E. Carroll:

Did you have a remark, Dr. Clark?

J. A. Clark:

Linde's experience is a good one to keep in mind. They use liquid hydrogen in a closed laboratory in a building almost like this room. They are very careful and have hydrogen detectors around. They treat it very casually, but they are very careful. In several years they have never had a single problem with it - or that they reported to us at least.

Question:

In the multi-layer insulation is the spacial layer between foils a continuous layer?

G. Van Wylen
Answer:

Yes, yes. But efforts are made so that it is a rough surface, so that you get only point contacts. You want just the opposite of good contact - you want to have point contacts here and there which separate these layers and prevent through conduction without having a real solid - I mean a solid path from one wall to the other through which heat can flow.

Question:

The vacuum would be of no advantage if the conductivity through this layer were as great as that of air?

G. Van Wylen
Answer:

Right. So there is an optimization involved.

Question:

There is a combination effect of reflective insulation and a vacuum?

G. Van Wylen
Answer:

Right.

Question:

You mentioned powder. I'm puzzled a little bit about the powder. Is this a special powder that has a very low conductivity, or does it have any other properties?

G. Van Wylen
Answer:

Well, I think what you say points out there is an optimization problem. When you fill this space with powder then you also have the possibility of a solid conduction type problem. If the powder is very fine you again get these contact resistances between the granules of powder, but it does cut down the radiation. Now, I read one statement to the effect that they estimate that perhaps a half or more of the heat transfer is by the solid conduction type of heat transfer when you have vacuum powder insulation. And if you pack this stuff in there too hard, of course, you would increase this conduction. On the other hand if you --

Question:

Probably what you are doing there, if you pack it too hard, the point contacts become surface contacts.

G. Van Wylen
Answer:

Yes, yes, that's right. So there is a real optimization which is necessary in vacuum powder insulation.

Question:

And this may be a function of the particle-size condition.

G. Van Wylen
Answer:

Particle-size is important. The material that you use in the vacuum space is also important, for its own conductivity will be a factor. The ability of the material to prevent heat transfer by radiation is a major factor.

Question:

What are some of these materials?

G. Van Wylen
Answer:

Well, the two that are most commonly used are Santocel and perlite, and they have been used extensively.

Question:

Do you use some metallic powders?

G. Van Wylen
Answer:

Yes, this is another thing which is used. Work has been done on mixtures of metallic powders and Santocel or perlite. And the powders tend to be more opaque to radiation then the Santocel or perlite. So lots of work has been done on this to get the right powder so that you have the minimum heat transfer when you combine the heat transfer by radiation and the heat transfer by conduction.

Question:

In the tank car you described, would they use a vacuum in addition to this insulation?

G. Van Wylen
Answer:

Yes, multilayer insulation with a vacuum, right. And, as a matter of fact, the vacuum requirements for multilayer insulation are quite stringent. You need a higher vacuum with multilayer insulation than you do with powder insulation. For most of these insulations the curve of heat transfer versus pressure, has an "S" shape like this. There is a certain vacuum which you need to get this minimum heat transfer, and you need a much lower vacuum with multilayer insulation than you do with the powder insulation to reach this minimum heat transfer.

Question:

What sort of order of magnitude is this vacuum?

G. Van Wylen
Answer:

Oh, may I look at my notes one minute, I can give you an answer in about 30 seconds here. This is multilayer insulation and microns right here at this point (see Figure 11), this is one micron, so you see that you - below one micron you don't gain much by lower pressure. In the case of multilayer insulation - I'm sorry, this was the multilayer insulation curve, vacuum powder, - I have millimeters of mercury here, this is 10 microns, so you see it's a factor of 10 about as far as the vacuum requirement is concerned.

Question:

Then is this continuously pumped?

G. Van Wylen
Answer:

No, they're usually sealed off, but you've got to make provision to pump then. Now, one interesting thing occurs in the case of liquid hydrogen and helium. If, for example, you put liquid hydrogen in the container and you have a 20 degree wall and you have any residual CO_2, or oxygen or nitrogen, it freezes out and you get a very good vacuum because the gases will simply freeze out the cold surface and the vapor pressure at 20° Kelvin is so low that about all you really have left that will exhibit any vapor pressure is helium and hydrogen. So that actually the vacuum may go down when you fill the container because of freezing out the gas from the vacuum space.

R. E. Carroll
Question:

Gordon, how much more of these cryogenic fluids do we use in engineering research on our campus today than we did five years ago, could you give us some idea of the order of magnitude?

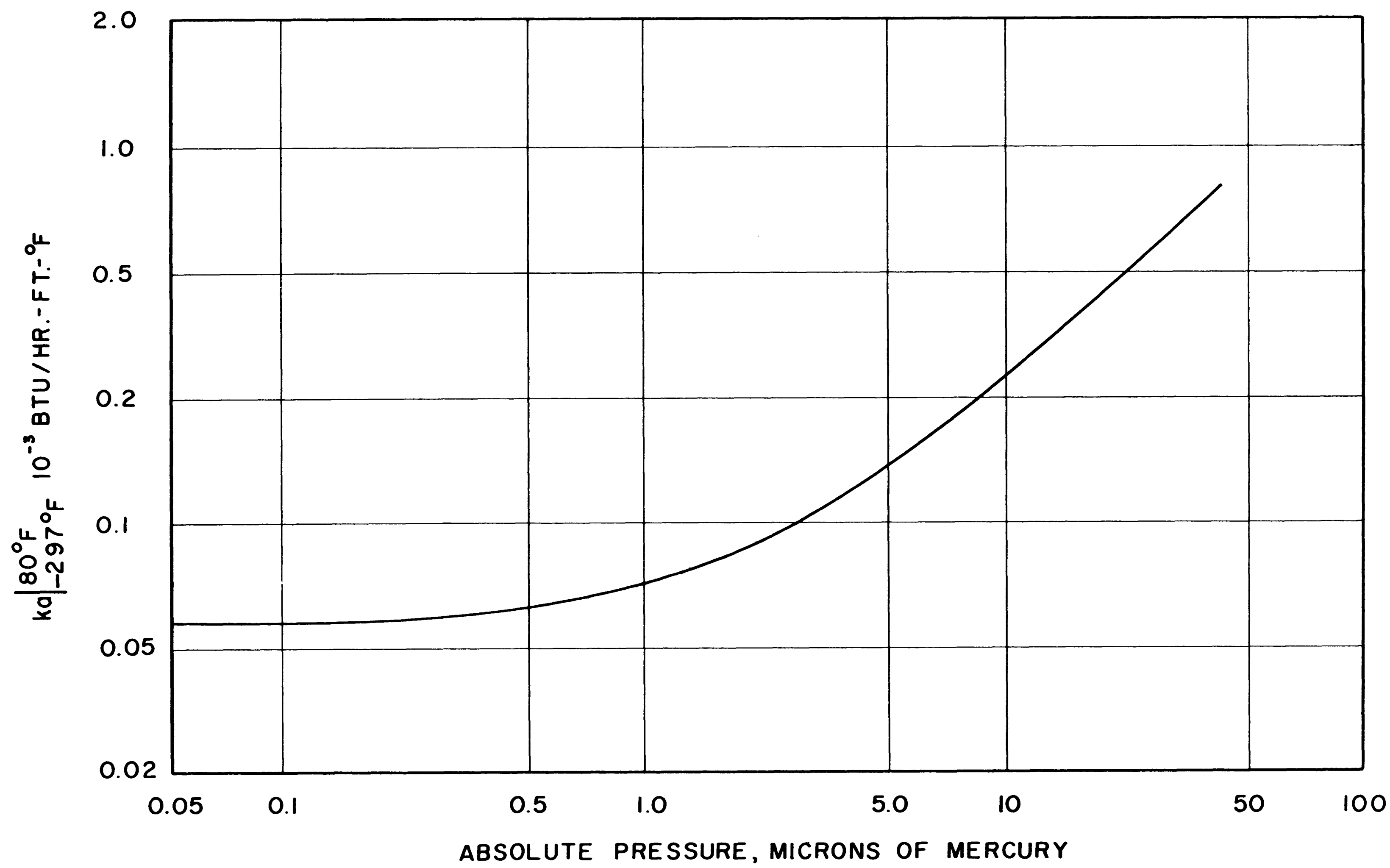


Figure 11. Apparent Thermal Conductivity Versus Pressure for Multilayer Insulation.

G. Van Wylen
Answer:

I had a little personal interest in this. I learned one thing from Dr. Collings at M.I.T., which is a little bit of a trade secret. He had a liquid nitrogen machine and sold this to the rest of the campus. He financed part of his operation from the sale of liquid nitrogen. So we have a machine and we sell liquid nitrogen to the campus. I think we now sell about 2000 liters per month. We have two machines with which we make it here, and we have a dual function for these. They become a very nice educational device, for we can take students into the laboratory and show them how liquid nitrogen is produced, stored, transported, and still at the same time we can sell it to the campus.

So, I think this is up by a factor of 5 in the last 5 years, or something like this. We have a variety of groups working in this field. For example, the medical school uses a good deal of liquid nitrogen in some of their research. And the whole matter of masers and lasers, of course, uses refrigeration. So, there are lots and lots of uses for it these days.

Question:

Do you know how much liquid helium is used?

G. Van Wylen
Answer:

Liquid helium is made in the Chemistry Department by Professor Westrum. I don't know the exact amount, but I know he does it for his own work with which you may be familiar, which involves the measurement of specific heat at low temperatures, and now he markets it around the campus as well. He probably runs the helium liquefier for two or three days each week. But I'm not quite sure of how much he actually sells.

R. E. Carroll:

Well, I guess there are no more questions right now, thank you very much, Professor Van Wylen. We've never been so close to being on time. It says on the program, "Coffee at 10:15". So we'll take 15 or 20 minutes out for some coffee and maybe something else out there too in addition to a little getting acquainted.

While we wait for two or three more people to come in from the hall, I'll just remark something about the timing on the program, as I mentioned to someone while we were having coffee, we've tried to run so many programs with precise timing for beginnings and endings of each talk for every part of the activity that we gave this up because it never works. You just can't seem to keep on time so, if you can't solve the problem you get around it. This is one of the adages we've heard lately, so we have these approximate times down below where we pay homage only to the cooks. We don't know yet when we are going to have lunch except that it will be somewhere around 12:15 in the Michigan League. But "when" in times of the program itself remains to be seen.

We may have a lunch break after Professor Haddad or after Professor Clark - and Professor Clark hopes it will be the latter because he has a very full afternoon in the laboratory.

I think we are all here now so I'll get on with the introduction of our next speaker, Dr. Stanley Autler. He received his Bachelors and Masters degrees from the City College of New York, and Ph.D. in Physics from Columbia University. From Columbia he went directly to M.I.T. Lincoln Laboratories where he worked on solid state physics, low temperature physics and high field superconductivity. Last October he went to Westinghouse Research Laboratories and his position there is Manager of the Low Temperature Physics Section. So we consider Dr. Autler is eminently qualified to speak on this subject of Superconducting Magnets. Dr. Autler.

SUPERCONDUCTING MAGNETS

Stanley H. Autler

Manager, Low Temperature Physics Section
Westinghouse Research Laboratories

Introduction

Professor Van Wylen anticipated a bit of the introduction of my talk by telling of some of Kammerlingh Onnes' contributions in the field of liquifying helium and his discovery of superconductivity. I can take up from there with a few other things that Onnes did in the early days of superconductivity. One thing he did was name it "superconductivity", and I think I can convince you that in the case of this phenomenon there isn't the problem, as with "super-insulation", whether the prefix "super" is really deserved.

The resistance really does go to zero when a material becomes superconducting. Onnes demonstrated this very well by his famous persistent current experiment. What he did was to make up a ring of lead, and place it in a magnetic field supplied by some sort of external magnet; he then cooled it below its transition temperature so that it became superconducting. Then he turned off the external field which results in the generation of a circulating current in the ring in the direction that tends to keep the flux linking the ring constant. If the lead ring has zero electrical resistance, the kinetic energy of the current should not be dissipated and the current should persist without decaying. This is what Onnes found, and he maintained the persistent current long enough to show that the resistance of superconducting lead is far less than the resistance of a normal metal.

This has since been done more thoroughly, for example, in the laboratory of Professor Collins at MIT. He kept a circulating current going for over two years in a lead ring. They then had some problems with the liquid helium and the experiment terminated; however, during the time of observation there was no visible decrease in the current ring. Even more refined experiments have been done, and these have established that the resistance of a superconductor is no more than 10^{-17} times the resistance of copper at room temperature. So, I think we are truly justified in saying that the resistance goes to zero in the superconducting state and it deserves its name.

Another thing that Onnes tried to do was to make a magnet out of superconducting material. It is obvious that if you made up a coil of superconducting wire and passed a current through it a magnetic field would be generated. If there was no voltage drop you could maintain this field without dissipating any power. Onnes made up a coil of lead wire and found he could indeed generate a magnetic field. He found, however, that if he tried to generate a field more intense than a few hundred gauss, resistance appeared in the coil; there is a critical field above which a superconductor loses its remarkable properties. The critical fields of all the other superconductors discovered in those early years were also so low that comparable field strength could be generated much more easily with room-temperature coils. There was a loss of interest in the possibility of generating useful fields with superconductors which continued until just a few years ago.

In the intervening period there was quite a bit of work done on superconductivity in the laboratory. Many new superconducting elements were discovered. Figure 1 is a periodic table of the elements arranged in a way that may or may not be familiar to you. The elements enclosed by boxes are the ones which are known to be superconducting at the present time. These elements fall more or less into two groups as you can see. The group on the right consists of elements, in which the inner shells of electrons are full. This includes common metals such as aluminum, zinc, lead, tin and others; and the other group is made up of so-called transition metals in which one of the inner shells of electrons is incomplete; it is with this group we are most concerned in the case of high field superconductivity. The superconducting properties of this group were discovered much later, which is probably why superconducting magnets came so long after the discovery of superconductivity. Niobium with a transition temperature of 9.2°K has the highest Tc of the elements.

Alloys can be made up, however, which have higher transition temperatures. Niobium-zirconium can have a Tc of 11 or 12°, molybdenum-rhenium goes up to about 12°, molybdenum-technecium alloys have Tc as high as 16°, and there are many others. There is one interesting thing that we can learn from looking at this periodic table. Notice that the transition temperature is high for niobium, low for molybdenum, high for technecium, low for ruthenium. This same alternation is also found in the row below; hafnium has a low transitional temperature, tantalum is higher, tungsten is very low, and rhenium is up again.

This is well illustrated in Figure 2, based on a paper by Matthias who discovered certain empirical rules for predicting the transition temperature of elements and alloys. Here the transition temperature, Tc, is plotted against the number of valence electrons per atom, which is 5 for niobium, 6 for molybdenum, etc. Niobium is near the peak of the oscillatory curve, molybdenum is near the trough, technecium is near the next peak, and so on. A good deal of this was known about 10 years ago, and as Professor Van Wylen has mentioned,

H																	He
Li 0.08 cub.	Be 0.06 hex.											B 1.3 hex.	C 1.2 hex.	N	O	F	Ne
Na 0.09 cub.	Mg 0.05 hex.											**Al 1.20 cub.**	Si 0.07 cub.	P 2.0 orth	S	Cl	A
K 0.08 cub.	Ca 1.3 cub.	Sc cub.	**Ti 0.53 hex.**	**V 5.1 cub.**	Cr 0.08 cub.	Mn 0.15 cub.	Fe 0.75 cub.	Co 0.06 hex.	Ni 0.75 cub.	Cu 0.05 cub.	**Zn 0.91 hex.**	**Ga 1.10 orth**	Ge 0.05 cub.	As 0.8 rhom	Se 1.3 hex.	Br	Kr
Rb 0.8 cub.	Sr 1.4 cub.	Y 0.10 hex.	**Zr 0.70 hex.**	**Nb 9.2 cub.**	**Mo 0.92 cub.**	**Tc 9.0 hex.**	**Ru 0.47 hex.**	Rh 0.09 cub.	Pd 0.10 cub.	Ag 0.05 cub.	**Cd 0.56 hex.**	**In 3.37 tetr.**	**Sn 3.730 tetr.**	Sb 0.15 rhom	Te 1.2 hex.	I	Xe
Cs 0.8 cub.	Ba 0.15 cub.	**La 4.37 hex.**	**Hf 0.35 hex.**	**Ta 4.4 cub.**	**W 0.01 cub.**	**Re 1.7 hex.**	**Os 0.71 hex.**	Ir 0.10 cub.	Pt 0.10 cub.	Au 0.05 cub.	**Hg 4.152 rhom**	**Tl 2.38 hex.**	**Pb 7.22 cub.**	Bi 0.05 rhom	Po mono.	At	Rn
Fr	Ra	Ac	**Th 1.39 cub.**	Pa	**U 0.8 orth**	Np	Pu	Am	Cm								

Rare earths

Ce 0.25 cub.	Pr 0.25 hex.	Nd 0.25 hex.	Pm	Sm	Eu cub.	Gd hex.
Tb hex.	Dy hex.	Ho hex.	Er 0.8 hex.	Tm hex.	Yb cub.	Lu hex.

From Shoenberg's book [2]. The framed elements are superconducting. The transition temperatures are given. For the normal elements, the lowest tested temperatures are indicated.

Figure 1. The Superconducting Elements in the Periodic System.

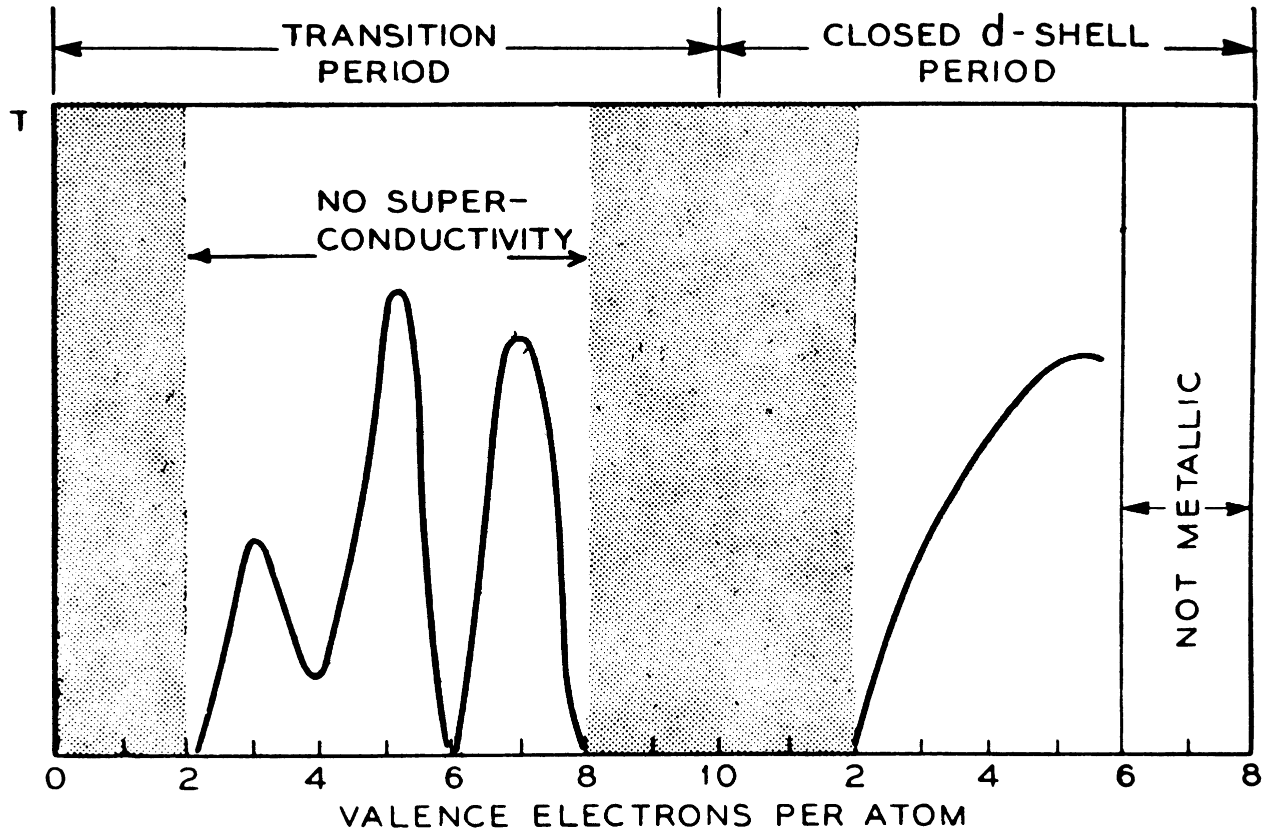


Figure 2. Qualitative Behavior of Superconducting Transition Temperatures Throughout the Periodic System. (Matthias)

a number of superconducting compounds with even higher transition temperatures, up to 18°K, had been discovered. Little attempt had been made, however, to investigate the magnetic properties of these materials.

In 1959 at MIT some of us were working with solid-state masers, extremely sensitive radio receivers of microwaves which operate in liquid helium and require variable magnetic fields in order to adjust the energy levels of the paramagnetic salts which are their amplifying elements. It occurred to us that it would be very useful if we could provide these variable fields with a superconducting magnetic. We wound up coils of cold-worked niobium, and to our surprise, almost immediately began getting fields of four kilogauss or more. Further work during the year brought the fields up to around 10 kilogauss which was about an order of magnitude higher than the fields that had previously been generated using superconductors. So, things began to look interesting at this point for superconducting magnets.

Figure 3 shows schematically a way in which one can set up a persistent current in a superconducting coil. Basically the idea is this: across the superconducting coil is connected a shunt which is also a superconducting material. An external power supply which just consists of a dry cell, variable resistor, and a switch is connected in series. Initially a part of the shunt is held above the liquid helium level, so it is normal rather than superconducting. If we turn the power supply on, all the current will flow through the superconducting coil; no steady-state current flows through the shunt for the shunt has a small but finite resistance and is in parallel with the coil which has zero resistance. One can then adjust the value of the current and the magnetic field by varying the value of the resistance. When you have it where you want it; say, when the maser is nicely tuned, one can lower the shunt beneath the liquid helium level. Then one has a completely superconducting path through the shunt and the coil, and the argument we went through before for the ring applies. You can not change the flux linking this circuit. At this point you can open the switch on the power supply and the current, which was flowing through the external leads and the coil will switch so that it flows through the shunt and the coil. It will then go on flowing indefinitely with no further contact with the power supply. This can all be done without actually moving the shunt; simply keep the shunt under the helium and attach a little heater to it. You can have the shunt normal by raising its temperature, or superconducting by turning the heater off. In this way one can set up a completely stable magnetic field using a superconducting magnet.

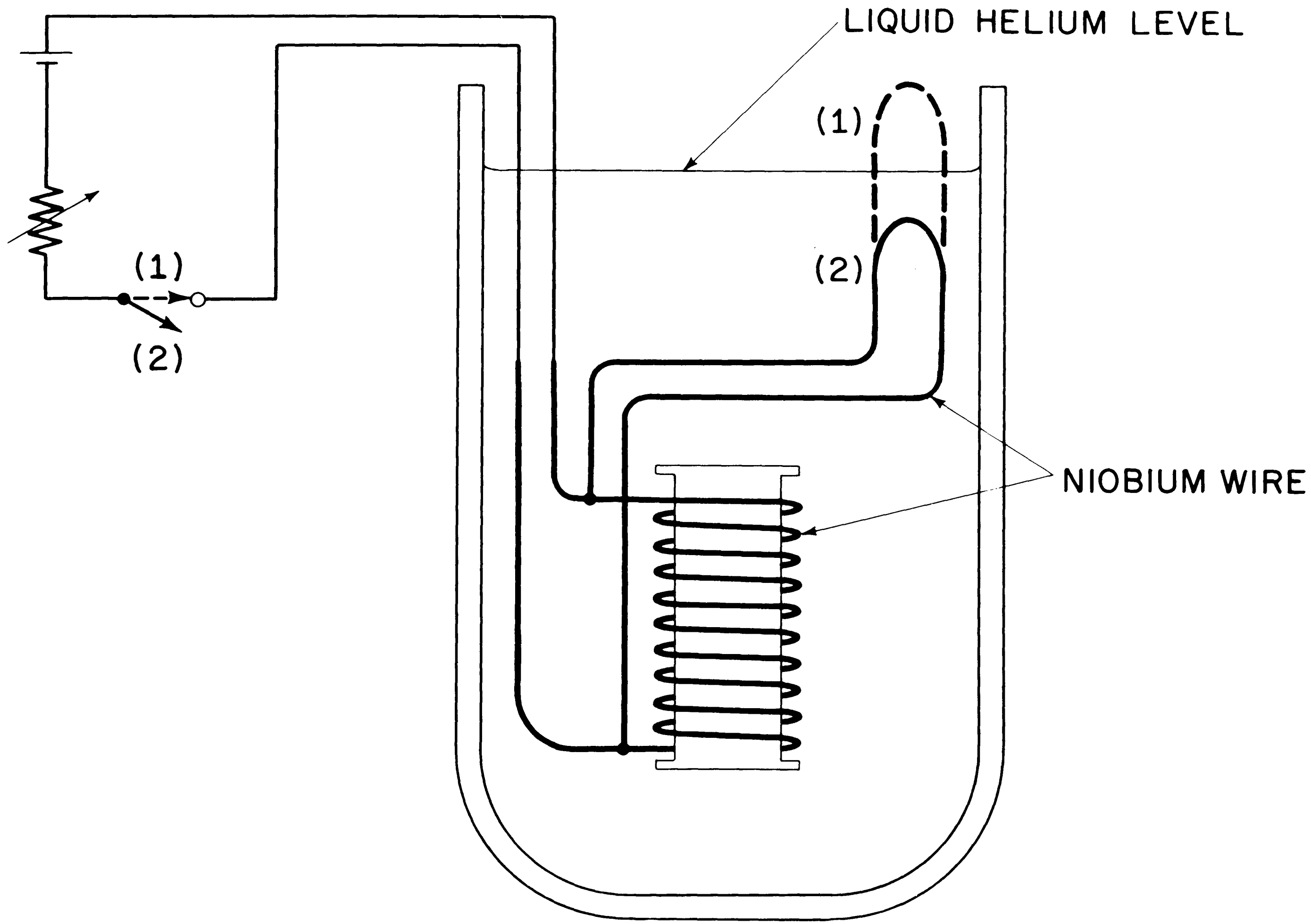


Figure 3. Schematic Representation of Method of Setting up Persistent Currents. (1) Auxiliary Wire is Raised Above Helium Surface and Carries no Current. Magnetic Field is Under Control of External Power Supply. (2) Auxiliary Wire is Completely Superconducting. Current Through Solenoid is now Independent of Power Supply Which may be Removed.

Figure 4 shows this early maser. Most of the apparatus in the picture is connected with a maser; at the bottom is the little coil of niobium wire which provides a field up to 6 or 7 kilogauss. The power supply for that coil, is a 1-1/2 volt dry cell and small variable resistor.

It was in the beginning of 1961 that the big breakthrough came. That is when a group at Bell Laboratories headed by Gene Kunzler, announced the results of some measurements they made on Nb_3Sn, a compound of niobium and tin. Briefly, they found that a sample of sintered Nb_3Sn encased in tube of Nb was capable of carrying a current density greater than $10^5 amp/cm^2$ in a field of 90 kilogauss without any apparent resistance. This promised another order of magnitude increase in the strength of magnetic fields generated with superconductors if this material could be produced in commercial quantities, and if one could solve the sort of practical problems that were bound to arise in using it. Many people in various places went to work on this problem of making a superconducting material such as niobium-tin practical.

It was only a few months later, that scientists at Bell and Atomics International announced results on an alloy of niobium and zirconium (Zr), having a transition temperature in the region of 11 or 12°K. This was found to remain to be superconducting, again up to current densities of about $10^5 amp/cm^2$, in fields up to 60 or 70 kilogauss. This not so high as niobium-tin, but there were certain advantages over niobium-tin. Nb_3Sn is an intermetallic compound, and these are characteristically very brittle. This causes a real problem in fabricating it into a wire or ribbon that one could use in making an electromagnet. Nb-Zr, however, is a ductile alloy and is much easier to make into a wire.

Figure 5 shows some test results on Nb_3Sn and Nb + 25% Zr. Nb_3Sn carries substantial currents (between 10^4 and $10^5 amp/cm^2$) up to fields well over 150 kilogauss. The high-field end of the curve is actually extrapolated; there are no fields available for testing the properties of these materials above 150 kilogauss. One can use pulse fields but the results one gets are somewhat questionable. However, there is indirect evidence to indicate that somewhere in the vicinity of 200 kilogauss, the current capacity of Nb_3Sn will drop off sharply. Cold-worked Nb-Zr wire, containing all the dislocations created during the wire-drawing process carries comparable currents up to about 70 kilogauss. If one anneals Nb-Zr wire, removing the dislocations, the critical currents drop sharply as seen in Figure 5c, although the ultimate critical field is not greatly changed. Figure 5a illustrates another characteristic of Nb-Zr which has turned out also to be true of other superconductors,

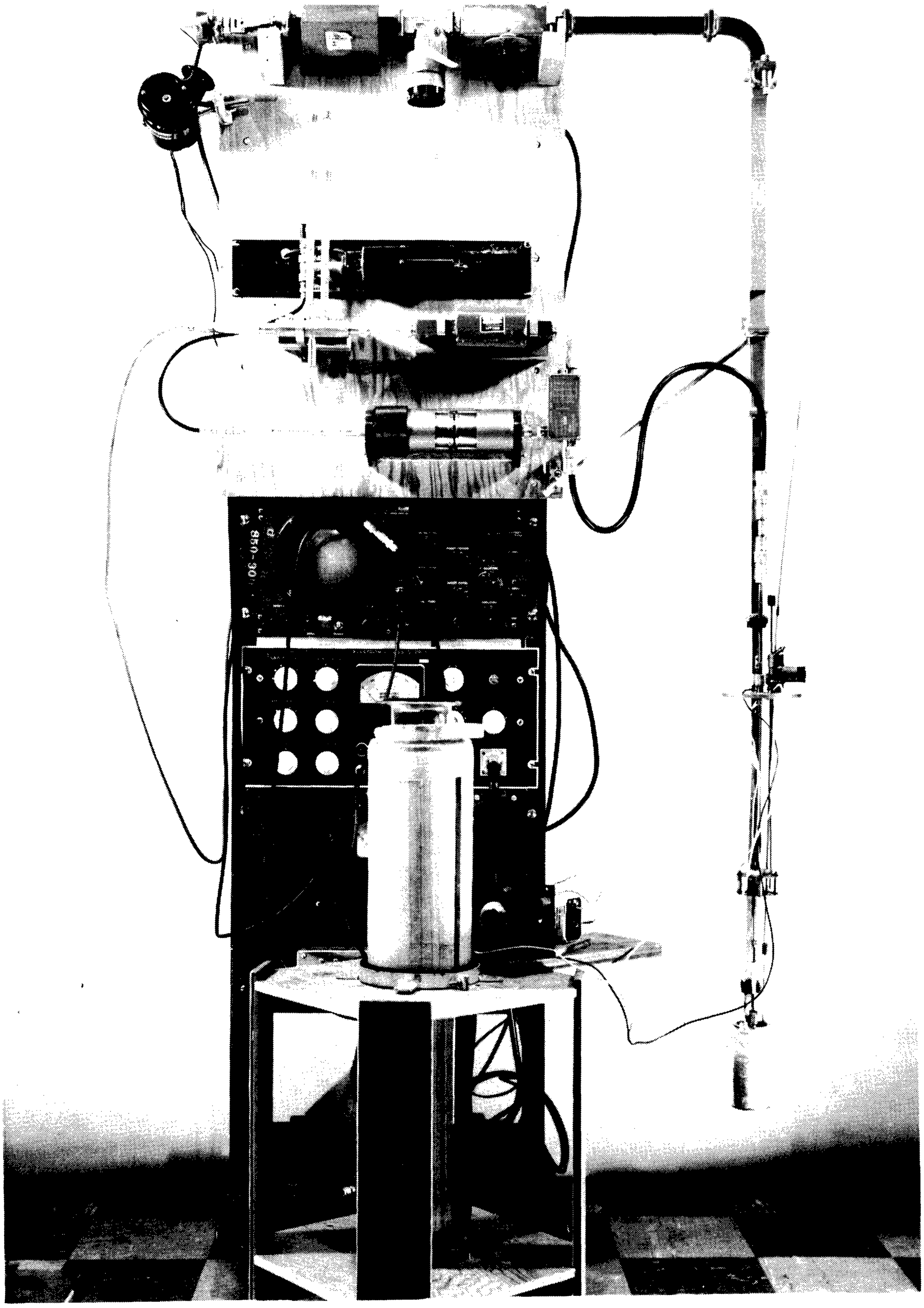


Figure 4. Tunable Solid-State Ruby Maser Which Amplifies 1350-1450 Mc and Operates at Liquid Helium Temperatures. Variable Magnetic Fields up to 7 Kilogauss are Provided by Niobium Solenoid at Lower Right. Current Supply is 1-1/2-v Dry Cell Which may be Disconnected After Persistent Current has been set up.

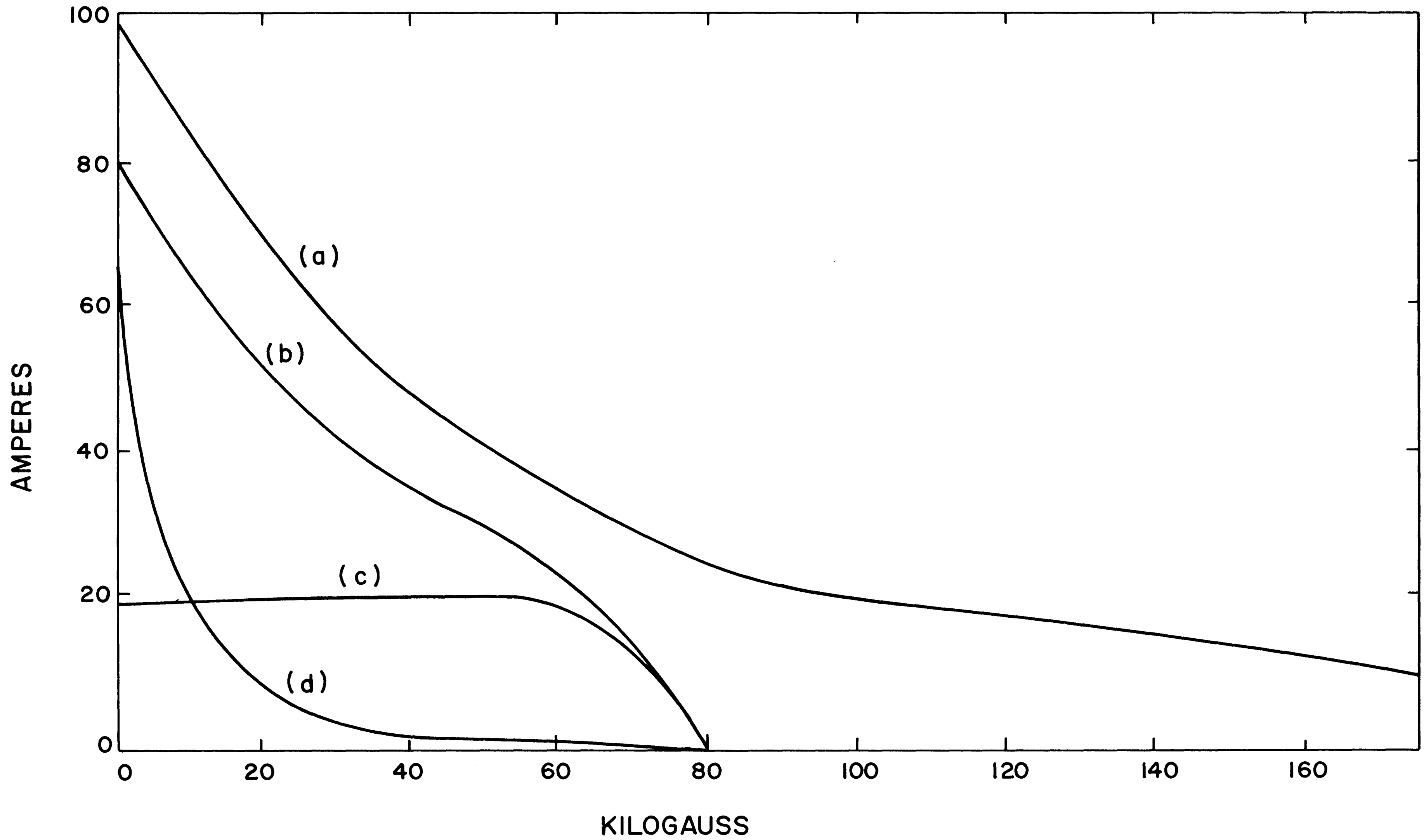


Figure 5. Typical Characteristics of Superconductors. (a) Kunzler-type Nb_3Sn Wire (.015 inch diam.) (b) Nb-Zr Alloy Wire, Cold-Worked (.010 inch diam.) (c) Same Wire as (b) but Wound into a Coil (d) Same Wire as (b) After Annealing to Remove Dislocations.

and which was quite a disappointment at first. If one takes a short (two-inch) length of the material and tests its current-carrying capacity as a function of magnetic field, a curve such as Figure 5b is obtained; if several hundred feet or more is wound into a small coil, the critical current as seen in Figure 5d is limited to about 20 amp even at low fields. This "degradation effect" is still not really understood, although we are gaining some insight into its causes. A similar effect is observed to a greater or lesser extent in other superconducting materials. Although the loss of a factor of 2 or 3 in Tc is regretable, it does not prevent the fabrication of useful coils; a great many superconducting magnets have been made using .010" diameter Nb-Zr carrying 15 to 20 amperes.

Recently Westinghouse has started producing an alloy of niobium and titanium, which extends the useful range of the ductile alloys to the 90-100 kilogauss region. It also promises to carry somewhat higher currents densities in coils.

In 1961, the year immediately following the announcement of the discovery of the remarkable properties of Nb_3Sn and Nb-Zr, a great deal of effort by physicists, metallurgists and cryogenics engineers went into learning to produce these materials in quantity and make powerful magnets. A "gauss race" developed to attain the highest fields and by the end of 1961, fields in 60 to 70 kilogauss region had been generated using both Nb-Zr and Nb_3Sn. The magnets were small, unreliable, and not very useful, but they did demonstrate that the job could be done.

Up to this point the work that had been done was really very empirical. The materials had been discovered more or less by accident, in the sense that it was unexpected to almost everyone, including the people who made the first measurements, that Nb_3Sn, would remain superconducting up to such high fields. Their rationale was basically: the higher the transition temperature, the higher the critical fields should be; and so we'll look at the material with highest transition temperature. They hoped to find that Nb_3Sn would have a critical field of, say 15 or 20 kilogauss, never expecting 200 kilogauss. It is only in the last couple of years, 1962 and 1963, after quite a bit of basic work, that some aspects of the behavior of high-field and superconductivity are beginning to be understood. I would like to talk about this, and I'd also like to tell you about some of the things that are not understood.

First, however, I will briefly summarize the present state of the technology of superconducting magnets. On a small scale, that is on a laboratory scale, magnets producing up to 60 or 70 kilogauss in holes an inch or two in diameter, are now being produced and marketed by a number of companies. They are quite reliable and useful tools in many laboratories. Progress has been slower on the larger volume magnets primarily because these are much more expensive to work on; you prefer to make your mistakes and iron out problems on small, relatively inexpensive coils before launching into the large, expensive ones.

Figure 6 is a picture of a magnet which was built recently at Westinghouse. This has a one-inch hole, and produces a field of 94 kilogauss. It is now in use in our lab, to do various experiments at fields up to 90 kilogauss. By making use of the experience gained, it would now be possible to make an equivalent magnet that would produce the same field in the same diameter hole using much less wire; it would be smaller, lighter and cheaper to make.

Figure 7 shows an insert that has been put into the one-inch hole of the magnet in Figure 6, in order to obtain the magic figure of 100 kilogauss. This was achieved, although the 1/8-inch hole does not make for a very versatile magnet. General Electric about 6 months ago announced 100 kilogauss field, also in a small hole. They have been having problems with the durability of their high-field coils but are making progress in improving this. RCA is using a niobium-tin coated ribbon and has announced 92 kilogauss in a half-inch hole. So, it looks as if small-volume fields in the 90 to 100 kilogauss region are here. Larger magnets have been made to operate at lower fields but much larger working volumes.

The Physics of High-Field Superconductors

I'd like to go into the physics of these new superconductors and explain some of the aspects of them that have gradually been better understood in the last couple of years. Let us start by reviewing some of the properties of a superconductor such as lead or tin. These are examples of the classic superconductors that Kammerlingh Onnes knew about, the so-called soft superconductors which exhibit the Meissner effect mentioned by Professor Van Wylen. That is, in the superconducting state no magnetic flux can penetrate the interior of such a superconductor. The material is completely diamagnetic except in a very thin layer near the surface. The thickness of this surface region into which the field penetrates is given by the penetration depth, λ , which is of the order of 10^{-5}cm. In a thick sample, this involves only a small fraction of the volume, so we can think of the flux density being essentially zero. Figure 8 shows the magnetization (which is negative in our case indicating that the material is diamagnetic) plotted against the external magnetic field for an ideal soft superconductor. Magnetization will

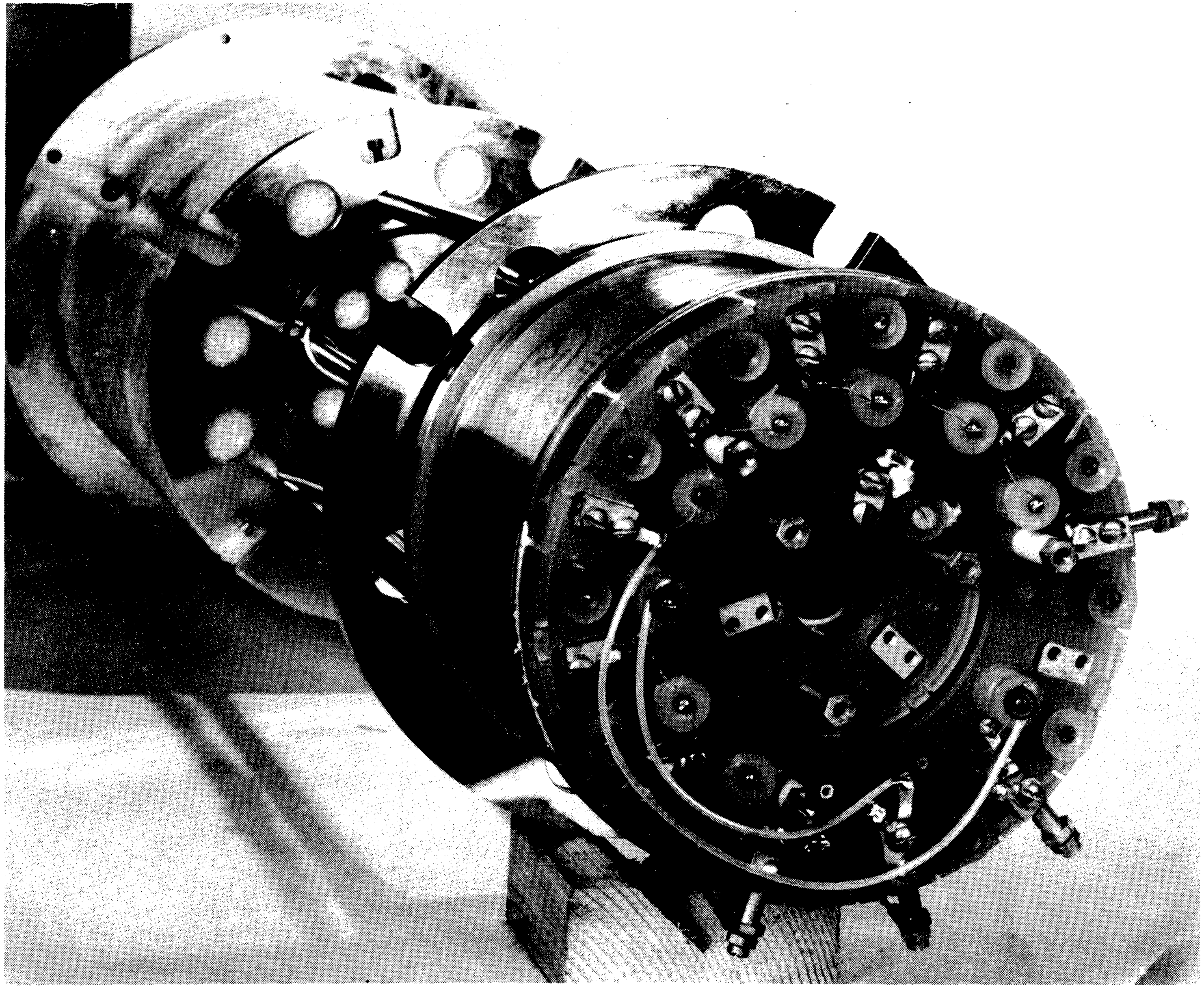


Figure 6. Westinghouse Experimental Superconducting Magnet Generates 90 Kilogauss in 1-inch Diameter Hole.

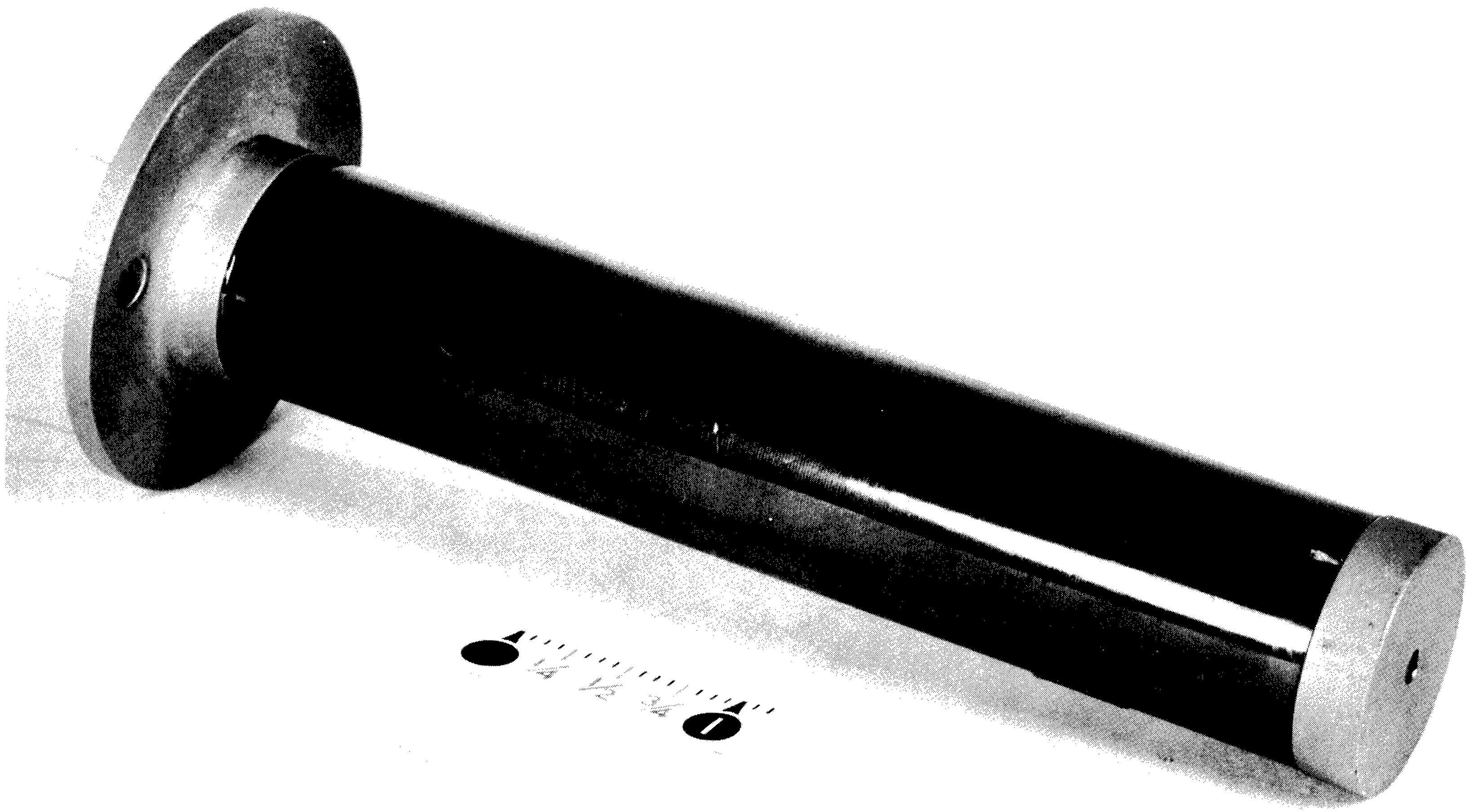


Figure 7. Insert for Magnet in Figure 6. With the Use of this Insert (made of Nb-Ti wire) Fields of More Than 100 Kilogauss are Obtained in the Small Hole.

be proportional to the magnetic field up to H_c , the critical field, where the material suddenly becomes normal and nonmagnetic. Also, the electrical resistivity is zero up to H_c , but sharply rises to its normal resistance above that field. In the case of a piece of well-annealed pure tin or lead, these relationships are quite closely obeyed. Also, I might say that the magnetization curve should be reversible; that is, if one observes this magnetization in a rising applied field, it will be retraced when one lowers the field to zero.

H_c, for a particular metal, is a function of temperature. In Figure 9 we see that this function is pretty well approximated by a parabola, and that for Pb the critical field is about 800 gauss at 0°K and of course goes to zero at the transition temperature, 7.2°K. Lead has the highest transition temperature and the highest H_c of the soft superconductors. For transition metals you see a somewhat steeper slope in this H_c vs T curve. Vanadium, although it has a lower transition temperature than lead, has a higher critical field at low temperatures. Niobium with Tc around 9°K has a critical field up around 2 kilogauss. This is the highest of the elements. For Nb_3Sn, with Tc of 18°K, the curve is approximately the same shape, and $H_c \approx 5$ kilogauss at 0°K. Notice that these figures are in the low kilogauss region; even for Nb_3Sn H_c does not exceed five kilogauss. Some of you may be confused at this point, since previously I was talking about critical fields over 100 kilogauss for Nb_3Sn. Well, we were confused to a few years ago, and it is only recently that it has been fully realized that there may be a number of different critical fields associated with a particular material. More precisely, the types of materials with which we are concerned have three critical fields of interest. I would now like to tell you more about these superconductors.

During the 1950's some Russian theorists were publishing papers which predicted a superconductor with somewhat different properties than in Figure 8. These theorists named Ginsberg, Landau, Abrikosov, and Gorkov,worked out a theory in stages which is now sometimes called the GLAG theory. It predicts the possibility of current carrying a resistanceless current up to a critical field much higher than five kilogauss. Figure 10 goes into somewhat more detail on the properties of these materials, which we will call Ideal Type 2 superconductors. First of all, by ideal, we mean that it is physically homogeneous; it has no defects, no physical inhomogeneities in it. Then, if one makes a measurement of magnetization as a function of magnetic fields strength, he should get the same curve while decreasing the field as while increasing it. We see from Figure 10 that the magnetization is linear in the filed up to a lower critical field, H_{c1} . In this linear region the material is completely diamagnetic, excluding all flux. Between H_{c1} and the upper critical field, H_{c2} , the magnetization begins to drop. Flux is penetrating

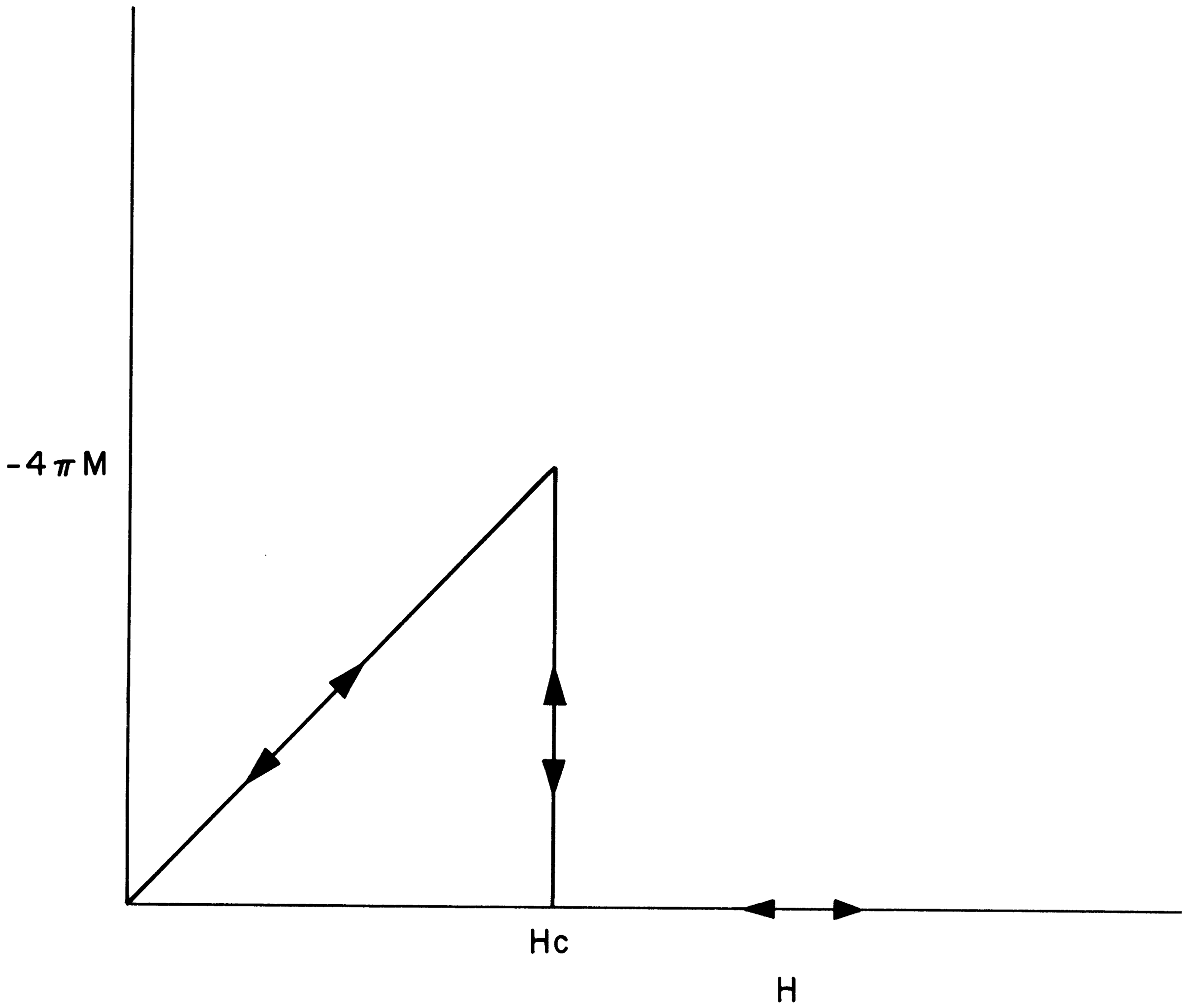


Figure 8. The Magnetization of an Ideal Type I Superconductor. The Magnetization is Reversible at all Fields. Electrical Resistance is Zero for $H < Hc$.

our superconductor but it is still partially diamagnetic. Finally at H_c2 the magnetization goes to zero and the material is nonmagnetic and non-superconducting. Quite a few examples have been found of this type of superconductor; many alloys fall into this class, and it has also been shown recently that one or two elements, in particular niobium, is a superconductor of this type. A third critical field, H_{cb} , the bulk or thermodynamic critical field, is perhaps most fundamental if we are interested in the energy changes in a superconductor, but does not show up directly in a magnetization measurement.

Figure 11 illustrates in a somewhat different way the properties of a Type 2 superconductor. We again see three regions. Below H_c1 the flux is zero, in the inside the superconductor and the magnetization is linear in H . Between H_c1 and H_c2 we are in a mixed state; part of the flux is penetrating the superconductor. And then above H_c2 all of the flux penetrates and the material is both magnetically and electrically normal. Notice however, that the resistivity remains zero up to H_c2 which can be much higher than the thermodynamic critical field which is limited to about 5 kilogauss even for Nb_3Sn. Here, then, is the key to the properties of these high-field materials. It is H_c2 which is the field up to which the resistance remains zero, and H_c2 may be as high as several hundred kilogauss.

Figure 12 is taken from Abrikosov's paper in which he predicts the form of this magnetization curve for different values of a certain parameter, κ , which is a measure of the mean free path of the electrons in the material. If there are impurities in the material which scatter the electrons, κ is increased. If κ is less than $1/\sqrt{2}$, M vs H has the triangular form characteristic of a Type 1 superconductor. However, if $\kappa > 1/\sqrt{2}$ the magnetization looks like the curve in Figure 10. Note that as κ increases the lower critical field goes down and the upper critical field goes up.

Figure 13 shows more experimental results obtained by Livingston at General Electric, on a series of lead alloys. What he has done is to start with pure lead which shows the triangular magnetization curve a Type 1 superconductor. Then he put increasing amounts of indium in the lead, thereby increasing the number of scattering centers for the electrons, and increasing κ . Notice how the magnetization curves resemble those predicted by Abrikosov for various values of κ . This is a clear demonstration that superconductors of this type do exist. While it is illustrated most clearly in the case of the series of lead alloys such as this, it has also been pretty well established that all the high-field superconductors; Nb-Zr, Nb_3Sn, etc. also fall into this category of Type 2 superconductors. Their usefulness at high fields results from

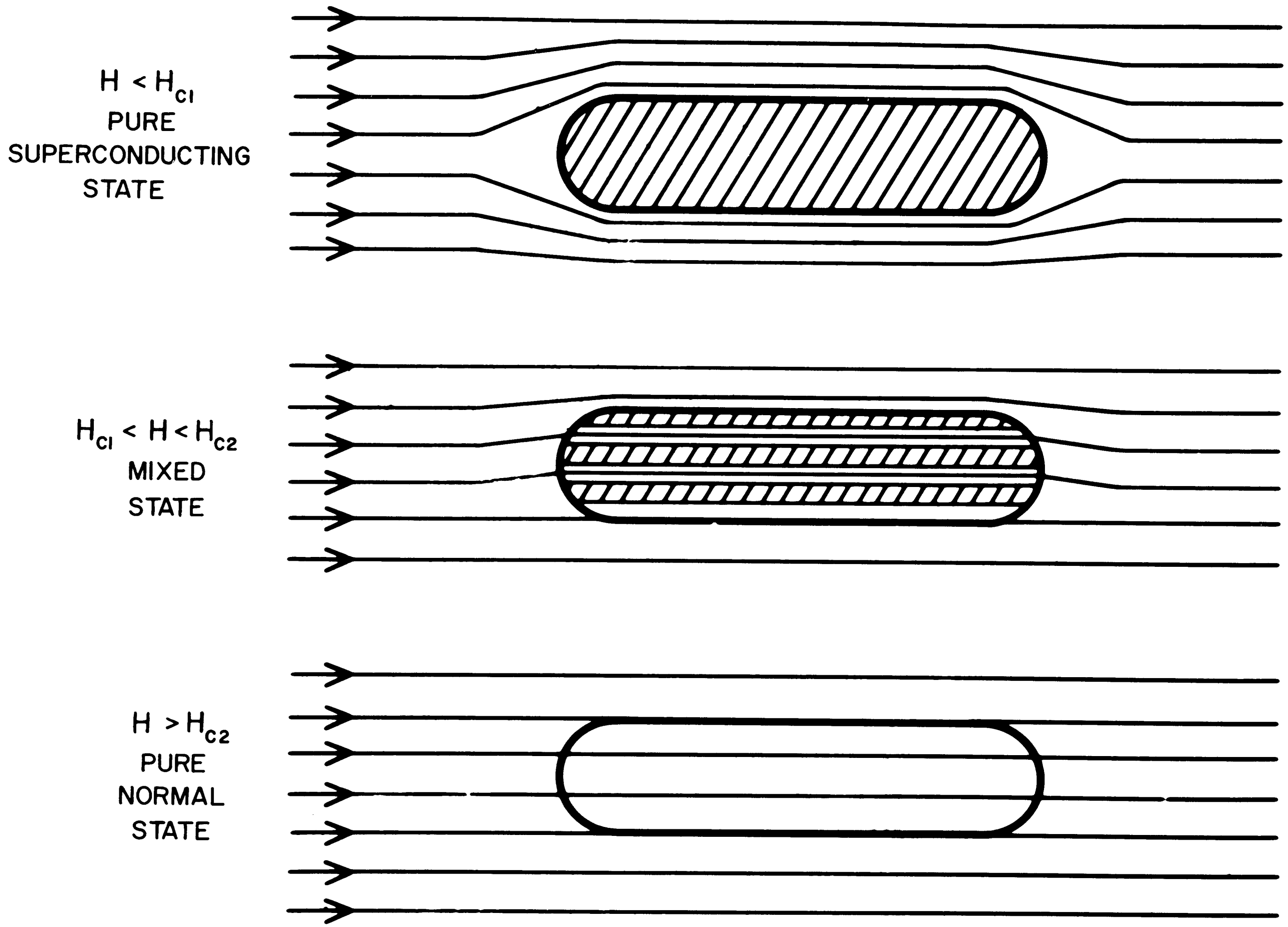


Figure 11. Illustration of the Magnetic Flux Configuration in the Meissner State, Mixed State, and Normal State of a Type-II Superconductor.

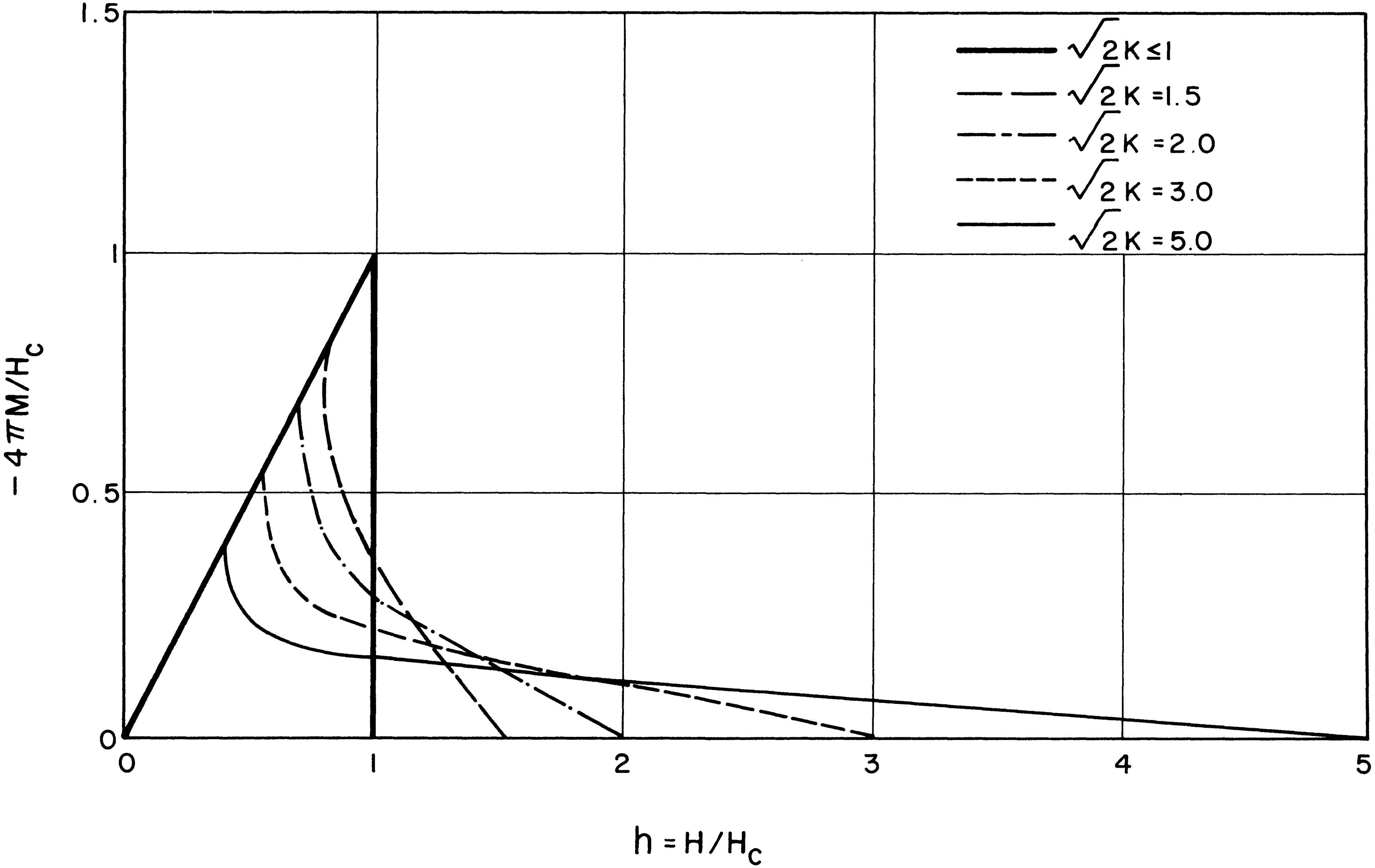


Figure 12. Magnetization vs Applied Magnetic Field for Various Values of the Ginsberg-Landau Parameter, K . For $K < 1/\sqrt{2}$ the Triangular Curve is Characteristic of a Type-I Superconductor. (Taken from Goodman's Plot of Abrikosov's Solution)

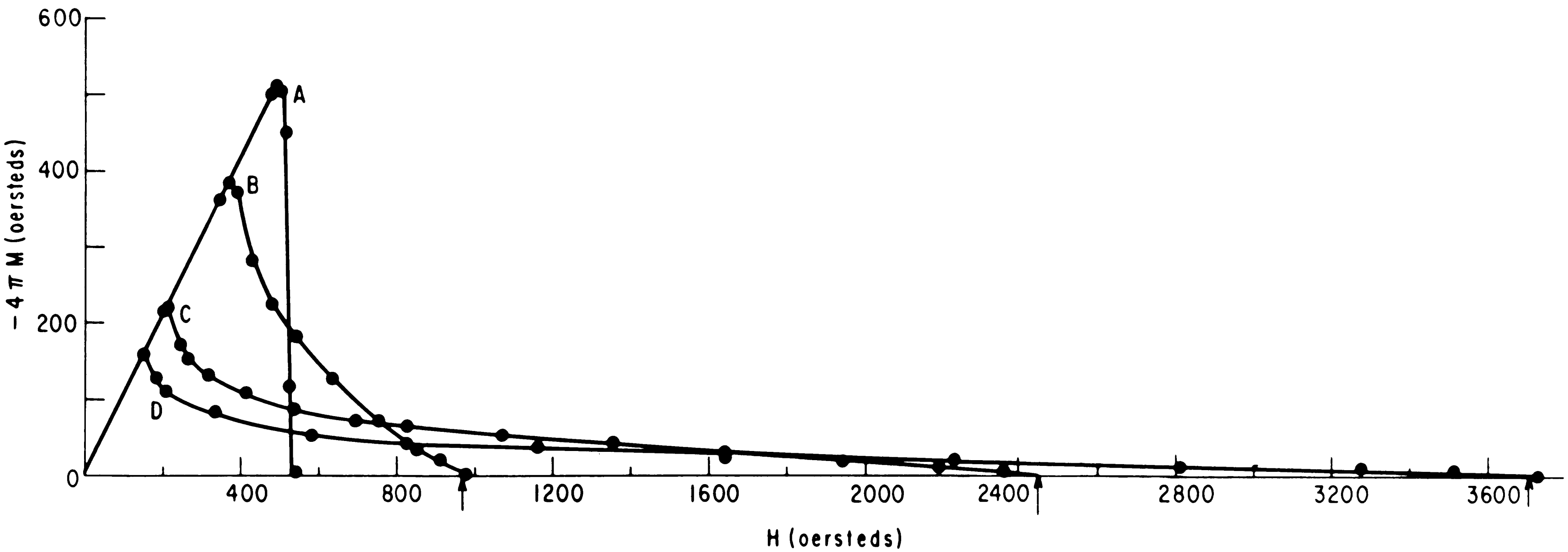


Figure 13. Magnetization Curves of Annealed Polycrystalline Lead and Lead-Indium Alloys Taken in Ascending Field at 4.2°K. (A) Lead; (B) Lead-2.08 w/o Indium; (C) Lead-8.23 w/o Indium; (D) Lead-20.4 w/o Indium. (Livingston)

large values of κ , which lead to upper critical fields, H_c2 , which are substantially higher than the thermodynamic critical field.

I am going to retaliate for Professor Van Wylen's invasion of my subject by using a little simple-minded thermodynamics which I hope will help give some insight into the origin of Type 2 superconductivity. We will treat the superconducting-to-normal transition as a phase change between two equilibrium states. The appropriate thermodynamic potential for our system in which the temperature and field intensity are independent variables is the Gibbs free energy, G(T,H.) This can be expressed as

$$G(T,H) = G(T,0) - \int_0^H M(T,H)dH$$

where M is the magnetic moment per unit volume.

Inside a completely diamagnetic (Type 1) superconductor the flux density, B , equals zero. That is B R $H + 4\pi M = 0$ so

$$M = -\frac{H}{4\pi} \quad \text{for} \quad H \leq H_c$$

We may then write

$$G_s(T,H) = G_s(T,0) + \frac{H^2}{8\pi}$$

In the normal state (say, $T > Tc$) $M = 0$ for a nonmagnetic metal, so

$$G_n(T,H) = G_n(T,0)$$

At $H = Hc$ the superconducting to normal phase change occurs, and

$$G_n(T,H_c) = G_s(T,H_c)$$

Therefore,

$$G_s(T,H) = G_n(T,0) - \frac{H_c^2(T)}{8\pi} + \frac{H^2}{8\pi} \qquad (1)$$

normal state energy	energy reduction resulting from "ordering" or "pairing" of electrons	energy required to exclude flux from interior of superconductor

Equation (1) is the fundamental thermodynamic equation for a Type 1 superconductor. H_c is the thermodynamic critical field and does not exceed five or six kilogauss for any known superconductor.

In Figure 14 G(H) is plotted for the normal state where it is independent of H, and the diamagnetic state for which the negative ordering energy and the positive field energy become equal at $H = H_c$. We also show a mixed state in which the sample may be thought of as partially superconducting and partially normal. There will be a smaller amount of ordering energy at $H = 0$, but some penetration of flux, so the energy involved in excluding flux is reduced. If this field energy is reduced by a smaller factor than the ordering energy, we have a Type 2 superconductor as illustrated. The equilibrium state will always be the one with lowest G. Thus, below H_c1 the superconductor will be completely diamagnetic; between H_c1 and H_c2 it will be in the mixed magnetic state; above H_c2 it will be normal and will be completely diamagnetic; between H_c1 and H_c2 it will be in a mixed magnetic state but will still have no electrical resistance; above H_c2 it will be normal.

Abrikosov calculated the form of G(H) for a mixed state, showing that if $\kappa > 1/\sqrt{2}$ the mixed state is the lowest energy state for $H_c1 < H < H_c2$. He also calculated the spatial distribution of magnetic field intensity in the mixed state. In Figure 15 the contours of constant magnetic field are plotted. The arrows on the contours indicate the circulating currents or vorticies which maintain this highly non-uniform flux distribution, for Maxwell's equations still hold and a non-uniform magnetic field must be accompanied by an electric current. The existence of such a periodic field structure has recently been confirmed in France by means of neutron diffraction experiments, so the GLAG theory seems well confirmed experimentally both in this respect and in its ability to predict quite well the value of H_c2 for various materials.

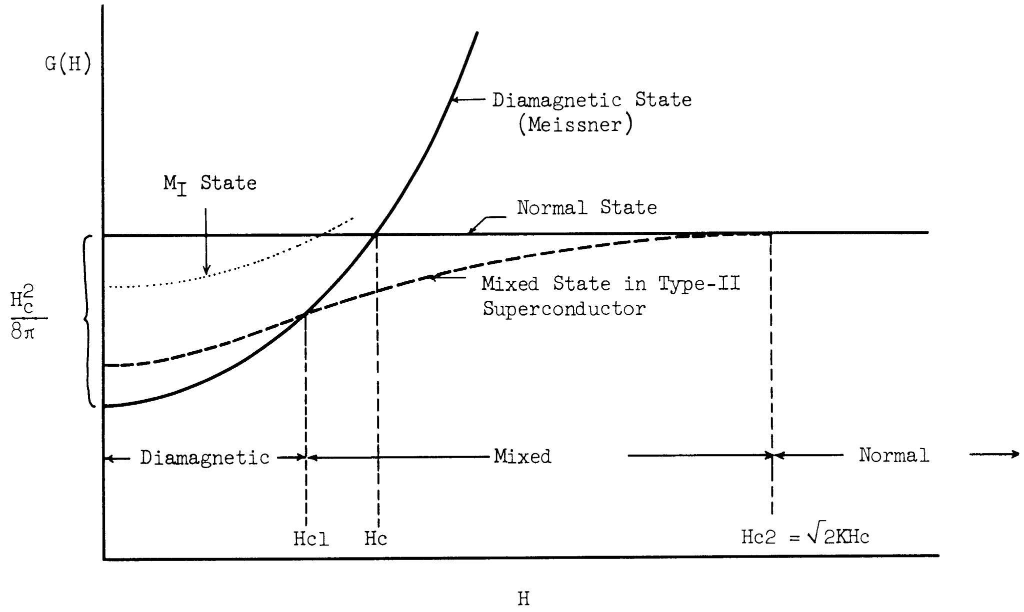


Figure 14. The Gibbs Free Energy, G(H), as a Function of H for a Type-II Superconductor. At any H, the State with Lowest G Will be the Equilibrium State.
M_I Shows G for a Hypothetical Mixed State in Which the Magnitude of the Electronic Ordering Energy is Greatly Reduced at H = 0. In This Case the Mixed State Never has the Lowest G and We Would Have a Type-I Superconductor ($K < 1/\sqrt{2}$) Which Goes Directly from the Diamagnetic State to Normal.

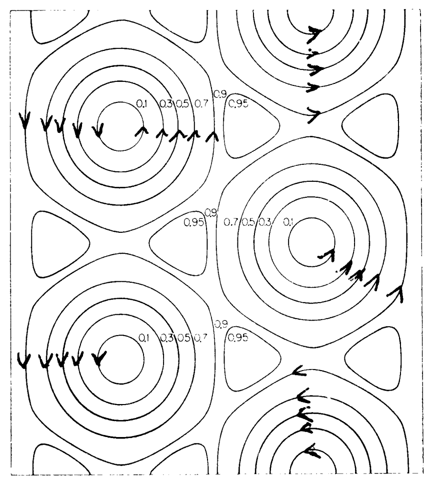


Figure 15. Contours of Constant Magnetic Field Strength in the Mixed State. The Field Maxima Occur at the Centers of the Circles ($H_{MAX} \approx H_{ext}$) and the Minima are Inside the Triangular Contours. The Arrows Indicate the Vortex-Line Superconducting Currents Which Flow Around the Contours.

Unsolved Problems

On certain other aspects of the behavior of high-field superconductors, our understanding is not nearly as good. I would like to devote a little time to a discussion of these unsolved problems as well as the technical problems which are now being actively worked on.

The GLAG theory only applies to a physically homogeneous superconductor which is carrying no transport current. Yet, we are very much interested in the ability of our superconductors to carry large current densities and we know that this ability is intimately related to the number and nature of defects, such as dislocations, in the material. Therefore a theory which can deal with defects is needed and it must be a non-equilibrium theory if it is to include states in which a measurable current is flowing. In the meantime there are models which are helpful, but still insufficiently detailed to guide us toward materials which might carry substantially higher currents than is now possible. A great deal of effort is going into both basic and empirical attacks on this problem.

One of the main engineering problems is the need to develop adequate means for protecting a magnet from its own stored energy. If a superconducting magnet goes normal the energy in the magnetic field must be dissipated. This energy is approaching a million joules in some of the larger magnets under construction, and if it were concentrated in a localized region of a superconductor, could easily anneal it, or even vaporize it. This problem is under good control in laboratory-sized magnets; the magnets pictured in the figures have been driven normal many times without harm. However, in larger magnets with much more stored energy the requirements are more severe, and new techniques will probably have to be developed. There is, however, no reason to believe that this will not be possible.

If superconducting magnets are to be used outside the laboratory, improved methods of cooling them will be required. The primitive technique of immersing a solenoid in a bucket of liquid helium will eventually be superseded by continuous refrigeration in a closed cycle system. Cryogenic engineers have been making some progress toward small-scale helium refrigerators, but they are still very expensive and relatively unproven. Significant advances in this area would greatly accelerate the demand for superconducting magnets.

Present and Future Applications

The first superconducting magnets have naturally been used in situations where liquid helium was already available, either in a laboratory or in apparatus such as masers. There are at least several hundred magnets in operation in research laboratories, mostly for low-temperature research, although their use is increasing for room-temperature experiments as well. They are reliable and useful tools at field strengths up to 80 kilogauss.

Some microwave masers incorporate superconducting magnets and a few are connected to closed-cycle refrigerators. Some infra-red detectors also make use of superconducting magnets.

Situations requiring extremely stable fields are made to order for superconducting magnets operating on a persistent current. Stability to better than a part in a million has been established, and better testing techniques would probably show that the stability is considerably higher. These highly stable fields are needed in nuclear magnetic resonance experiments. They would also be of importance in electron microscopes. The present resolving power of the best electron microscope is of the order of five A°, and some people think that the main limitation on this resolving is the stability of the magnetic field in the focusing magnets. One would like to get the resolving power down to one or two A° at which point one could see individual atoms. This would be quite a triumph, and it would be extremely useful in chemistry and biophysics and biochemistry if one could actually photograph the atomic structure of molecules. It may be that superconducting magnets will be able to make a contribution here; universities and companies interested in electron microscopes are investigating this possibility.

Nuclear instruments such as bubble chambers make use of liquid hydrogen or helium and require strong magnetic fields to deflect the particles. Superconducting magnets are being developed for this application.

Most of the expense in the giant nuclear accelerators which produce particles having many billion electron volts of energy is in the magnets which focus and deflect the beam. The possibility of large savings and improved design by using the higher fields attainable with superconducting magnets cannot be ignored. The A.E.C. laboratories are studying this potentiality.

As mentioned previously, the energy stored in an intense magnetic field can be very large. In applications such as exciting lasers or creating hot discharges in plasmas, a substantial amount of energy must be released in a hurry. Presently, condenser banks are usually used to store this energy, but for energies well over a million joules, magnetic storage should be more economical. There are serious switching problems to be solved, but I believe this may eventually be an important application for superconducting magnets.

A far-out application is connected with the need to shield space ships from rather intensive charged particle radiation now known to exist in interstellar space. At times, such as after a solar flare, this intensity is high enough to be extremely dangerous. It is possible to design a magnetic field to deflect most of these rapidly moving particles (mostly protons) away from the interior of the ship. The only conceivable way of generating and maintaining such fields is with large superconducting coils operating on persistent currents. While superconducting magnets of this large volume are beyond the capability of present technology, NASA is supporting research directed toward developing this capability by the time manned interplanetary travel becomes feasible.

Ionized gas plasmas are being seriously studied in connection with electric power generation. The so-called MHD (magneto-hydro-dynamics) generators make use of a hot plasma jet in a magnetic field to generate power. With conventional magnets, a large fraction of the power generated by the plasma must be expended to maintain the magnetic field; with superconducting magnets this would be saved. MHD is not yet competitive with other methods of generation, but it is close enough so that a considerable amount of work is going into it. If it should become important, the demand for superconducting magnets and associated refrigeration would become great indeed.

The ultimate application is probably thermo-nuclear energy generation. This is the fusion of hydrogen to form helium, with the release of enormous amounts of energy. This is the source of energy in the sun and in hydrogen bombs. If it could be carried out in a controlled way the problem of energy generation would be forever solved; for the water in the oceans would be an inexhaustible supply of the required fuel, hydrogen. In order for fusion to occur, however, a plasma must be heated to a temperature similar to that at the center of the sun - about a hundred million degrees. At these temperatures no material container could hold the plasma; the only conceivable way of containing it is in a "magnetic bottle" which could most reasonably be maintained by superconductors. It will be quite a while before thermo-nuclear energy will be practical - if ever, but a great deal of research is going into the effort all over the world. Suitable superconducting magnets should be useful in the meantime as part of this research effort.

Limitations

The history of this subject is a wonderful illustration of the fact that it is dangerous to say - or believe - that anything is impossible. Fields have been generated which are roughly a hundred times stronger than was generally believed possible with superconductors less than five years ago. Yet, with this caution in mind, I would like to close by coming down to earth and briefly discuss what we presently know of the limitations on superconducting magnets.

I think that the strongest field we can reasonably expect to generate with known superconducting materials is roughly 200 kilogauss. Niobium-tin is the material most likely to be used for this, although compounds such as V_3Ga, V_3Si, or Nb_3Al are possibilities. To achieve much higher fields than this we will have to discover materials with transition temperatures substantially higher than 18°K. Of course, higher transition temperatures are desirable for other reasons also - the advantages of having superconductors at liquid hydrogen, and liquid nitrogen, or even room temperature are obvious. At the moment there is no adequate theoretical guide as to what the ultimate limit is. People working in superconductivity love to think about this, and are working on trying to push Tc up. However, it has been stuck near 18°K for about ten years now, and to make great progress would seem to require either a better understanding or better luck. Tentatively then, unless Tc is raised substantially, fields above 200 or 250 kilogauss with superconductors do not seem likely.

A disappointing area is the generation of intense varying fields. Alternating fields generated losslessly would be highly desirable, but the materials we have been talking about seem to be quite lossy when subjected to varying fields. Probably the losses can be somewhat reduced as we learn more about the dissipative processes, but at the moment there is not much reason to be optimistic that strong alternating magnetic fields will be generated in a truly lossless manner. Perhaps, however, the losses will be reduced enough so that they will not be prohibitive.

R. E. Carroll

We have quite a bit on the program for this afternoon, so let's get busy with it. The first thing we'd like to do is to subject Dr. Autler to a few questions. I must say I wrote down quite a few questions while he was talking, but he answered about half of them before he finished, mostly in the last five minutes, because that was when he was talking about applications. I just wonder, Dr. Autler, if you could, for a few of us here who don't have a feel for 10 killogauss or 100 kilogauss, could you just give us a rough idea of the strength of a charged Alnico magnet, the kind you run into every day?

S. H. Autler
Answer: Well, I'm not sure. I would say Alnico probably saturates somewhere around 6 or 7 kilogauss. The highest field strengths you can get with Alnico is in that range. The highest field strengths you can get with an electromagnet, using soft iron pole pieces, is somewhere around 20 kilogauss. By pushing real hard you may be able to get 25 kilogauss; with an iron magnet that's about the limit.

R. E. Carroll:
So, you're talking about field strengths that are quite a bit out of our everyday experience. Okay, who's next?

G. J. Van Wylen
Question:
I would just like to pursue this question a little bit further. What strengths are being obtained?

S. H. Autler
Answer:
They make 100,000 and they talk of 250,000.

G. J. Van Wylen
Question:
Suppose you want to produce 60 kilogauss in the conventional way, how much apparatus would you need to get a comparison?

S. H. Autler
Answer:
Well, let's talk about 90 kilogauss, since we can now make 90 kilogauss with a superconducting magnet, and that's about what they've been making. Well, they have magnets which produce 90 kilogauss in a two-inch hole, and a motor generator set which delivers 1.8 megawatts of power into that magnet, which they then have to carry out by flowing water - I don't know how many thousands of gallons of water per minute - through the magnet, so roughly about 2 megawatts of power to produce 100 kilogauss is the figure using conventional means. In their new laboratory which was set up fairly recently, they're aiming to produce around 200 or 250 kilogauss; this will provide about 10 megawatts of power into a water-cooled copper magnet.

Question:

You mentioned putting these slugs into the hole of the solenoids and decrease the size to go from ---

S. H. Autler:

These inserts you mean?

Question:

What was the material of the inserts?

S. H. Autler
Answer:

Oh, niobium titanium. In this big magnet the inner sections were made up of this niobium titanium alloy, the outer sections which are exposed to smaller fields were niobium zirconium.

Mr. Campbell
Question:

You mentioned that niobium tin compound was brittle as a metallic compound. Did you later learn how, or have we learned how to heat that to make it ductile, to spin it out into wire?

S. H. Autler
Answer:

Well, the Bell Labs people who first came out with these measurements went through the following process. They took niobium wire and tin wire and packed it into a niobium tube and then they drew this tube down into a wire of the order of 15 mills in diameter which had niobium and tin powder inside and niobium and tin reacted to form the compound Nb_3Sn .

Question:

It's a brittle wire?

S. H. Autler
Answer:

It's still brittle. Now the same thing has been done - magnets have been made that way too. You form the wire but you haven't formed the niobium tin yet. You wind it and then you react, you heat it after you've wound it and form a compound and so you don't have to bend it. There is, however, another process that RCA is developing where they deposit thin layers of the niobium tin compound on a substrate. They use some sort of stainless steel ribbon and deposit thin layers of niobium tin on that and that is bendable because the layers are thin, they can wind that. How fragile it is or how rugged it is I don't really know yet. I'd worry a little about it as compared with niobium zirconium or niobium titanium which are extremely strong alloys. They have tensile strenghts of the order of 300,000 pounds per square inch; they are really good structural materials.

Question:

You really haven't got around that problem?

S. H. Autler
Answer:

Well, I don't know, maybe they have. They have this magnet that they've made which generated 92 kilogauss in a half-inch hole (RCA did that) that was wound after the compound was formed. So they can do that. But whether it will take a beating in constant use I think remains to be seen.

Question:

You had one slide where you pointed out the differences limiting current density in a straight wire or helical coil. Were you referring to a wire having an appreciable cross section?

S. H. Autler
Answer:

No, no, this was 10 mill diameter wire.

Question:

Is it possible for a current at that density to actually flow in a helix without having some cycling values around the edge of the conductor, that is, without having the axial component of the current becoming quite important?

S. H. Autler
Answer:

I'm not sure I understand your question. If you're saying can there be local currents -local little circulating loops of current- flowing in the wire in addition to the series current, main current, the answer is Yes. This is probably at the heart of the problem and we don't really understand this but it does involve these little circulating loops of current which in some sense compete with the transport current that you want to put through the coil. But this is pretty qualitative and we really don't have the details.

Question:

At the very beginning of the talk you showed the slide with the various elements which could be superconducting. I notice that you mentioned that molybdenum was found to be superconducting at nine-tenths of a degree?

S. H. Autler
Answer:

Yes.

Question:

The slide showed that it hadn't been found to be superconducting down to the point of .05 where there is ---

S. H. Autler
Answer:

Yes, that's a matter of purity; they found that unless you went to great pains to remove all traces of iron from the molybdenum it would not be superconducting. Iron can act as a pretty strong poison against superconductivity and so when they really got pure enough molybdenum the transition temperature went to 9/10th of degree.

Question:

Is there a theoretical method for predicting which materials won't be superconducting, instead of which would?

S. H. Autler
Answer:

If you know which ones won't then you'd know which ones would. No, there's a little argument going on about that. Mathias likes to claim that all the metals will become superconducting, all the metals except the ferromagnetic ones, such as iron and nickel, will become superconducting if you can just get them pure enough. Not many other people believe that. But it's hard to disprove because if something isn't superconducting he just says, "Well, you've got to make it pure."

Question:

What do these superconducting magnets that are commercially available cost? For instance, you showed a four-inch diameter 30,000 gauss magnet - what is the price on this?

S. H. Autler
Answer:

I don't know. I can give you the name of the sales manager who can give you a quote. The name is Chuck Berrington, in the Cryogenic Systems Division of the Westinghouse Research Center. But I really don't know.

Question:

The advertisements never carry the price.

S. H. Autler
Answer:

That's right. Well, actually there are many variables in these things. There are a lot of parameters that people like to specify, such as in addition to just the field there's the volume, there's the homogenity; different people have different requirements on the homogenity of the field. All of these things come into the price, so it would really be quite a table if they were to show every possibility on a price connected with it. But a letter to Chuck Berrington will get you a firm quote.

Question:

What is the explanation for the fact that the ferromagnetic fields cannot be made superconducting?

S. H. Autler
Answer:

I don't know. I have a simple-minded view, I'm not sure it's right, I'll tell it to you if you want. An iron atom has an unpaired electron spinning in it, and this can result in quite high local fields very close to the atom, say inside the atom or just outside the atom. This unpaired electron spin can result in fields of the order of hundreds of kilogauss. Well, these electrons are conduction electrons moving around through the superconductor so it means every once in a while these electrons see this very high field when they get close to the iron atom. Well, sufficiently high fields are death to superconductivity. So you can sort of think of it that way. If you have very high localized fields in your lattice that will break up the superconductivity.

Question:

Are there any problems with insulation, electrical insulation of cryogenics systems?

S. H. Autler
Answer:

Are there any problems with electrical insulation of cryogenic systems? You mean Magnets?

Question:

On the magnet winding?

S. H. Autler
Answer:

Yes, there are problems, but in the early days when people were trying to make magnets they used simply niobium zirconium wire and then some sort of plastic insulation outside of it. If a piece of wire went normal then this normal region would propagate quite rapidly through the magnet, since you've got current flowing. As soon as you get any resistance then you get I^2R heating and this normal region propagates and if there's enough voltage, enough inductance in the system to keep the current flowing, this means that this current of 20 amperes can be flowing across a region which can have a resistance of thousands of Ohms. And voltages, big voltages build up. You can build up hundreds of thousands of volts under these conditions, and then you're arcing and breaking down insulation, so during this gauss race in 1961 at MIT we got the largest length of niobium zirconium wire which had been made up to that time, about 8,000 feet of it, and we thought, "Oh, boy, we're off. We're going to break the record." We wound this thing up and we ran the current up and we would draw a great big arc inside of our magnet and burn up the wire and all sorts of horrible things would happen. Well, the cure for that has been two things: 1) good insulation which prevents arcing if a big voltage should build up, and 2) the wire now used is copper plated. Niobium zirconium has a plating of copper over it and so even if the material goes normal, there's protection. These alloys are like resistance wire when they're in the normal state. A 10 mill niobium zirconium wire has a resistance of about 2 Ohms per foot as soon as it goes normal, and yet zero when it's superconducting. So by using a copper plating on the surface even if the niobium zirconium goes normal the current just shunts into this copper sleeve on the outside and this keeps the voltages from building up very high. And this is really what has resulted in the greatly increased reliability of these superconducting magnets. You also need good insulation though.

R. E. Carroll:

Thank you very much, Dr. Autler, for an extremely interesting presentation. If any of you have further questions later you can probably catch Dr. Autler directly after the meeting.

R. E. Carroll

The next three talks on the program will be reports on research at the University of Michigan in the field of Cryogenics. They will be somewhat shorter talks and somewhat descriptive of the type of research rather than an attempt to cover a field. So we are going to hear the number two on the program first. Professor John Clark received his Bachelor of Science and Engineering at The University of Michigan. His Masters of Science from M.I.T. He was appointed Professor here at the university in 1956; Associate Director of the Heat Transfer Laboratory at that time, I believe - let's see, you were Professor at M.I.T. also, is that correct John? In the field of active participation with industry, he has quite a history of consulting practice with such firms as Westinghouse, Atomic Power Division; Knolls Atomic Power Laboratories; General Electric, Argonne National Laboratories; Polychemical Division of DuPont; Minneapolis-Honeywell Regulator Company; U. S. Army Corps of Engineers; Kelsey-Hayes, Power Reactor Development and so forth.

In the field of research he has been recently working on projects such as NSF Projects on Vibrations on National Convention Heat Transfer; the Study of the Influence of Acceleration on Boiling and Non-Boiling Heat Transfer; AEC sponsored work on Boiling Heat Transfer at Low Heat Flux; the Air Force sponsored work on Boiling Heat Transfer to Liquid Metals under A-gravitic conditions; and NASA sponsored work on the Pressurization of Liquid Oxygen Containers and included in recent publications, such things as Transient Condensation on Insulation Substrates, Boiling Heat Transfer Data for Liquid Nitrogen at Standard and Near Gravity, and the Cooling of Cryogenic Liquid by Gas Injections. We will very likely hear some echoes of this work in the presentation that Professor Clark will give us on Cryogenic Heat Transfer. Professor John Clark.

CRYOGENIC HEAT TRANSFER

John A. Clark

Professor of Mechanical Engineering

Thank you Mr. Carroll and good afternoon gentlemen. The work that I am going to describe for you has been sponsored by the Federal Government, especially the National Space Agency, the NASA. We of course, are very anxious that any of the work we have been able to do under this sponsorship finds its way into the private sector of the economy as quickly and as thoroughly as it is possible to do.

I would like to give a general background on the subject of heat-and-mass transfer at low temperatures. The technological applications I think have been outlined very well this morning, including such things as the rocket propulsion systems. Here we find an important application of heat and mass transfer, and especially in the use of liquid hydrogen in both the nuclear and chemical rocket propulsion systems where high specific impulse if obtainable. Recently we have orbited a hydrogen-oxygen system which could be restarted in space giving some element of controllability of thrust. In medicine we find cryogenic applications, as well as in the production of industrial gases and food preservation. Our last speaker has outlined the cooling of magnets where heat transfer problems, of course, are pivitol in the design of those systems. And in the production of low vacuums for industrial purposes we find the applications of heat transfer in Cryogenics.

I think the principal question that we might want to direct our attention at today and which might be of greatest interest to us on the subject of heat and mass transfer, is this: Is there any real difference in the performance of physical systems from the standpoint of heat transfer at low temperatures, in comparison to that we see at high or ambient temperatures? From the standpoint of its basic physics, is there, in fact, a principal difference? Now the answer to this question from my own perspective is mostly no, there really is not a significant difference. I think this is an important point. We have encountered an exception, of course, today in the behavior of helium II, which is helium below about 2.2° Kelvin, but, except for that particular fluid, most fluids we deal with in cryogenic engineering are fluids which we identify as being classical.

The common fluids we encounter are nitrogen, oxygen, hydrogen and helium. These are classical in the sense that they obey the laws of similarity which is very important in the application of heat transfer and mass transfer. The principles of physical simulitude and the scaling laws appear to be valid from our present experience in the laboratory and in design in the use of these fluids. They seem to follow the well-established principles of mechanics and thermodynamics; which is to say they fit into the broad general classification of heat transfer phenomena which we have been familiar with for the past 30 or 40 years. A very important conclusion for engineers to realize, I think, is that many of the previous concepts and ideas they have had in handling ordinary fluids, water, oil, etc., can be carried over into the application with the cryogenic fluids. Remember Helium II is an exception. It is a non-classical fluid. We just have to forget about that for now, but most of the others, the ones you see in the table are classical. This means the concept of a Reynolds number can be employed to describe the behavior of the flow, the Nusselt number and the Prandtl number, and the Peclet number - all of these well-known dimensionless parameters can be employed in a generalized description of the behavior. This is important because it means that experiments conducted on air, for example, and correlated in the generalized fashion can be used to predict the performance of oxygen or hydrogen. There may be a slight change in exponents or maybe coefficients in the correlating equations, but there appears to be no great difference to be encountered.

Helium has an unusually low thermalconductivity in the liquid stage and an unusually low kinematic viscosity. This will give a little different behavior but not anything that would be impossible or even particularly difficult to take care of in an engineering design. The properties of water, are listed in the table for your reference. Finally Helium II, below 3.6°R, really is an unusual substance. It is a non-classical fluid. Its thermalconductivity is about 200,000 times that of water.

I feel I should say a word about Helium II so far as engineering is concerned. Large quantities of this are not presently in use. Presently there is heat transfer being done on Helium II to identify what does happen at a surface in contact with it and since the temperature differences are so small one is not really sure what is next to the surface. A film of vapor or highly conductive film of Helium II breaking down to normal helium a few millimeters from the surface is a possibility. Some work is being done elsewhere on that particular question.

Most calculation in heat transfer accomplished today are done in constant property systems. Hence we find that in some solids at low temperatures we do get into the possibility of a new kind of a problem. We encounter the question of how do you compute heat conduction for variable conductivity. I might just show you a very useful transformation we have recently developed for the thermal diffusion problem. Let me show you how we treat this kind of a problem and I think you might find it interesting. When we are dealing with thermal diffusion, you will recall that we must solve the diffusion equation. We define a new function. Let me call it E for now, which is the integral from some reference temperature T_o , to the temperature T , of this simple product kdT . By this simple transformation we go from a non-linear for to a linear form, with exactness. We have the complete problem solved and it makes little difference how k varies the temperature. We have to know the variation of course, but you have to have this for the classical problem anyway. It also means that all the steady state and some transient problems which have been tabulated in the past as the solution to the constant property equation apply exactly to the variable property problem using the function E . So we have broadened that considerably. The equation that I have shown here is primarily for a steady problem and the unsteady problem has a slight variation which I can not go into right now. It still can be treated and various kinds of boundary conditions can be handled. For certain geometry for which we simply do not have the exact solution we always have to put it on the computer and solve the variable property problems on the computer.

In the area of solids, I suppose one might say that the multi-layer, vacuum insulation, that we heard about this morning is a very prominant application of the behavior of solid systems at low temperature. The Linde Co. is putting as much as 150 layers per inch of aluminum foil in a vacuum space. This gives a conductivity in round numbers of about one onethousandth of that of air. In a study we conducted for the Jupiter-Saturn program in Huntsville for NASA we determined the property you might be interested in governing the transient response of a surface when it is subjected to a condensing gas. We would select insulation, for example, not on thermal conductivity in this case, but on another property for transient response. The property is $k\rho c_p$. The product of those three properties is the property one should use to estimate how rapidly a surface would respond to a change in an ambient condition. In other words a good insulator is not necessarily one that has a low thermal conductivity for this application, but one which has a low $k\rho c_p$ product. In transient studies one often thinks of the thermal diffusivity, the symbol a on the chart I just showed you, k divided by ρc_p as the principal governing parameter. But when I was speaking of the response of the surface it turns out it is not k over ρc_p but $k\rho c_p$ product.

At the University of Michigan there are heat transfer studies being conducted both in the departments of Chemical and Metallurgical engineering, where interested parties are Professor S. W. Churchill, and Donald L. Katz, and the Department of Mechanical Engineering - myself and my collaborators, Professors H. Merte, V. S. Arpaci, and

W. J. Yang in the Heat Transfer Laboratory. We are studying the problems in cryogenics, heat transfer, and mass transfer at low temperatures. I do not know what your time will be today but you are certainly welcome to visit our laboratory any time you wish. The studies we are dealing with are both experimental and analytical. They deal with both steady-state and transient problems. They deal with free convention problems, boiling problems, and multi-phase problems and problems with high gravity and problems with low gravity. Also studied are problems dealing with the interfacial exchange of heat and mass. The details of these studies I might list here for you briefly. We are using mostly liquid nitrogen because of its convenience. We study the transient problem of pressurization of the container which is filled with a cryogenic liquid and determine the response of the gas phase as a result of the pressurization and expulsion of the liquid from the container. We call that the pressurized discharge problem and it has led to design equations and formulations, enabling an optimization of the pressurized discharge process from large rocket boosters. In the area of high gravities we have completed studies on the influence of g up to about 20 times normal gravity for non-boiling and boiling heat transfer to liquid nitrogen. We have capability in the laboratory of extending this work to 1000 times normal gravity. At the other end of the scale we go to almost zero gravity in our drop tower. In this apparatus we drop cur test package freely through a height of about 32 feet. During this time the system is so designed that the acceleration forces on it are no greater than that you would find in a 0.001 of a normal gravity field. With suitable counter weighting on our drop tower we can get gravities intermediate between zero and 1. We found, incidentally, that the effect of gravity in certain types of boiling is not large. The kind of boiling you find in your teakettle, for example, which we identify as nucleate boiling, does not seem to be particularly effected by the increase or the decrease in the gravity field.

I might mention a problem that was encountered in the Saturn vehicle which we have studied in the last three or four years. This is the cooling of the oxygen lines from the tank to the pumps. While this vehicle sits on the launching pad in the hot Florida atmosphere the liquid oxygen becomes heated. The cavitation probability is great, should this hot oxygen enter the pumps when Saturn first fires and the reliability of performance would fall off. The problem is to cool an oxygen line in the simplest possible way with zero weight. The solution is to bleed helium gas into the hot oxygen line. The cooling effect within the oxygen line is the same as one experiences when he steps out of a shower. A line can be cooled 10 or 15° in just a matter of 5 minutes or less.

In liquid hydrogen technology we are going to conduct much of the same experiments at low gravity, that I have just described to you.

Thank you very much.

PROPERTIES OF CRYOGENIC LIQUIDS AT 1 ATMOSPHERE

(Relative to liquid water at 100F, except Prandtl Number)

Liquid	T ^{o}R	$\frac{k}{k_w}$	$\frac{\rho}{\rho_w}$	$\frac{c_p}{c_{p_w}}$	$\frac{\mu}{\mu_w}$	$\frac{\nu}{\nu_w}$	$\frac{a}{a_w}$	P_R
N_2	139	0.221	0.815	0.488	0.220	0.263	0.556	2.20
O_2	162	0.239	1.150	0.406	0.287	0.240	0.510	2.21
H_2	36.7	0.186	0.071	2.30	0.021	0.285	1.145	1.17
He-I	7.6	0.040	0.126	1.15	0.0047	0.036	0.277	0.613
→ He-II	3.6	$(2)10^5$	0.148	1.15	0.00117	0.0076	$(1.17)10^6$	$(3.05)10^{-8}$

PROPERTIES OF LIQUID WATER AT 1 ATMOSPHERE

	T	k_w	ρ_w	c_{p_w}	μ_w	ν_w	a_w	P_R
	^{o}R	$\frac{BUT}{HR\text{-}R\text{-}Ft}$	Lb_m/Ft^3	$\frac{BUT}{Lb_m\text{-}R}$	$\frac{Lb_m}{HR\text{-}Ft}$	Ft^2/HR	Ft^2/HR	(1)
H_2O	560	0.364	62	1.0	1.65	$(27.6)10^{-3}$	$(5.88)10^{-3}$	4.52

R. E. Carroll

George I. Haddad was born in the country of Lebanon. He received his Bachelor of Science in Electrical Engineering in 1956, his Master's degree and Ph.D. were also received from the University of Michigan. From 1957 through 1958 he was associated with the then Engineering Research Institute where he was engaged in research on electromagnetic accelerators. In 1958 he joined the Electron Physics Laboratory and has been engaged in research on electromagnetic accelerators. In 1958 he joined the Electron Physics Laboratory and has been engaged in research on masers and electron beam devices. This is a part of our Electrical Engineering Department. He served as an instructor in the Electrical Engineering Department from 1960 through 1963 and is presently an Assistant Professor. We're very pleased to present George Haddad who will give us a discourse on Cryogenics and Solid-State Electronics at The University of Michigan. George.

CRYOGENICS IN SOLID-STATE ELECTRONICS

George I. Haddad

Assistant Professor, Electrical Engineering

The use of cryogenics in solid-state electronics is widely employed at the present time and it is rather common place to find cryogenic equipment at university, government and industrial laboratories. The reasons for this are:

1. Operation at a low temperature results in new devices which are useful in systems' applications. We heard this morning, for example, how extremely high magnetic fields may be obtained by employing superconducting magnets which require extremely low temperatures. Such magnetic fields may be employed in several applications.

2. Certain material properties can only be measured at low temperatures. This increases our knowledge of the structure and properties of these materials.

3. The characteristics of certain devices can be improved considerably by operating them at low temperatures. For example, the power output of solid-state lasers may be considerably enhanced. Most solid state lasers operate continuously only at low temperatures.

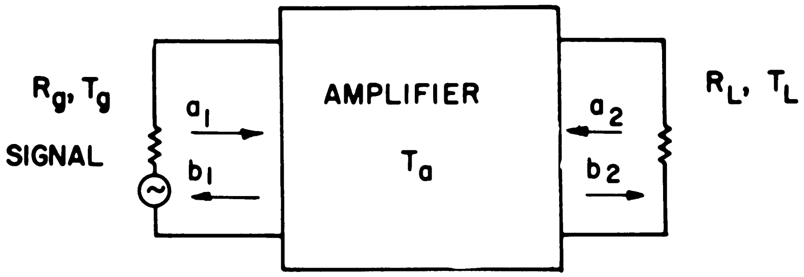
One area which has benefited a great deal from cryogenic temperatures is the area of low-noise microwave receivers. The receivers, such as the maser and parametric amplifier, have such low-noise figures that the amplifier is no longer the weak link in a communications system. My talk will be mainly concerned with this area. Before we go into any details of such amplifiers, it is worthwhile to see first what is meant by a low-noise amplifier and where its use improves the system's performance.

Let us then consider the amplifier shown in Figure 1. The Noise Figure F of the amplifier is defined as,

$$F = \frac{\text{Signal input/noise input}}{\text{Signal output/total noise output}} \qquad (1)$$

$$= \frac{\text{Total noise output}}{\text{G x noise input}}, \qquad (2)$$

where G = the power gain of the amplifier.



$$\text{Noise Figure} = 1 + \frac{T_a + (|\rho_2|^2/G)\, T_2}{T_g}$$

$$= 1 + T_a/T_g \qquad \text{for} \qquad |\rho_2| = 0$$

T_g = The equivalent noise temperature of the source

T_a = The equivalent noise temperature of the amplifier

Figure 1.

The total noise output is given by

$$\text{Total noise output} = G \cdot P_n(R_g, T_g) + P_n(\text{ampl.}) + |P_2|^2 \cdot P_n(R_L, T_L)\,, \qquad (3)$$

where

$P_n(R_g,T_g)$ = the noise power input to the amplifier which may be the effective noise power of the antenna, background noise and other equipment preceding the amplifier,

$P_n(\text{ampl.})$ = the noise power due to the amplifier,

$P_n(R_L,T_L)$ = the noise power of the load resistance and

$|P_2|$ = the reflection coefficient at the output.

As is well known, a resistance at temperature T gives a noise power which may be expressed as,

$$P_n(R,T) = k\,T\,B\ , \qquad (4)$$

where

k = Boltzmann's constant
B = the bandwidth.

We can then define an amplifier noise temperature as,

$$P_n(\text{ampl.}) = G \cdot k\,T_a\,B\ . \qquad (5)$$

The Noise Figure F then becomes,

$$F = 1 + \frac{T_a + (|P_2|^2/G)\ T_L}{T_g}\ . \qquad (6)$$

In most practical situations $(|P_2|^2/G)\ T_L \ll T_a$ and may be neglected. This results in

$$F = 1 + \frac{T_a}{T_g}\ . \qquad (7)$$

Of course the lower the noise figure is, the more sensitive the receiver.

Figure 2 illustrates the minimum detectable noise power for different values of T_a and T_g. It is seen then, that has a great advantage at low values of T_g but has relatively little advantage at high values of T_g and would not be worth the expense. This is why I said at the beginning that the amplifier is no longer the weak link but other components such as the antenna and associated equipment must be improved in order to realize the full capability of the maser.

Another application of a low noise receiver is illustrated in Figure 3. As illustrated there, a low noise receiver may be employed to measure the temperature of a certain object $T_{g_u}\ T_{g_r}$.

If the amplifier receives a signal of Power $P_{sig.}$,

$$\text{Power Out} = G\left[P_{sig.} + k\,(T_g + T_a)B\right]$$

∴ Minimum Detectable Signal $= P_{min.} = k\,(T_g + T_a)B.$

k = Boltzmann's constant

B = Bandwidth of the receiver

For TWT ; $T_a \cong 1000°$

For a Maser ; $T_a \cong 10°$

$$\frac{P_{min.\ Maser}}{P_{min.\ TWT}} = \frac{T_g + 10}{T_g + 1000}$$

$\cong 1/4$ for $T_g = 290°K$ (Room Temp.)

$\cong 1/25$ for $T_g = 30°K$.

Figure 2.

Also Used for Measuring T_g

$$P_1 = Gk\,(T_{g_r} + T_a)B$$

$$P_2 = Gk\,(T_{g_u} + T_a)B$$

$$\frac{P_2}{P_1} = \frac{T_{g_u} + T_a}{T_{g_r} + T_a}$$

∴ if $T_a \ll T_{g_u}$ or T_{g_r} then, $\frac{P_2}{P_1} \cong \frac{T_{g_u}}{T_{g_r}}$

if $T_a \gg T_{g_u}$ or T_{g_r} then, $\frac{P_2}{P_1} \cong 1$

T_{g_r} = Known Reference Temperature

T_{g_u} = Unknown Temperature.

T_a for a maser $\cong \frac{T_{Bath}}{I}$

Some Uses of Masers

1. Radio and Radar Astronomy
2. Satellite and Space communications
2. Laboratory Low Noise Receivers.

Figure 3.

Extremely low noise temperatures may be achieved by employing parametric amplifiers at low temperatures. A maser amplifier requires liquid helium for amplification, whereas a parametric amplifier can operate at room temperature but with a higher noise figure. The reason for cooling a parametric amplifier to liquid helium temperatures is to improve its noise figure. The cryogenic equipment that is required for either of them is quite similar. It is very desirable, of course, to have a closed-cycle refrigerator to keep the amplifier at a low temperature. Otherwise, it would be necessary to refill the Dewar with the appropriate cryogenic liquid where required. The second method has been the one widely used in laboratory and field applications to date, but the rapid rate of development of cryogenic refrigerators makes it likely that closed-cycle ones will be employed more widely. A closed-cycle refrigerator at liquid helium temperature is presently used to cool an S-band traveling-wave maser at the California Institute of Technology, Jet Propulsion Laboratory.

Since I am more familiar with masers than parametric amplifiers, the rest of my talk will be concentrated on this device. The noise temperature in a maser is directly proportional to the bath temperature in which it is located. They may be expressed approximately as,

$$T_a = T_{Bath}/I \; , \tag{7}$$

where I is the inversion ratio of the maser material and is of the order of one. Thus, the noise temperature is approximately equal to the bath temperature. The gain in the maser is inversely proportional to temperature. Thus lowering the temperatures reduces the noise figure and enhances the gain.

Masers have been employed in several important applications. Some of these are:

1. Radio and Radar Astronomy: Radar signals bounced off Venus were detected by M.I.T.'s Lincoln Laboratory by a maser amplifier. The Radio Telescope here at The University of Michigan employed a maser amplifier built by the solid-state laboratory at Willow Run to detect and locate new stars and detect signals from Saturn for the first time. It is employed in the detection of stars which cannot be detected optically and thus helps in mapping outer space.

2. Satellite and Space Communications: The Bell Telephone Laboratories employed masers in their systems for detecting the weak signal from the satellite. The maser would be especially useful in outer space communications since the atmospheric noise will be absent there.

3. Laboratory Low-Noise Receivers: There are several properties of materials which require a highly sensitive receiver for their measurement. Such things as nuclear magnetic resonance and electron spin resonance would benefit a great deal by employing a low noise receiver such as the maser.

Next, I would like to explain briefly the basic principles and characteristics of the maser. The word "maser" is an acronym for "microwave amplification by the stimulated emission of radiation". The "laser" which stands for "light amplification by the stimulated emission of radiation" and has received a great deal of publicity is essentially an "optical maser"; i.e., it operates at optical frequencies. Suppose then, we have an atomic medium of some sort. It is characteristic that the atoms in the system will occupy a set of discrete energy levels which are determined by the atoms. Suppose, for simplicity, we have a system with two allowed energy levels only such as that shown in Figure 4a. At thermal equilibrium, the atomic populations of the two levels are related by the Boltzmann relation,

$$\frac{n_2}{n_1} = e^{-(E_2 - E_1)/kT} , \qquad (8)$$

where

n_1 = the atomic population of level <° which has energy E_1
k = Boltzmann's constant and
T = temperature of the medium.

Equation (8) essentially shows that at thermal equilibrium, more atoms will be in a lower energy state E_1 than that in E_2. If the temperature is decreased, the population of Level 1 will increase and that in Level 2 will decrease. If an electromagnetic signal is coupled to the medium whose frequency is related to the energy difference by

$$hf = E_2 - E_1 , \qquad (9)$$

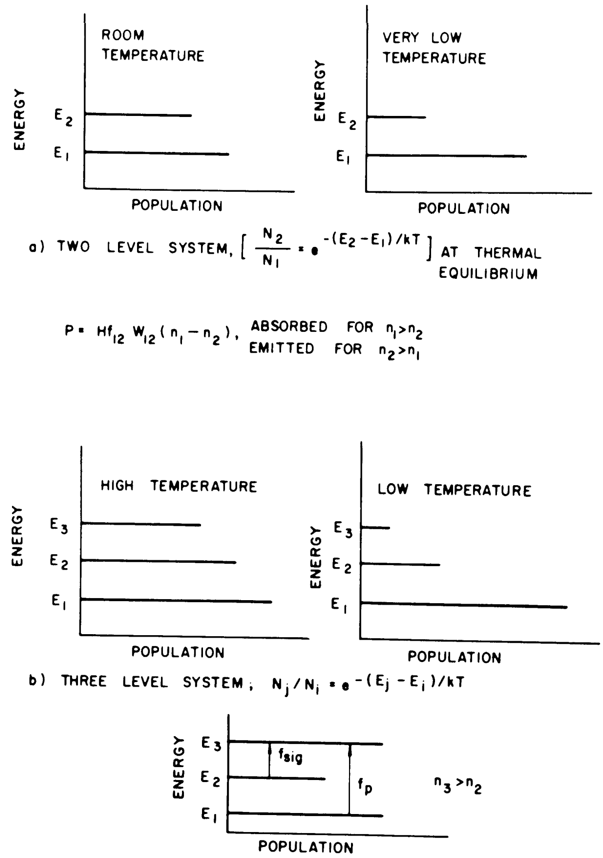


Figure 4

where

h = Planck's constant
f = frequency of the signal ,

then the medium will absorb an amount of power which is given in the Figure. As seen there if $n_1 > n_2$ (i.e., more atoms in the lower energy state) then power will be absorbed and the signal will be attenuated. However, if $n_2 > n_1$ then power will be emitted and the signal will be amplified. So the main idea in a maser is to get an "inverted population" (i.e., $n_2 > n_1$ in Figure 4a). One way of achieving this and obtaining continuous amplification is to choose a medium which has at least three energy levels shown in Figure 4b. At thermal equilibrium, the population of the difference energy levels is shown where the length of the horizontal lines is proportional to the number of atoms in that energy level. It is seen for example that the number of atoms in each level depends on the energy of level and lower energy levels are more populated than higher energy ones in accordance with the Boltzmann distribution. Again here if the temperature is lowered, more atoms will come down to lower energy levels.

Population inversion between two levels, say 2 and 3, may be achieved as follows. If electromagnetic power at a frequency corresponding to the energy difference between Levels 3 and 1 is coupled to the medium, the medium will absorb this power and for each photon absorbed an atom will jump from Level 1 to Level 3. This power at f_{13} essentially "pumps" the atoms from Level 1 to 3 and is called the "pump" and its frequency is referred to as the pump frequency f_p. This absorption process continues until the populations of Levels 1 and 3 are equalized. However, when the populations of Levels 1 and 3 are equalized, the number of atoms in Level 3 will exceed that in Level 2 and thus population inversion between Levels 3 and 2 is achieved. Signal power at a frequency corresponding to the energy difference between Levels 2 and 3 will then be amplified by the medium and thus a maser amplifier is achieved. In this conventional three-level maser the pump frequency must be at least greater than twice the signal frequency. Other pumping schemes may be employed however to obtain amplification at a signal frequency higher than the pump.

The energy levels shown in Figure 4 may be employed to amplify at one frequency only. It is desirable, however, to be able to tune the signal frequency. This may be achieved by varying the energy separation between the levels. One method of achieving this in several materials is by varying the magnetic field applied to the crystal. A typical set of energy levels in Ruby (chromium-doped alumina) is shown in Figure 5 as a function of the d-c magnetic field. It is seen there how the energy difference between the various levels may be varied by changing the magnetic field. Thus a particular signal frequency may be obtained merely by adjusting the d-c magnetic field to the proper value.

The remaining problem is the coupling of the pump and signal electromagnetic power into the maser crystal. This may be achieved in two ways. The first utilizes a cavity which is designed to be resonant at the pump and signal frequencies and the resulting device is called a "cavity maser". The other and more recent one employs a slow-wave structure and the device is called a "traveling-wave maser".

The traveling-wave maser has several advantages over the cavity one. These include higher gain-bandwidth product, better stability and tunability over a considerable frequency range. Since the traveling-wave maser is superior to the cavity one I will discuss some of its features and characteristics.

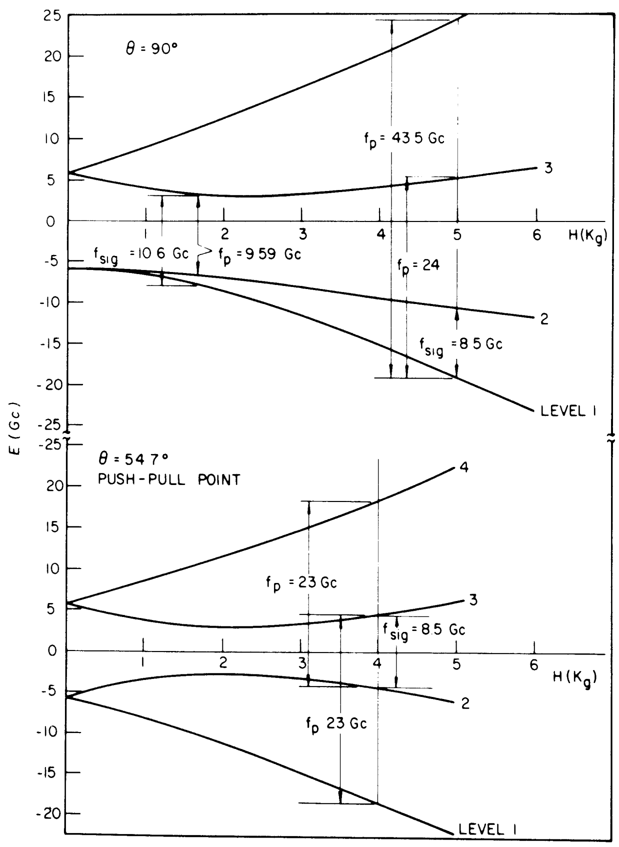


Figure 5.

The electronic gain in a traveling-wave maser may be expressed as,

$$G_{db} = \frac{27.3\ S\ N}{Q_m} \quad , \tag{10}$$

where

$S = C/v_g$ = slowing factor,
C = the velocity of light in free space,
v_g = the group velocity in the waveguide system,
$N = \ell/\lambda_o$ = the number of free space wavelengths in the structure,
λ_o = the free space wavelength,
ℓ = the length of the structure, and
Q_m = the magnetic Q which depends on the maser material, its location in the structure and the operating point of the material (i.e., ratio of pump to signal frequency).

Since the gain is directly proportional to the slowing factor it is desirable to have this as high as possible. If a regular rectangular waveguide is filled with the maser material, S will be approximately equal to $\sqrt{\epsilon_r}$. For ruby, $\epsilon_r = 9$ and $S = 3$. Also for ruby $Q_m \cong 100$ at 10 Gc. Thus if a regular rectangular waveguide is used a length of approximately 40 inches would be required to obtain 30 db of electronic gain. However, if a slow-wave structure is employed where a slowing factor of 100 may be easily obtained, the length of the structure is reduced by a factor of 33. Since a very long structure is impractical because uniform magnetic fields over such a length are hard to obtain and the size of the structure is very large, the use of a slow-wave structure at the lower microwave frequencies is necessary.

If we first fill the slow-wave structure with the maser material then gain in both the forward and reverse directions will be present and any slight mismatches at the input and output of the structure will lead to oscillation, which of course is undesirable. In order to obtain stability in the amplifier we have to provide nonreciprocal attenuation. This may be achieved by choosing a structure which possesses accessible regions of opposite r-f field polarization. A ferrimagnetic material may then be employed which when properly located in the structure will not affect the wave traveling in the forward direction but will attenuate the reflected wave.

We have built a traveling-wave maser in the X-band frequency range (8-9 Gc). This maser utilizes ruby for the active maser material and a YH-rium Iron Garnet slab for isolation. A double-ridge Karp-type slow-wave structure was employed. Cross-sections of the maser are shown in Figure 6. The r-f magnetic fields are maximum near the side walls and that is where the ruby is located. The r-f fields are circularly polarized in opposite senses above and below the ladder line. A wave traveling in the forward direction will interact mainly with the ruby at the bottom of the ladder line and is amplified. The ruby on the top of the ladder will contribute slightly to this gain depending on the ellipticity of the r-f fields. The reflected wave will interact mainly with the material on top of the ladder line and as seen in the figure an absorbing YH-rium Iron Garnet (YIG) slab is placed there to attenuate the reflected signal. Short-circuit stable operation may be achieved in this manner. Of course we must provide means of propagating the pump power so it will interact with the material and provide the necessary population inversion. In this case the pump power is propagated in a ridged-waveguide mode in the structure enclosing the ladder line.

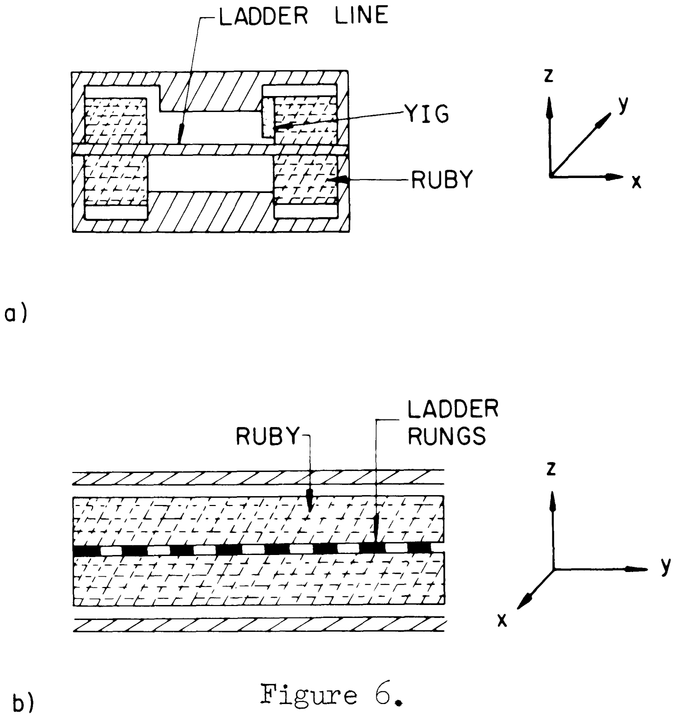


Figure 6.

The slow-wave structure may be designed to have a desired finite passband and the signal frequency may then be tuned over the passband by changing the magnetic field and pump frequency as mentioned earlier.

An assemble view of the traveling-wave maser is shown in Figure 7. There the two coaxial lines are for the signal input and output and the waveguide is for the pump. This, of course, is an experimental model which fits into a laboratory Dewar and thus most of the hardware shown there would not be necessary in an operational device. A view of the interaction region is shown in Figure 8. This is the necessary region where the amplification is obtained. In this structure and at X-band, electronic gains of 15 db/inch at 4.2°K and 40 db inch at 1.6°K may be obtained. In order to obtain 30 db of gain in this structure at X-band, its dimensions would be approximately .5" x .5" x 2".

A typical laboratory setup for testing the maser is shown in Figure 9. There the Dewar which is placed between the magnet pole pieces is shown. The maser is located in the liquid helium bath inside the Dewar. The magnet shown is a 12" electromagnet. In a field operational amplifier, most of the bulky equipment would not be required. For example, the huge electromagnet may be replaced by a small permanent magnet or a small superconducting solenoid. Since liquid helium temperatures are required for the operation of

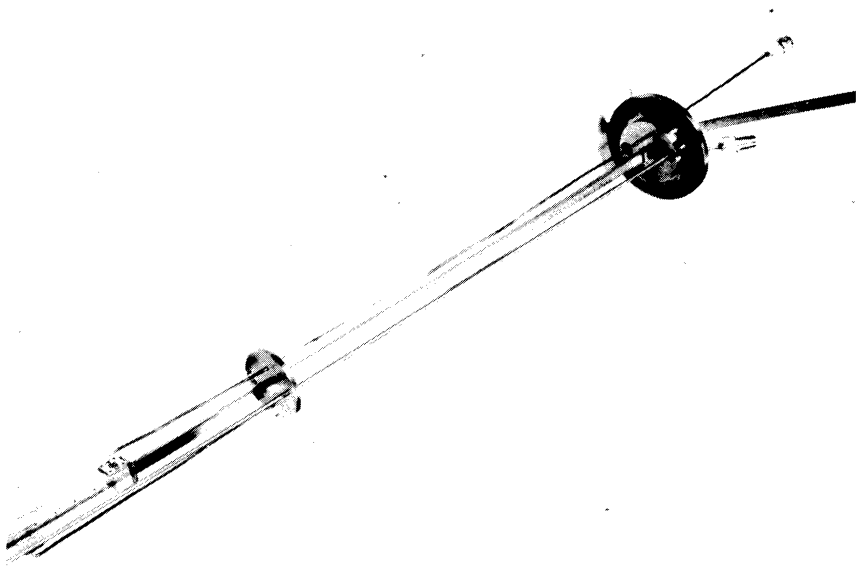


Figure 7.

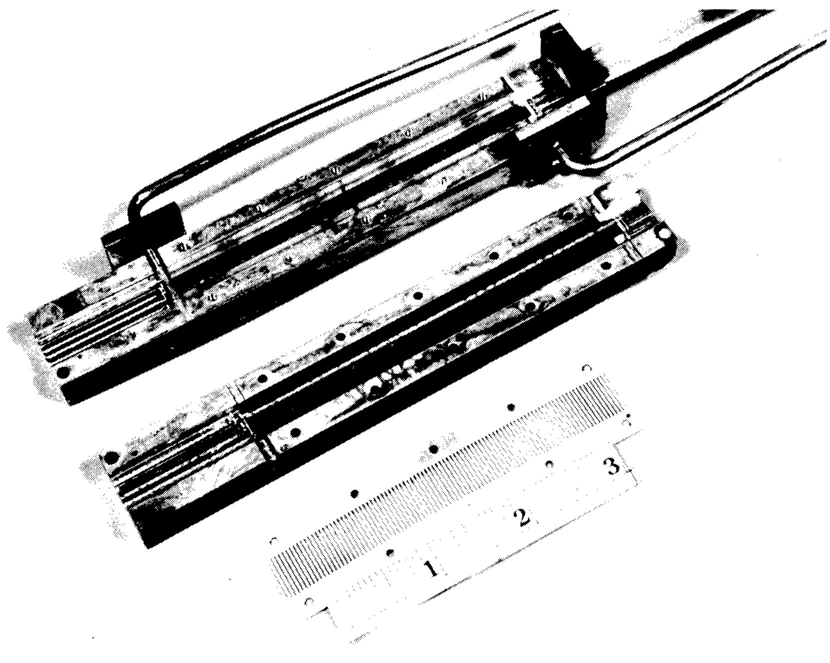


Figure 8.

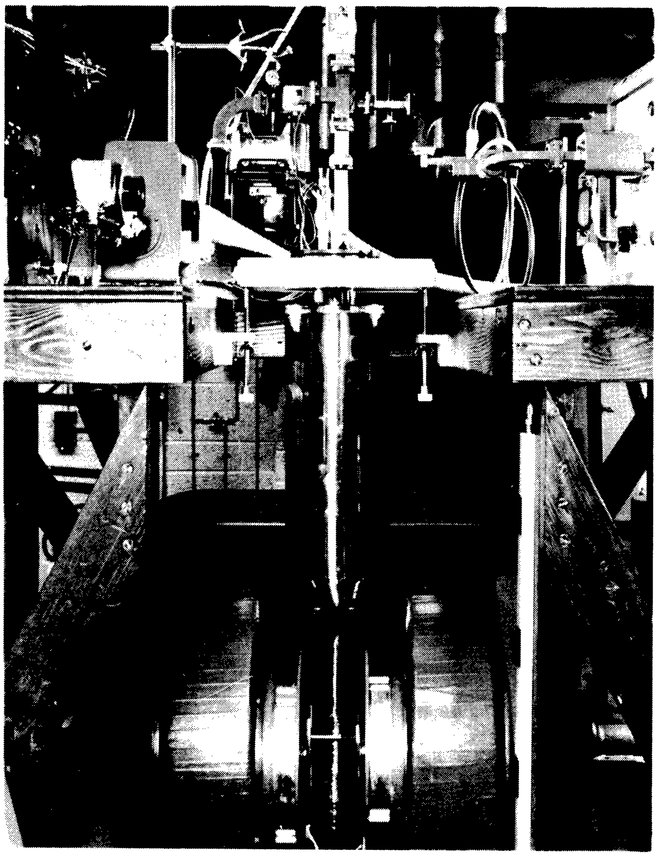


Figure 9.

the device, a superconducting magnet may be readily incorporated in it. The laboratory Dewar shown in the figure is quite large and a smaller one may be employed in a unit designed for field operation.

Figure 10 shows a field operational unit which is employed at The University of Michigan's Radio Telescope. This unit is mounted at the focus of the antenna. This cavity maser device was built by the staff of the Solid-State Laboratory at Willow Run. One fill of liquid helium lasts about 4-6 hours in this unit and has to be refilled after that. Of course with the maser at the focus of the antenna this is not an easy job and here is where a closed-cycle refrigerator which would result in continuous operation would be extremely useful.

We are presently doing some work on traveling-wave masers in the millimeter wave range. The material we are investigating at the present time is chromium-doped rutile. Ruby, which is a very nice material to work with cannot be used above 12 Gc approximately. Rutile has a very high dielectric constant and this places severe

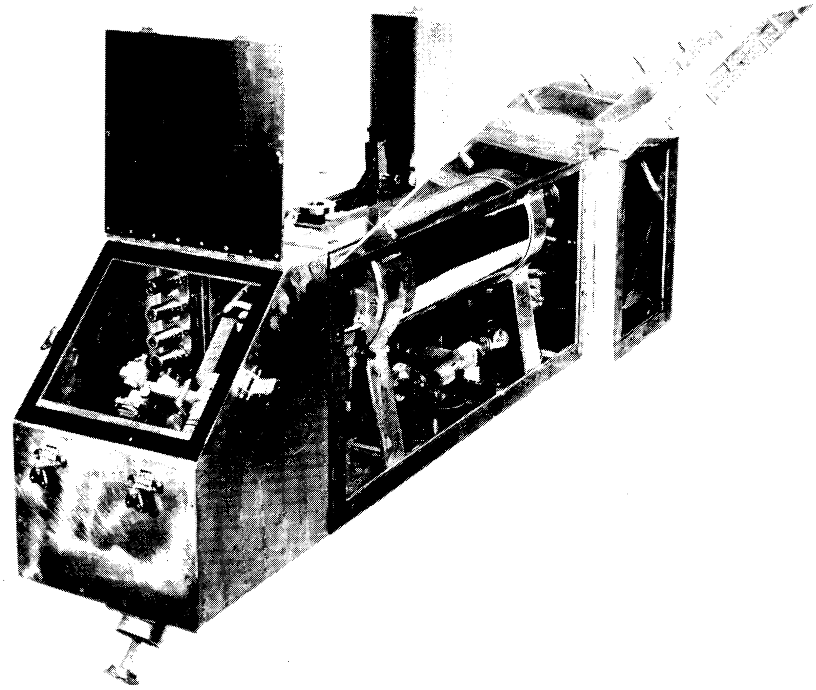


Figure 10.

limitations on the tolerances in the structure. The dimensions of a traveling-wave maser operating at 35 Gc and using rutile for the maser material at 4.2°K and 30 db of gain will be approximately .050" x .050" x .5", certainly a very small structure.

Again I would like to say that a low noise parametric amplifier will require the same cryogenic equipment as the maser. A relatively inexpensive and reliable closed-cycle refrigerator would be very useful in both laboratory and field operation. This is something for the cryogenic people to think about. Thank You.

R. E. Carroll:

Thank you very much, George. Do you get your liquid helium from Prof. Westrum?

G. I. Haddad:

Yes, we also get liquid nitrogen from Professor Van Wylen.

R. E. Carroll
Question:

It sounds like he has a pretty good business. George, how much cooperation is there between the different laboratories and the engineering college and this kind of business? I'm thinking, for example, Radio Astronomy people use masers, electron physics people design and build masers, traveling wave tubes and so forth and various other units around the campus and the Willow Run Laboratories are all working in the same general field. At least there is an overlap; and what kind of communication goes on?

G. I. Haddad
Answer:

Well of course the people at Willow Run have built this cavity maser for Prof. Haddock's group in Radio Astronomy. I don't know if Prof. Haddock knows about our activity in traveling-wave masers. The traveling-wave maser has, as I said, several advantages over the cavity one, but is also more expensive.

R. E. Carroll:

We have a question over here.

Question:

In this traveling-wave maser, does your pump-frequency wave go along that same ladder?

G. I. Haddad
Answer:

No, the signal travels along the ladder line and is slowed down. The pump propagates in the TE_{10} node in the ω ridge waveguide which encloses the ladder line. Now since a TE_{10} node has its electric field perpendicular to the ladder line the pump power will not be coupled to the ladder line. This is, of course, what we want. We do not want pump power to come out through the signal waveguide for then a filter would be required to suppress the pump power.

Question:

How high in frequency can you operate such devices?

G. I. Haddad
Answer:

The maser principle which I discussed earlier applies in any frequency range. The laser is essentially a maser operating at light frequencies. There is a wide frequency gap, however, in the millimeter and submillimeter wave range where such devices do not exist. However, a great deal of work is presently underway to close the gap. One way of achieving this for example is to beat the output of two lasers and generate power at the difference frequency. In the regular three level maser, the pump frequency must be at least greater than twice the signal frequency. Thus for high signal frequencies no pump sources are available. However, there are pumping schemes which may be employed to obtain a signal frequency higher than the pump. We are presently investigating such a scheme here. At least four energy levels are required for such a scheme. To illustrate, suppose we have four energy levels located in such a manner that $f_{14} = 2f_{23}$. Pumping Levels 2 and 3 will saturate these levels and also will saturate Levels 1 and 4 via a process called "harmonic spin coupling". This will result in inversion at a signal frequency f_{13} which is higher than the pump frequency at f_{23} .

R. E. Carroll:

Thank you very much, George.

R. E. Carroll

The next man on our program, Richard E. Sonntag, received his Masters from the University of Michigan in 1957, his Ph.D. in 1961; he is Associate Professor of Mechanical Engineering. His principal areas of interest are Thermodynamics, Fluid Flow, Fuels, Gas Turbines, Compressors and, of course, Cryogenics. Dick Sonntag will, as you see, speak on the subject "Phase Equilibrium Research at Low Temperatures" - Dick.

PHASE EQUILIBRIUM RESEARCH AT LOW TEMPERATURES

Richard E. Sonntag

Associate Professor, Mechanical Engineering

PHASE EQUILIBRIUM RESEARCH AT LOW TEMPERATURES

Thank you, Ray. I would like to discuss briefly this afternoon some of the research that we have conducted in the area of thermodynamics, in particular two systems that are examples of phase equilibrium at low temperature, both of which are binary two-phase systems. Now before I discuss these particular systems let me mention one analogous problem, this being the system air-water vapor at atmospheric conditions. Everyone is familiar with the problems associated with mixtures of air and water vapor. The atmosphere always contains a certain amount of water vapor, and we describe the amount in terms of a parameter that we call relative humidity. As an air-water vapor mixture is cooled, eventually some temperature is reached at which the mixture becomes saturated, this temperature being called the dew point temperature of the mixture. If we continue to cool the mixture further some water will condense out of the mixture in the form of liquid. On the other hand, if we cool a mixture that contains only a very small amount of water vapor, the dew point is below 32°F in which case the water comes out of the mixture going directly from the vapor phase to the solid phase.

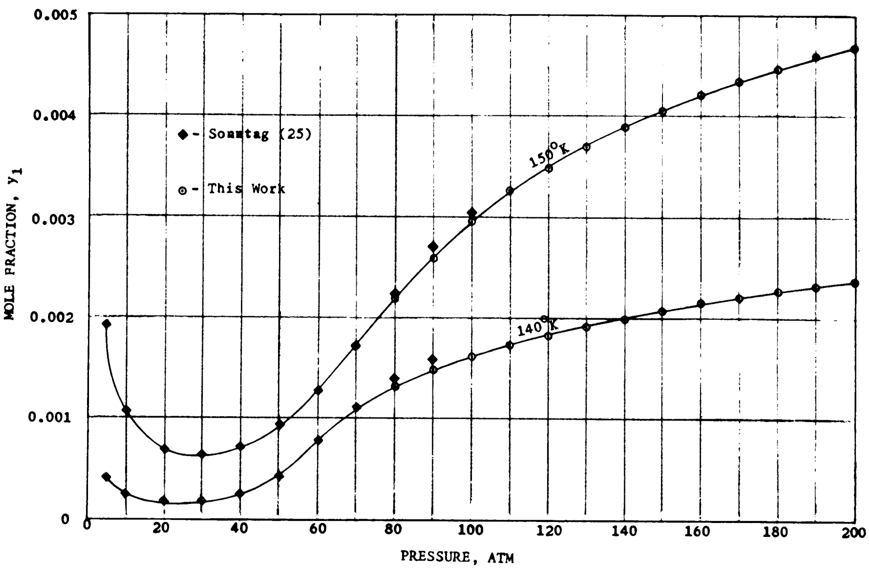
In each case we are able to describe and determine relative humidity quite simply because the air-water vapor mixture is at low pressure and behaves essentially as a mixture of ideal gases, which makes it a very simple problem from analytical standpoint. We encounter the same type of problems with other mixtures at temperatures below the ambient temperature, where the saturation regions of all substances we normally consider as gases at room conditions, are reached. In some cases we observe this as sublimation, that is a component condensing from the vapor directly to the solid phase. An example of this is carbon dioxide with air, in which case we might be interested in solid-vapor equilibrium and in particular the equilibrium concentrations of carbon dioxide in the vapor phase. This is one of the problems that we examined. On the other hand the CO_2-air mixture might behave more like the mixture of water vapor and air at higher percentages of water vapor, in which case the component may condense to the liquid phase. This would result in a binary equilibrium of liquid and vapor, and this is related to another study that we have also made recently.

Let me first discuss the solid-vapor system that we investigated, both from an experimental and a theoretical view point. In this work we considered a mixture of carbon dioxide and nitrogen.

This problem is associated with the solidification of carbon dioxide from air in air liquefaction plant. We chose to use nitrogen instead of air because we were interested in the theoretical aspect of this problem and it is much easier to handle a pure substance such as nitrogen than it is to analyze a mixture of many gases comprising air. We prepared mixtures of carbon dioxide and nitrogen with carbon dioxide concentrations somewhat greater than expected at equilibrium and stored these in gas cylinders at room temperatures and very high pressure. Now, the mixture is precooled in a heat exchanger and enters the cryostat. This system is called a flow system. That is, a mixture of gas flowing through the cryostat, and is cooled to a low temperature where some of the carbon dioxide freezes out of the mixture. There is a solid carbon dioxide trap at the equilibrium point, in which we hope to trap out all the particles of solid CO_2 that have been formed. Then we allow the vapor mixture, mostly nitrogen with small percentages of carbon dioxide remaining, to warm back up to room temperature and pass through a regulated back-pressure control to hold the flow conditions constant. A small portion of this gas is passed through an infrared analyzer where the percentage of carbon dioxide in the vapor is determined.

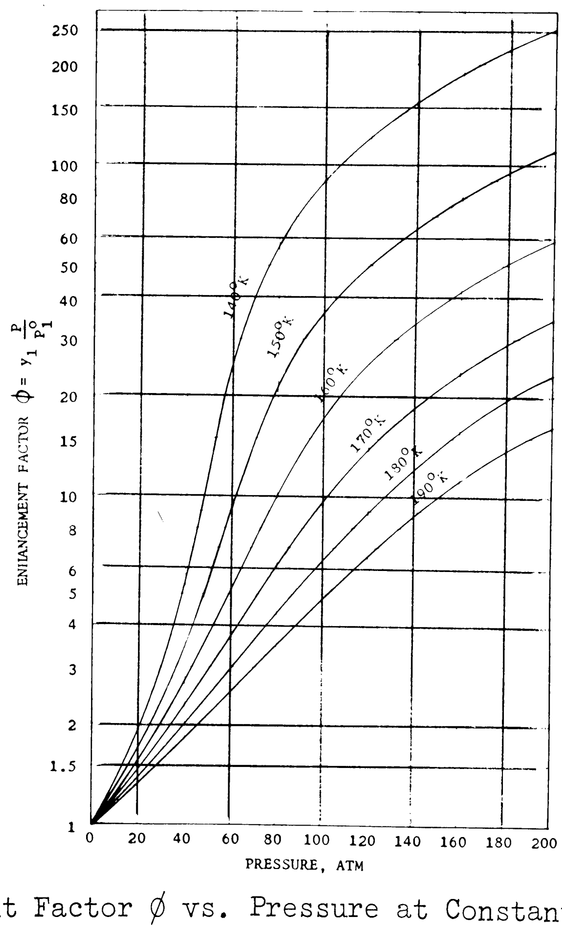
Figure 1 shows the experimental results that we found at two temperatures. The mole fraction of carbon dioxide is plotted versus the pressure for each temperature. We note one thing that is quite interesting, the existence of a minimum point in carbon dioxide concentration at each temperature. At higher pressures than this minimum point, there is a larger equilibrium concentration of CO_2 in the vapor. So this is a very important result as far as a consideration of the purification of gas mixtures by selective freezing is concerned. If we were to operate at 150°K, for example, in a mixture of this type, we would like to operate at a pressure of about 30 atmospheres in order to minimize the carbon dioxide concentration in the vapor and hold it to a very small value.

From a theoretical standpoint, we were interested in predicting the equilibrium concentrations for this system and this problem is considerably different from that of the air-water vapor mixture that we mentioned before. At very low pressure where we can treat the mixture as an ideal gas, then the problem becomes quite simple. From the pressure and saturation pressure of carbon dioxide, and using ideal gas laws we could predict the concentration of CO_2 in the vapor phase mixture. At higher pressures, however, the mixture behavior becomes more and more non-ideal. Eventually the minimum point is reached, above which pressure the carbon dioxide concentration



Mole Fraction y_1 vs. Pressure at 140° and 150°K

Figure 1



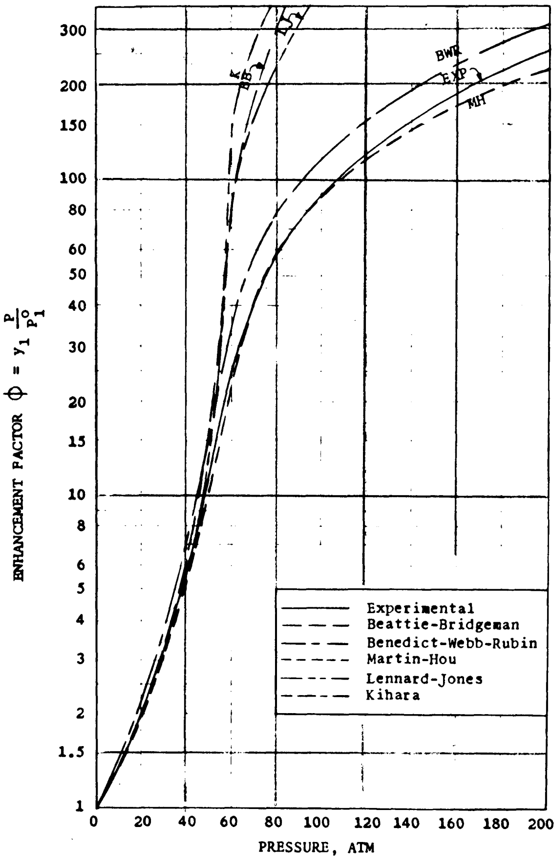
Enhancement Factor ϕ vs. Pressure at Constant Temperature

Figure 2

actually begins to increase again. This is largely to the non-ideality of the gas mixture. Figure 2 shows the experimental results plotted here in terms of a quantity called the enhancement factor. The enhancement factor is a parameter that is defined as the ratio of carbon dioxide concentration in the vapor phase to that predicted for ideal behavior. This factor then gives an indication of the departure of this mixture from non-ideality. An enhancement factor of unity would of course mean that the mixture behaves as an ideal system. We see that at 140°K at the higher densities the enhancement factor actually becomes greater than 200. That is, there is over 200 times as much CO_2 in the vapor phase as would be predicted by the ideal gas law. Now, using the procedures and equations of thermodynamics, we are able to make predictions that are certainly much better than that predicted for ideal system behavior. The equations that we obtain require an equation of state for the gas mixture, which is not well known. Most of the equations of state are empirical in nature, but we also studied this system from a theoretical standpoint. Using both the empirical and theoretical equations of state and applying the equations to both the pure carbon dioxide and the mixture, we have compared the predicted values with the experimental. It is convenient to present these comparisons in terms of enhancement factors.

The results are shown here at one temperature, 140°K, which was the highest density studied in this investigation, two to three times the critical density, and in fact values that are higher than the equations of state are intended to represent. Figure 3 shows the experimental enhancement factor at this temperature compared with the results of several equations of state. We see that all the equations are good at low to moderate density, that is, up to a pressure of about 40 to 50 atmospheres, approximately the critical density of the mixture at this temperature. At higher densities than this, there is quite a difference between most of the predicted values and the experimental. However, two of the complex equations of state, the Benedict-Webb-Rubin and the Martin-Hou equations, still give a very good correlation with the experimental results.

The results at the other temperatures of interest, up to 190°, were similar to this. The densities were not quite so high and consequently the predicted and the experimental results are even a little closer than they are at 140°. I showed only the extreme case, that of the highest density. These results should certainly be of interest in so far as predicting equilibrium concentrations of gases that may freeze out of mixtures as they are being cooled in either experimental or commercial installations. There needs to be a lot more work done



General Solutions at 140°K

Figure 3

on the equations of state, because constants are not known for many substances for some of the better equations of state.

The other system that I would like to discuss here is a different type of system with a somewhat different interest. This is an example of a liquid-vapor equilibrium system. In particular the substances we were concerned with were hydrogen and helium. The interest in this problem arises from the liquid hydrogen industry where liquid hydrogen is very commonly transferred by pressurizing with helium gas. Therefore, it would be very desirable to know the amount of helium gas that dissolves in the liquid phase. We are again concerned with a binary two-phase system, in this case hydrogen and helium, with the liquid phase being primarily hydrogen and the vapor phase primarily helium. The region of liquid hydrogen temperatures is fairly far above the critical point of helium, so we would expect helium concentrations in the liquid to be quite small. In this type of system the problem is a little more complex as far as experimental work is concerned because the liquid phase has to be sampled. This is the phase of primary interest, concentration of helium in the liquid phase being the desired quantity.

In this case, we used a vapor recirculation type of equilibrium system. The equilibrium cell is maintained in a cryostat held at a fixed temperature, as shown in Figure 4. The cell is initially charged with liquid hydrogen and is then pressurized with helium, with the vapor recirculated so as to achieve equilibrium fairly rapidly. The vapor phase is withdrawn from the cell pumped around a loop and back into the cryostat again, and bubbled through the liquid, this promoting equilibrium between the two phases quite rapidly. The system is run for about half an hour under these conditions at which time a condition of equilibrium is assured. In order to sample, we isolate a portion of the vapor that is being recirculated in a vapor trap, after which a sample is collected in sampling bottles. The liquid sampling is more difficult because the sample is drawn through a very fine capillary tube placed in the equilibrium cell. A critical flow must be established in this small line in order to avoid fractionation of the liquid phase with a resulting change in composition, such that the sample that we eventually collect in the sample bottles would have a different concentration of helium than the liquid actually had in the cell.

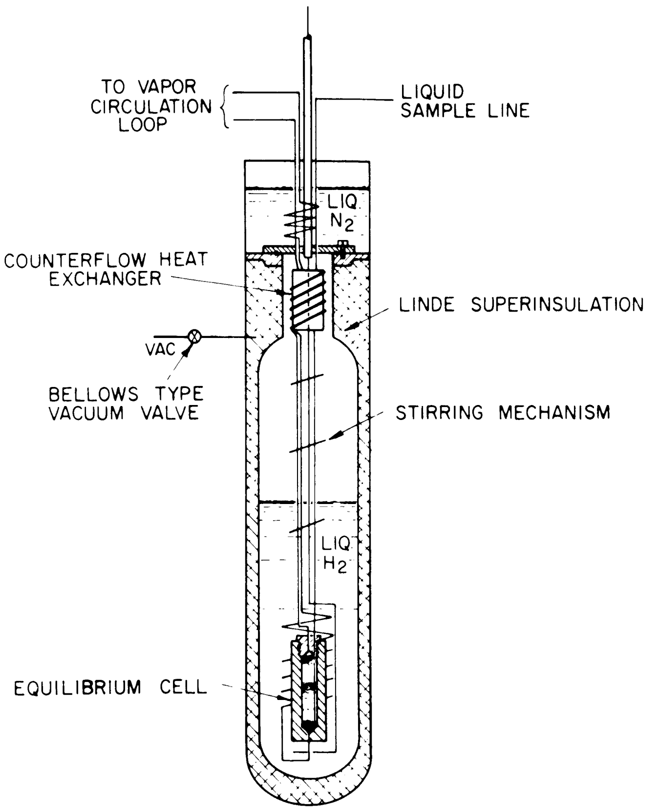


Figure 4. Section Through Cryostat Showing Equilibrium Cell.

The equilibrium cell is fairly low in the cryostat. The cryostat is filled with liquid hydrogen and the vapor pressure controlled, such that a uniform and constant temperature is maintained. There is some heat leak into the cryostat, primarily down the inner walls from the liquid nitrogen shield above, but most of the heat load actually comes with the vapor that is being recirculated. The vapor is drawn out of the system, recirculated through the external loop and back to the cryostat. The vapor is cooled here to liquid nitrogen point and then passes through a counterflow heat exchanger, but still this is the bulk of the heat load that is introduced to the cryostat.

We studied this system over the whole range from 15.5° to 32.5°K, that is almost to the critical point of hydrogen. We found, as expected, that at the lower temperatures the vapor is primarily helium, and the liquid phase primarily hydrogen, with the helium concentration increasing somewhat with increasing temperature and pressure. Near the critical point of hydrogen we see a closure on some of these loops. At 30.6 we see that one of these loops has closed and the critical point for this particular isotherm is at the top of the loop. That is there can be no saturation or two-phase equilibrium conditions at higher pressures for this temperature. This critical locus is seen to be a function of temperature and pressure is liquid-phase helium concentration versus pressure at different temperatures is shown in Figure 5 on an extended scale from what was shown on the previous diagram. Again we see that the data seem to be quite consistent from 0% helium at the saturation pressure for pure hydrogen and increasing somewhat with increasing pressure.

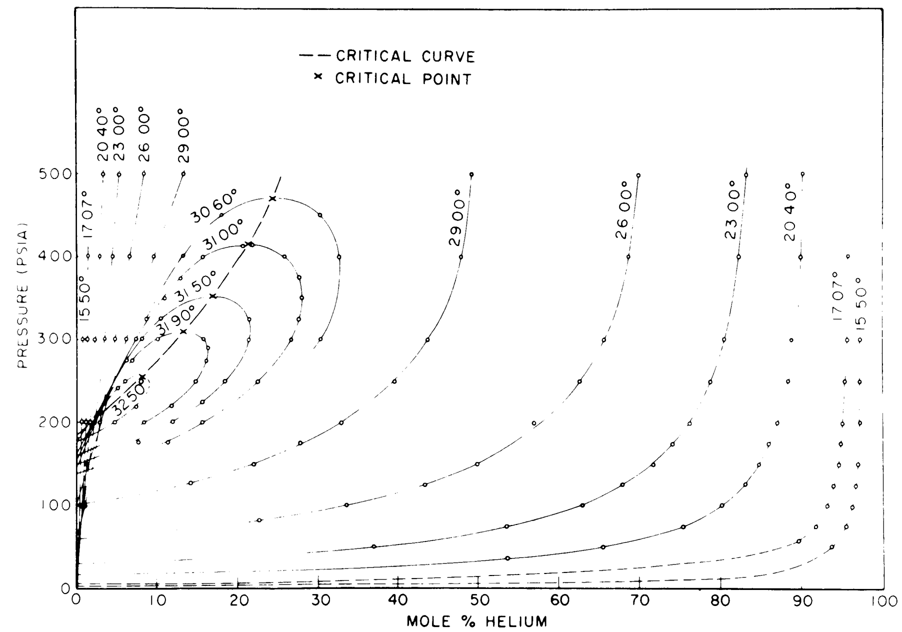


Figure 5. Isothermal Pressure-Composition Diagram.

The liquid phase does not contain very much helium except at the higher temperatures, of the order of magnitude of 26°K.

These studies were made using normal hydrogen, which is room temperature equilibrium hydrogen. We are now conducting studies using 20.4° equilibrium hydrogen, which is almost pure parahydrogen. The results are slightly different than those shown here because of the slightly different properties of equilibrium and normal hydrogen. This cryostat has also been used to study the system nitrogen-helium in the vicinity of the critical point of nitrogen, in an attempt to resolve some discrepancies in the published data on this system. We have also begun investigation of the three-phase system hydrogen helium in the vicinity of the triple point of hydrogen, around 13°K, and are extending the measurements on the hydrogen-helium liquid-vapor system to pressures higher than 500 pounds per square inch.

There is a phenomenon of particular interest in the hydrogen helium system. We have observed this phenomenon at the lower temperatures - 15.5 and 17°K - within the pressure range already studied, up to 500 pounds per square inch, and this is the phenomenon of phase inversion. That is, as the pressure is increased on this system at any given temperature eventually some point is reached at which the vapor phase becomes denser than the liquid phase. Consequently, in our equilibrium cell, we found that the liquid phase was at the top and the vapor phase was at the bottom of the cell, and our system doesn't perform well under these conditions. Instead of recirculating the vapor phase, we actually pull the liquid out of the cell, vaporizing and causing some instabilities in the recirculation. Then as it is returned to the cryostate, it again liquefies, again causing pressure fluctuations and also introducing a very large heat load into the cryostat. We are now building a glass equilibrium cell in order to locate the particular pressure at which this phase inversion occurs at a function of temperature, and we hope to take some pictures and study this phenomenon in greater detail.

R. E. Carroll:

Thanks a lot, Dick, sounds like quite a fascinating Alice in Wonderland world, should we say, when the liquid gets to be less dense than the gas. Do you have any questions?

Question:

At the temperatures and pressures used in missile systems where you would use a pressurized liquid, hydrogen, from what you say you should have no practical effect on varying of the oxygen-hydrogen mixture --

R. E. Sonntag
Answer:

Well, this would be of course, equilibrium hydrogen which is one of the things that we are studying now, and we are essentially finished with this work. We found that there is essentially no change in the liquid phase composition for the two systems, that is, equilibrium hydrogen with helium compared with normal hydrogen-helium whereas the vapor phase composition is changed somewhat between the two systems. Now, the percentages of helium in the liquid phase are not really very large, certainly less than one percent, and this would not have a large effect on the performance of a rocket engine, although it is certainly very desirable to know the percentage of helium, and to make allowances for it in the calculations of the rocket engine performance.

Question:

Do you know if there is any data on the solubility of helium in solid hydrogen?

R. E. Sonntag
Answer:

No, this is a system that is similar to the system CO_2-Nitrogen that I discussed. We are presently investigating the two and three-phase behavior of this system.

Question:

One of your curves showed a minimum in your equilibrium between CO_2 and nitrogen. Did you folks attempt to consider the surface energy and the minimum number of molecules that constitute a solid or liquid?

Years ago we did some work in the field of water, and air and found, for instance, that 8 molecules is the minimum number that could exist as a liquid. And we found that we had to take into consideration the surface energy in considering such small numbers of particles.

R. E. Sonntag
Answer:

No, we haven't done any work of that type.

Let me say a few words about our test facilities. I think there was some interest expressed in this earlier. We are very fortunate to have a nice test facility at the Automotive Laboratory on North Campus to do the hydrogen-helium work. The test cells are all individual cells, each cell having its own ventilation system. We had to modify this somewhat to use liquid hydrogen in the room because the rooms were designed to use substances that were heavier than air. The air enters the room at the ceiling and goes out through a tunnel at the floor. We had to reverse this procedure to bring air in at the floor and withdraw it through the ceiling, and also had to put a high capacity explosion-proof blower in the room immediately over head, where the ventilation system is located.

We also had to have fairly extensive ventilation on our cryostat and other portions of the system. That is, the cryostat was contained in an enclosure that was approximately four feet square. We built an exhaust hood over this entire system that was completely enclosed except for a space a few inches above the floor where air was drawn in. This hood leads directly to the explosion proof blower. There are also other ducts at the ceiling to withdraw any hydrogen that might possibly have gotten out of the hood system. The capacity is sufficient to give about 30 or 40 complete air changes per hour in the room, so that there would be no problem in building up hydrogen concentrations in the room. Blowout panels were installed to replace the windows in the cell, and hydrogen detection systems were located at the ceiling level. The liquid hydrogen is stored outside and brought in only to transfer from the storage Dewar into the cryostat itself.

All electrical fixtures are explosion-proof and are placed very close to the floor. The lights are also explosion-proof, and all of the electrical conduits and boxes have to be sealed to prevent the possibility of any hydrogen getting into the electrical conduit system.

R. E. Carroll:

Thank you very much, Dick. While I introduce Professor Lady, I might suggest that maybe you would want to stand up and improve the circulation for about ten or fifteen seconds. I know it gets a little bit numb in the nether regions after you have been sitting an hour and a half. We really don't have time for a mass exodus and reconvening. I would appreciate if you would just stand where you are unless its absolutely essential. I think this next talk may have interest to quite a few people. I've seen some representatives from a pump company, a compressor company, rotating machinery company, a refrigeration company, and several others who, no doubt, have some direct interest in the subject of refrigeration systems for very low temperatures. Particularly, we've heard today that some of the users of the cryogenic fluids would be very happy if they could just push a button and have the temperature brought down where they want it and for the length of time they want it, without having to transport cryogenic fluids back and forth from the generator and so forth to keep their systems filled with these very cold liquids.

Also there is the question, if you do need cryogenic fluids where you're going to get them, how much they cost, who's in the business, and what kinds of plants are in operation now-a-days. So I think we'll hear some of the answers to these points and also some others from Professor Lady.

R. E. Carroll

Professor Lady received his Masters of Science Degree from M.I.T. We have several M.I.T. degrees represented here today I noticed, Ph.D. from the University of Michigan. He became an instructor on our staff in 1961, Associate Professor in 1963. He has worked with the Linde Air Products Company, Carbide and Carbonic and Carbon Chemicals Corporation and was with Air Products Incorporated for 10 years. And just incidentally, Professor Lady will be chairman of a two weeks intensive course in Cryogenic Engineering beginning May 25. So it is with great pleasure I introduce to you Professor Edward R. Lady, who will talk on Cryogenic and Refrigeration Systems and other things close to this, Ed.

CRYOGENIC REFRIGERATION SYSTEMS

Edward R. Lady

Associate Professor, Mechanical Engineering

CRYOGENIC REFRIGERATION SYSTEMS

I. Introduction

The title "Cryogenic Refrigeration Systems" has been made rather broad so that our discussions may cover considerable ground. In the general context, we may consider as a cryogenic refrigeration system any system or device which produces or maintains a temperature lower than -100°F to -200°F, the exact limit being quite arbitrary. Under this definition both a vacuum bottle of liquid nitrogen (temperature -320°F) and a 25 million dollar liquid hydrogen plant may be included. Since most of us are well acquainted with the vacuum bottle, we shall concentrate on somewhat more complex cryogenic systems.

II. Compact and Miniature Cooling Systems

One class of cryogenic refrigeration systems may be described as compact or miniature cooling systems. These systems are required to provide small quantities of refrigeration for such electronic devices as infrared detectors, masers, parametric amplifiers, or superconducting elements. The temperature level at which the cooling is required may vary from 2°K to 100°K, expressed temperature in the absolute centigrade scale. Although the refrigeration load may be less than a watt, a sizable amount of work is required to extract this energy if the absolute temperature is very low. The theoretical minimum work for a refrigeration system is that of a Carnot cycle. The ratio of the Carnot cycle work to the refrigeration load as a function of temperature is shown in Figure 1. The work of a real refrigeration cycle, complete with friction, irreversible heat exchange, and other losses may be two to one hundred times the Carnot work. It is evident that the temperature level is a most significant factor for cryogenic refrigeration systems.

Miniature cooling systems may be divided into two categories - open and closed cycle. The open cycle system makes use of the refrigerant once only and vents it to the atmosphere. The closed cycle system recirculates a fixed charge of refrigerant and, theoretically at least, can operate indefinitely.

Of the three open cycle systems shown in Figure 2, the most elementary is the liquid storage system. In essence, it consists of

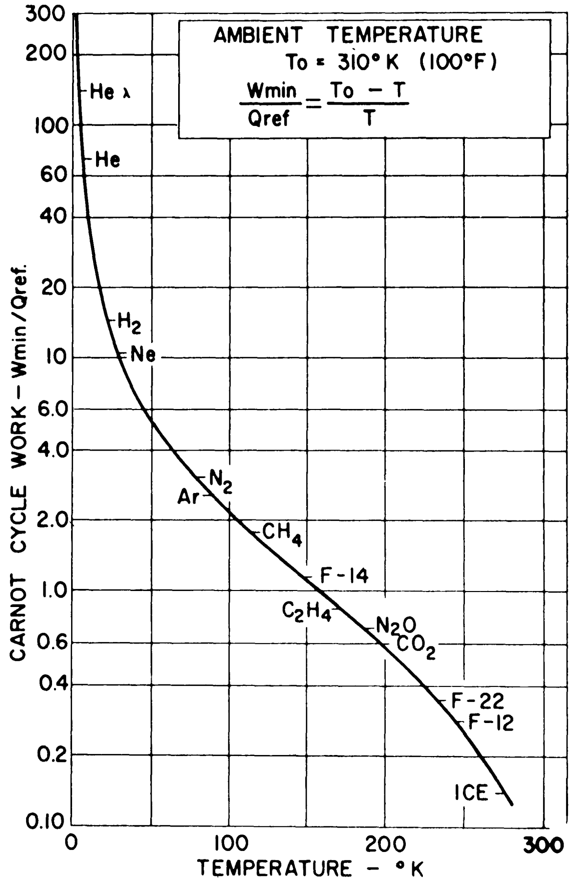


Figure 1. Effect of Temperature Level Upon Carnot Cycle Work.

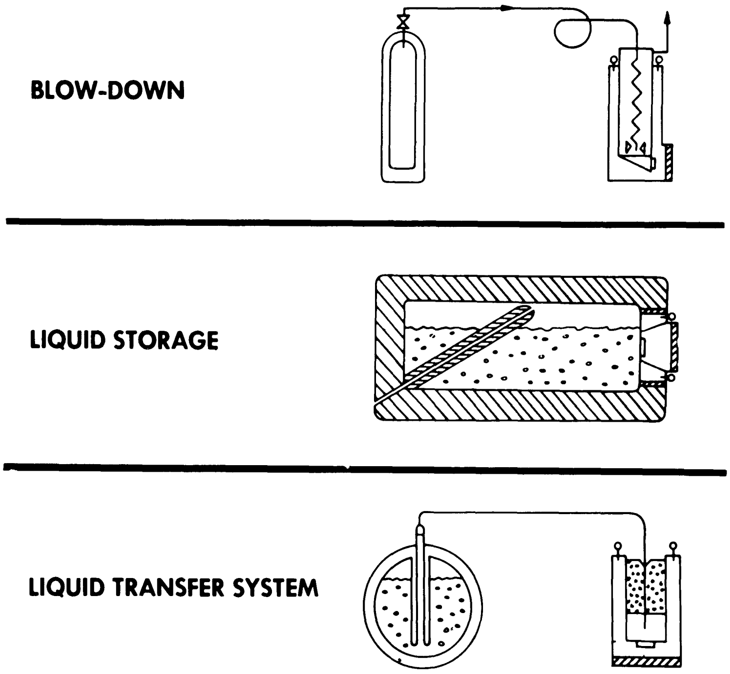


Figure 2. Open Cycle Cryogenic Refrigeration Systems

a well insulated vessel filled with a cryogenic fluid - liquid helium for example. The temperature level is fixed by the saturation temperature of the fluid. For atmospheric pressure, these temperature levels are indicated on Figure 1. The temperature level is held as long as liquid remains to be evaporated. Therefore, this system is suitable for short stand-by and short duty requirements. An outside source of the cryogenic liquid is an obvious necessity.

The liquid transfer system is a variation of the liquid storage system in that the storage and use of the cryogenic liquid are physically separated. This gives it a greater flexibility than the storage system, at the expense of slight additional complexity. Again, an outside source of cryogenic liquid is required and, once the system is filled, a slow but continuous loss takes place.

The only open system which can tolerate long stand-by is the blow-down system. In this case compressed gas is bled from a storage cylinder at ambient temperature. For gases with a positive Joule-Thompson effect (all gases except helium, hydrogen, and neon) a temperature drop occurs when the gas is throttled from high to low pressure. This effect, combined with a highly efficient heat exchanger, can cause a fraction of the gas to liquefy. The compressed gas in the cylinder is soon exhausted, however, thus limiting the usefulness of this system to short duty cycles.

An example of this type of system is seen in Figure 3. In this system, pure nitrogen is passed through a tiny heat exchanger encased in a vacuum bottle. The heat exchanger is a spiral of hypodermic tubing, .020" O.D. by .01" I.D., through which passes the compressed nitrogen. The low pressure nitrogen flows out around the tubing. In order to increase the heat transfer area, a fin is wrapped spirally around the tube. This fin is .010" high by .003" wide and has a pitch of 88 per inch. This system cools down to liquid nitrogen temperature (77°K) in about 70 seconds.

Two closed cycle systems are shown in Figure 4. The Joule-Thompson system has a cooling system identical to the blow-down open cycle system. A compressor has been added to maintain a continuous supply of compressed gas. We now have introduced a moving mechanical element, although it operates in a warm, or ambient temperature, environment. Because the compressor is operated at normal temperatures, conventional lubricants may be used, provided all traces of the lubricant are removed prior to admitting the compressed gas to the heat exchanger. Any contaminant in the gas

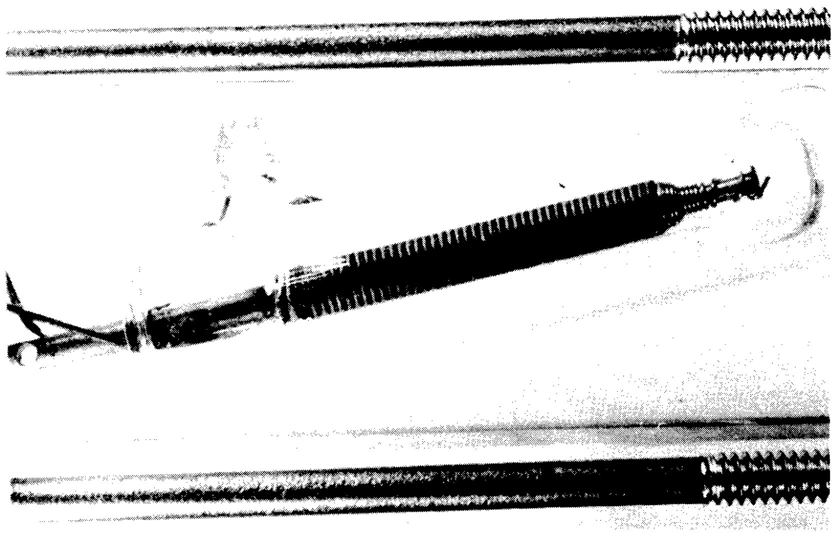


Figure 3. Miniature Heat Exchanger for Blow-down System.

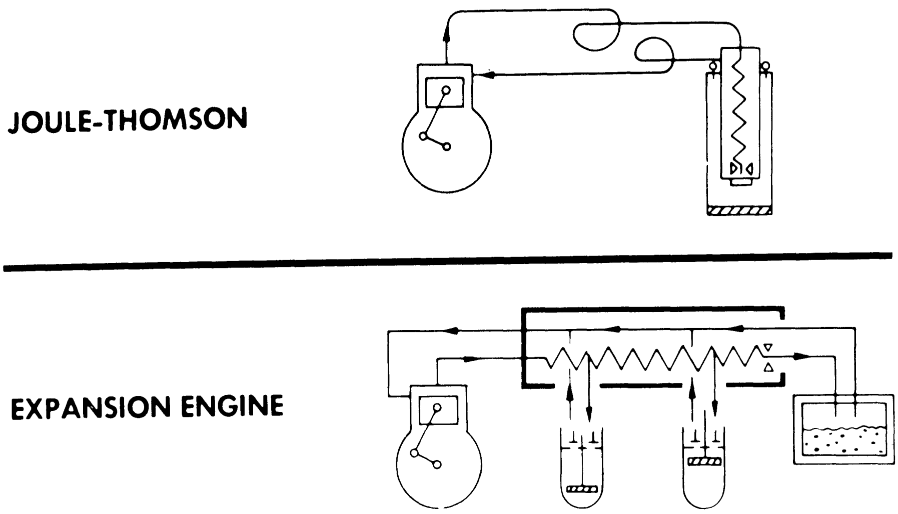


Figure 4. Closed Cycle Cryogenic Refrigeration System.

stream, whether lubricant, water or carbon dioxide will freeze out at low temperatures and plug the small bore heat exchanger tubing. Frequently the gas is kept free of contamination by a hermetic sealed, oil-free compressor using a diaphragm or a piston with filled - Teflon rings.

The lowest temperature which may be achieved by a single fluid, Joule-Thompson, system is about 77°K. For lower temperatures, a two fluid system may be used to reach 20°K and a three fluid system to reach 4.2°K. In the latter case, the nitrogen system is used to pre-cool hydrogen and helium streams, the hydrogen, in turn, precooling the helium stream. The pressures involved are quite high. One system which was studied used nitrogen and hydrogen pressures of 1000 psi and a helium pressure of 300 psi. Although pressures are high, the Joule-Thompson system is reliable and requires that very little equipment be cooled to low temperatures.

The most efficient, and also the most complicated, cryogenic cooling system is the expansion engine system, shown in Figure 4. In this system a gas, usually helium, is compressed to a moderate pressure at room temperature. The compressed gas is cooled in a heat exchanger and then portions of the gas are expanded in small engines, operating at very low temperatures. The primary purpose of the engines is the removal of energy, in the form of work, from the gas rather than the production of useful power. As the gas expands and work is performed on the piston, the temperature drops significantly. The cold gas is exhausted to the heat exchanger where it cools the entering compressed gas.

With helium as the working fluid and pressures less than 200 psi an expansion engine system can provide refrigeration as low as 4.2°K, the boiling point of liquid helium. The expansion engines, operating at very low temperatures and without lubrication, may cause this system to have increased maintenance and a lower reliability than the other systems.

Two examples of miniature cryogenic refrigeration systems will serve to illustrate the features of the open and closed systems. The first is the NASA specification for a cryogenic cooler for use with infrared detectors that will be suitable for one-year operational lifetime on board a satellite spacecraft. This specification was issued in February, 1963, and the work is being performed by Aerojet. The system is capable of maintaining the detector at a constant temperature of 11°K. The refrigeration load at this temperature is 200 milliwatts. The total system must weigh less than 150 pounds, occupy less than 26 cubic feet, have no moving parts, and require less than 500 milliwatts of power. The last requirement alone eliminates any closed system because the ideal Carnot cycle, absorbing 200 milliwatts at 11°K and rejecting it at the operational temperature in orbit of 200°K, would require 3400 milliwatts. As we stated earlier, real systems have power requirements far in excess of the Carnot cycle.

The solution to this problem is obviously a form of liquid storage system in which sufficient cryogenic fluid is sent aloft to provide cooling for one year. Due to the zero gravity conditions existing in a satellite, it is desirable to avoid liquids which might wander out the vent line with the vapor. By pulling a vacuum on liquid hydrogen, its temperature can be reduced from the normal boiling point of 20.4°K to 13.96°K, the triple point. A further reduction in pressure to 5.62 mm Hg will cause the hydrogen to solidify and maintain a sublimation temperature of 11°K. Thus we have a cooler similar to the block of dry ice used by the ice cream vendor. Maintaining the low absolute pressure of 5.62 mm Hg is scarcely a problem in a satellite. One merely controls the leakage rate of hydrogen gas to the hard vacuum of outer space.

The second example is the continuous cooling of a maser, such as is used for the Telstar communications system or the discrimination radar of the NIKE-ZEUS ballistic missile defense system. In this case the cooling system is mounted on a movable antenna which remains at a fixed ground location. Any reasonable power consumption is permissible but continuous extended operation is required. Weight and size are also relatively unimportant factors. The refrigeration load is less than one watt at a temperature level of 4°K.

Two solutions to the maser cooling problem have been achieved by two companies in the field - Arthur D. Little, Inc. and Air Products and Chemicals, Inc. Although the details vary, both companies chose the closed system, expansion engine concept, using helium as a working fluid. These units have been designed for a service life of 10,000 hours and unattended continuous operating periods of 2,000 hours between scheduled shutdowns.

Prototype tests indicate that such a service life is a feasible, though stringent, goal.

III. Tonnage Liquid Oxygen and Hydrogen

Plants which produce liquefied gases, such as liquid oxygen or liquid hydrogen, are fundamentally large scale cryogenic refrigeration systems in which the refrigeration effect is evidenced by the production of a very cold product. Plants to produce liquid oxygen from air have been in commercial use for three decades and liquid hydrogen has been produced on a large scale since 1959. Let us look at one of the largest liquid hydrogen plants in this country in order to understand the scope and complexity of such major cryogenic systems.

Air Force Plant No. 74, located in the Everglades near West Palm Beach, Florida, was the first of several tonnage liquid hydrogen plants built to meet the growing demand for this high performance fuel. The plant capacity is 30 tons per day, or almost 400,000 liters. This daily capacity represents a greater quantity of liquid hydrogen than all that produced throughout the world in the fifty years following Sir James Dewar's success in first liquefying hydrogen in 1898. An aerial view of the plant is seen in Figure 5.

Before producing liquid hydrogen, one must first have a source of gaseous hydrogen. Four sources of such raw hydrogen gas are oil refinery by-product gas, steam reforming of hydrocarbons, partial oxidation of hydrocarbons, and coke oven gas. The plant in Florida uses the partial oxidation of natural gas, although the original operation used crude oil. For the partial oxidation process air must be separated to produce oxygen and simultaneously liquid nitrogen can be produced to pre-cool the hydrogen. A simplified flowsheet of such an air separation plant is shown in Figure 6. The principal components are air compressor, air purifier to remove carbon dioxide, air drier to remove moisture, heat exchanger, expansion engine, and distillation column. The similarity to the small cryogenic coolers is obvious, although the tank truck hauling away the product emphasizes the size factor. A view showing the two oxygen plants serving the hydrogen plant are shown in Figure 7. Each air compressor, housed in the building behind the cold boxes shown, requires a 4000 hp motor to drive it.

The hydrocarbon feed, crude oil or natural gas, is partially oxidized in the feed gas plant shown in Figure 8. This is a necessary step to obtain hydrogen but can hardly be classed as a

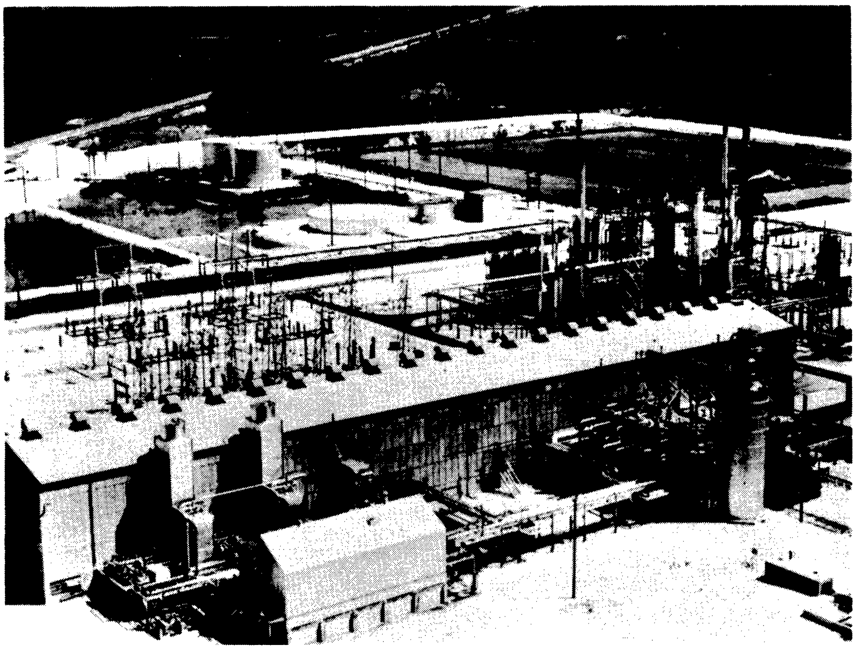


Figure 5. Aerial View of Tonnage Liquid Hydrogen Facility.

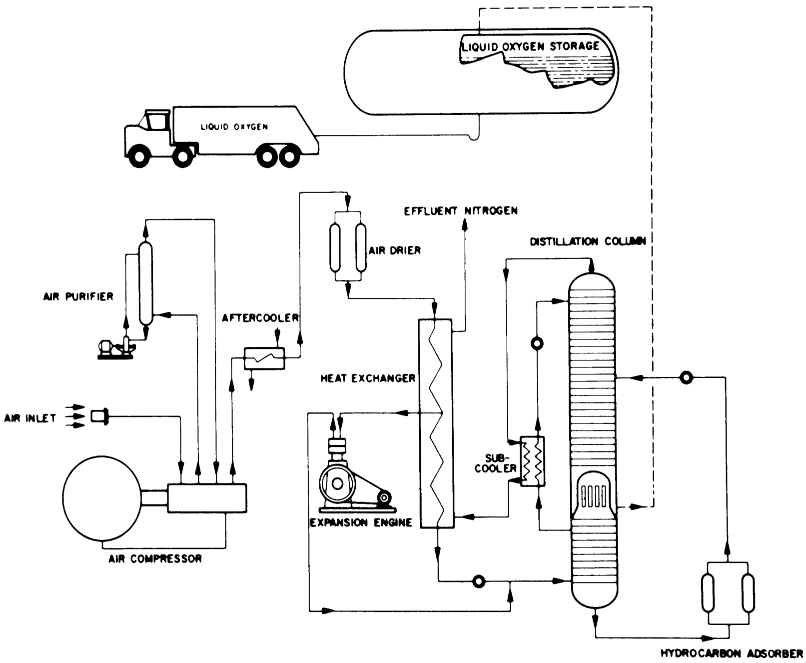


Figure 6. Simplified Flow Diagram, Typical High Pressure Air Separation Plant.

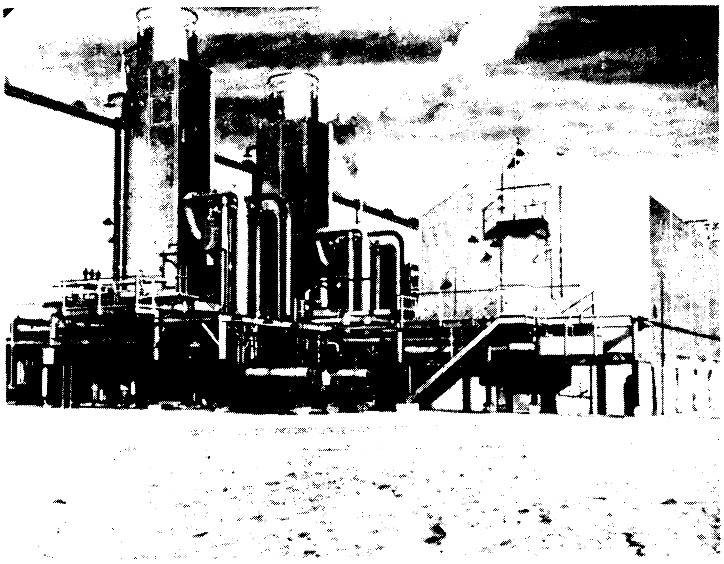


Figure 7. Two Liquid Oxygen-Nitrogen Plants and Insulated Storage Building.

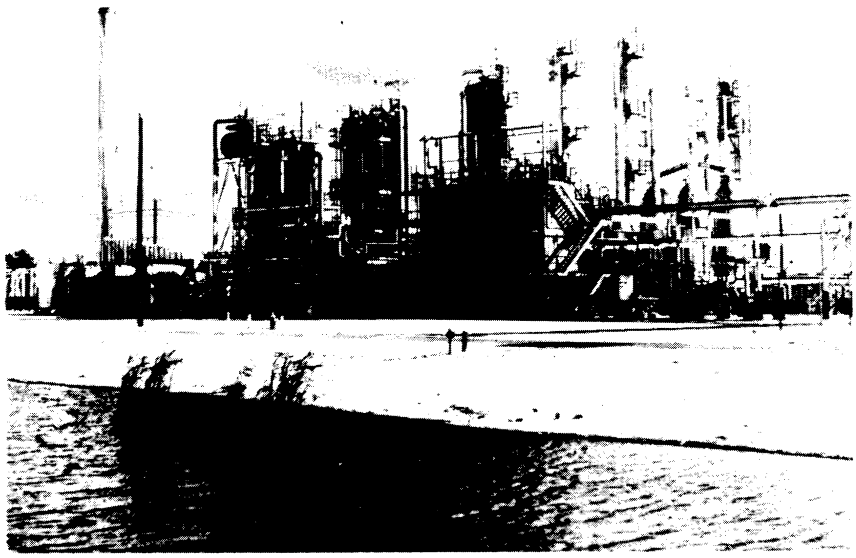


Figure 8. Feed Gas Plant for Crude Oil Gasification to Provide Raw Hydrogen.

cryogenic process, since the basic reaction takes place at 2200°F. The hydrogen produced by the feed gas must be purified so that less than one part per million impurity remains. This purification step occurs, either in specially designed adsorbers and scrubbers, or in the heat exchangers as the temperature is reduced to 20°K. In the latter case, the exchangers would soon plug up with frozen impurities. In general, cryogenic liquids are very pure products.

Huge compressors, driven by 5,000 hp motors, compress the hydrogen feed gas and deliver it to the liquefaction plant. It is readily seen that large scale liquefaction of hydrogen means huge electrical power demands. The plant that we are discussing was the largest single user of power in the state of Florida at the time of its construction in 1959. After the compressed hydrogen is pre-cooled with liquid nitrogen and in counter-current heat exchangers, a major portion is expanded in small, high speed expansion turbines such as seen in Figure 9. Only the warm end of the turbine can be seen in the picture. This is the power absorption end and consists of an air compressor, much like a supercharger. The hydrogen turbine end, operating at -400°F, is buried in insulation. Figure 10 shows such an expansion turbine. The wheel on the left is the turbine wheel; the one on the right is the air blower wheel. A rigid shaft, mounted on oil lubricated journal bearings holds the wheel. This turbine is about 10 in. diameter and rotates at about 20,000 rpm.

Once liquid hydrogen is produced it flows via a vacuum jacketed pipeline to large storage vessels. These are also vacuum insulated to reduce the heat gain from the outside air. The pipeline and storage tanks may be seen in Figure 11. The storage tanks are located at a remote distance from the producing plant for safety's sake. The barricades around the tanks have been removed since these pictures were taken so that air may dilute the hydrogen more rapidly in case of a spill.

Liquid hydrogen is shipped via 28,000 gallon rail tank cars, 13,000 gallon semi-trailers, or smaller containers. Figure 12 shows a trailer being filled with liquid hydrogen for transport to the launch site at Cape Kennedy. Although huge quantities of liquid hydrogen are used in the flights of such space vehicles as Centaur and Saturn, much larger amounts are used in development and static tests of rocket engines. It is fortunate, indeed, for all of us tax payers that large scale production of liquid hydrogen has reduced the cost to about 25 cts/gal. compared to the $19 per gal. which we

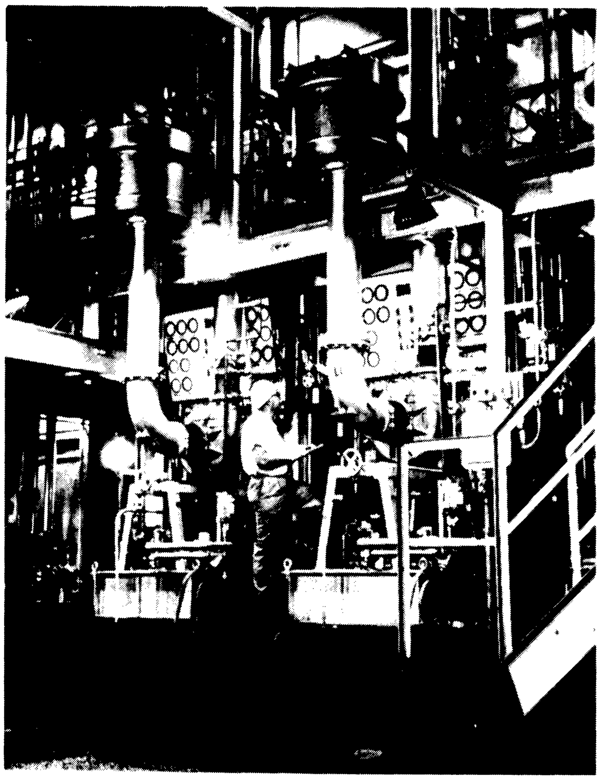


Figure 9. Hydrogen Gas Expansion Turbines Which Produce Refrigeration at -423°F.

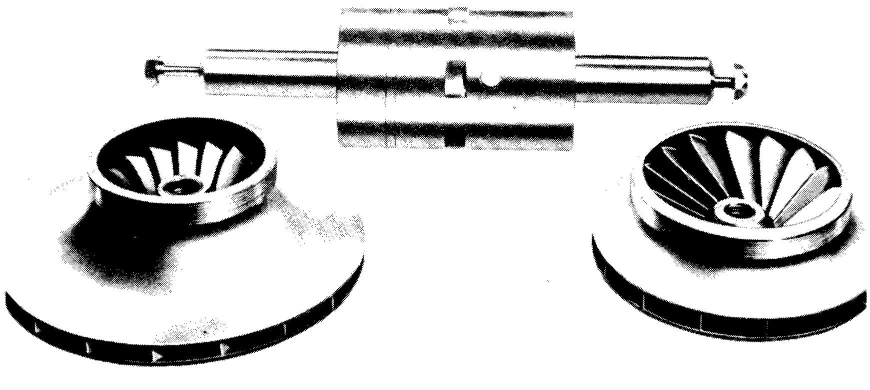


Figure 10. Rotating Parts of Hydrogen Expansion Turbine.

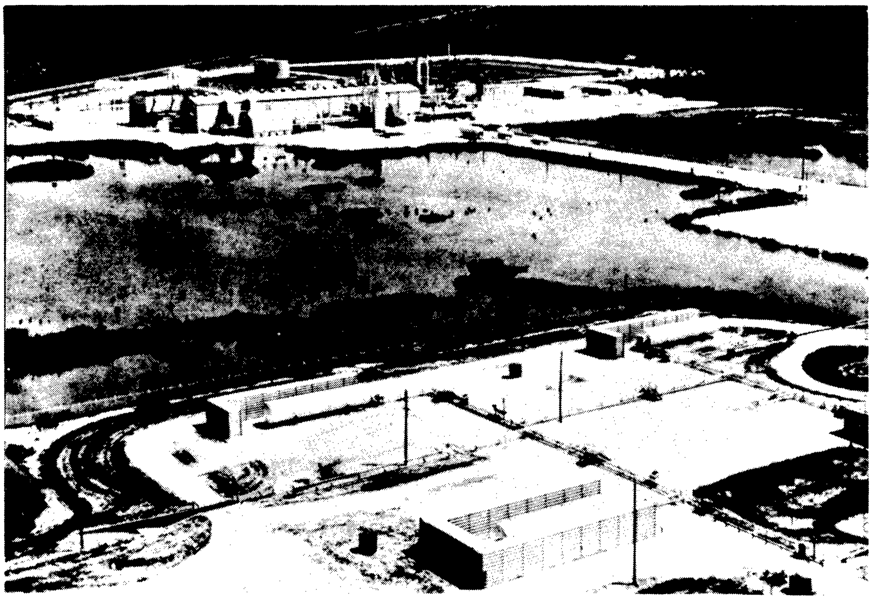


Figure 11. Vacuum Insulated Storage Tanks for Liquid Hydrogen.

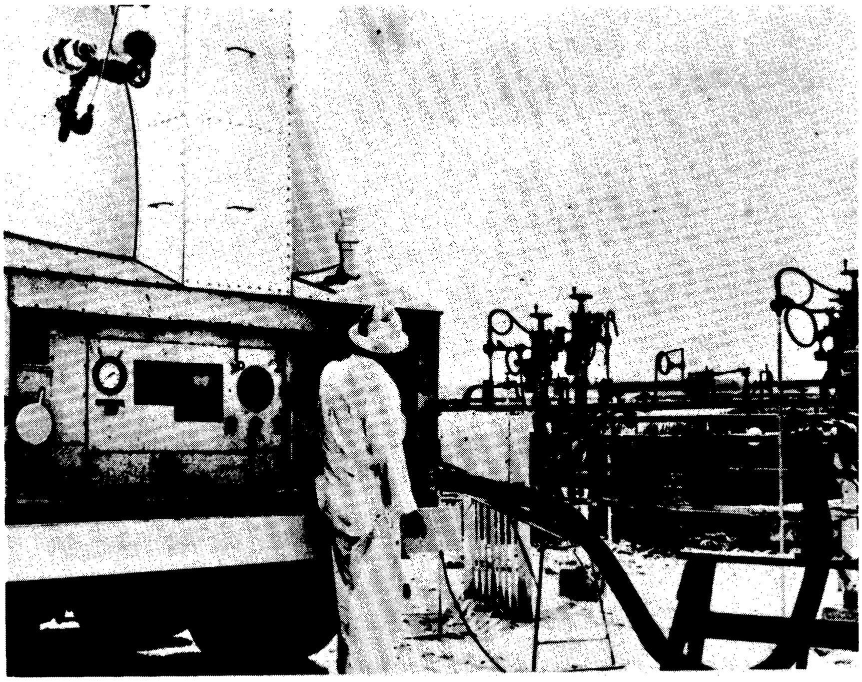


Figure 12. Filling Liquid Hydrogen Transport Trailer.

pay at Michigan for small quantities of liquid hydrogen used in research.

IV. Properties of Materials at Low Temperatures

All of us know that temperature affects the physical properties of materials such as electrical conductivity, specific heat and tensile strength. As we approach absolute zero (-460°F) the temperature dependence of the physical properties is of overwhelming importance. The very term "Superconductor," used in the titles of two of these talks, connotes this effect. Cryogenic refrigeration systems must operate at very low temperatures and therefore the designer of such systems must know the characteristics of various materials as a function of temperature.

It is beyond the scope of this presentation to discuss in detail the effect of temperature on physical properties. However, to make the point that it cannot be ignored, let us quickly examine several properties. Figure 13 shows the variation of specific heat of common metals with temperature. Remembering that room temperature is about 530°R, we see that the specific heat of iron drops to one percent of the original value as the temperature drops from 530°R to liquid hydrogen temperature, 37°R.

Another example of changes in physical properties is seen in Figure 14, showing the thermal expansion of metals. The coefficient of expansion decreases with decreasing temperature and approaches zero at very low temperatures. In certain cases there is a slight negative coefficient.

Turning from purely physical properties to engineering properties, Figure 15 shows the effect of varying the amount of nickel in steel and how the impact strength of steel can be preserved, even though the temperature is reduced. For very low temperatures, 9% nickel steel or 18-8 type stainless steel must be used. Figure 16 shows the stress-strain diagram for Type 347 stainless steel. The increase in ultimate tensile strength as temperature is decreased to liquid hydrogen temperature is almost three-fold.

V. Cryogenic Engineering Laboratory - National Bureau of Standards

Having made the point that properties of materials at cryogenic temperatures differ from those measured at room temperature,

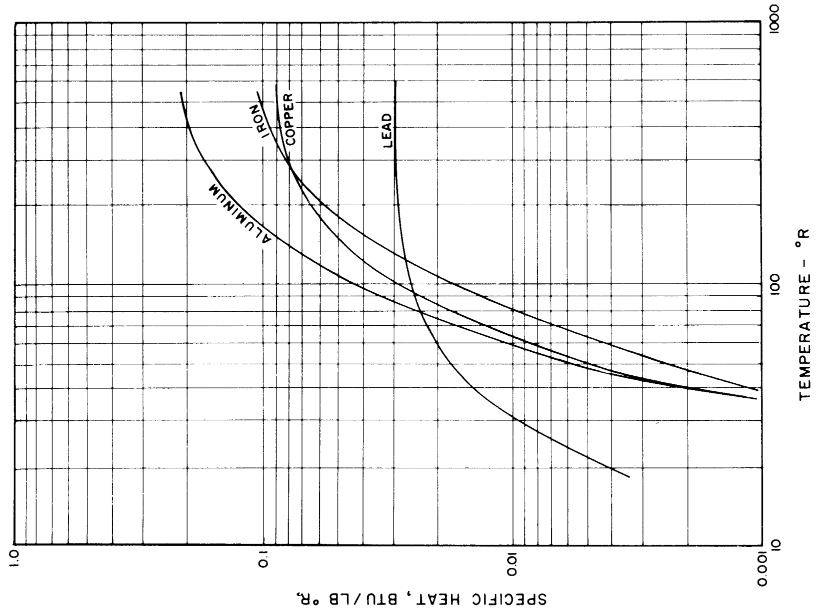


Figure 13. Specific Heat of Metal.

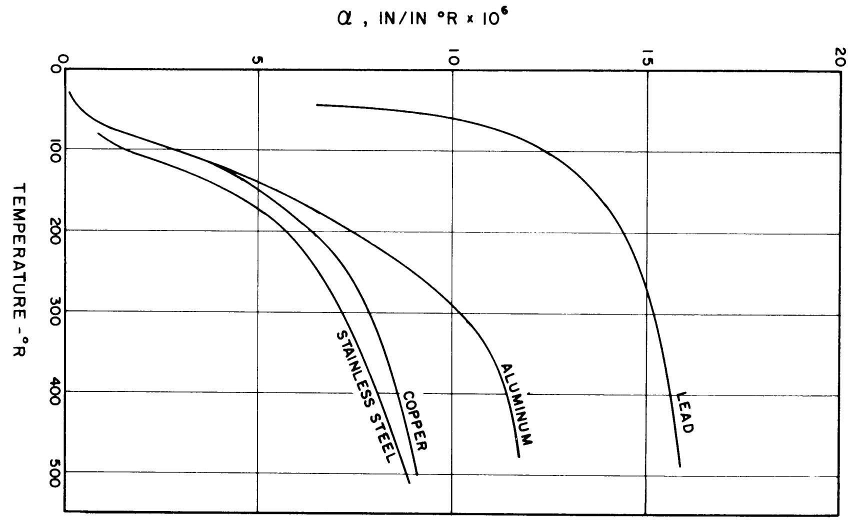


Figure 14. Thermal Expansion of Metals.

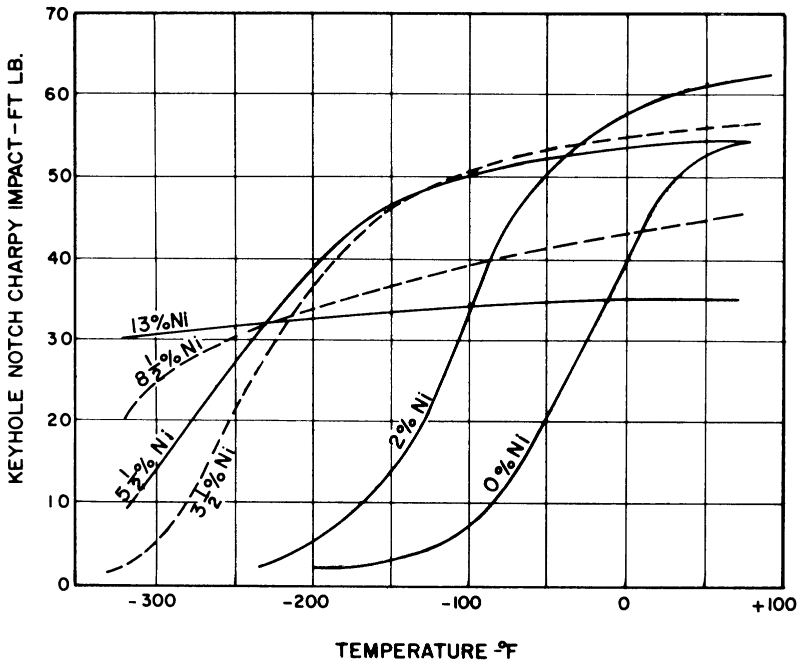


Figure 15. Effect of Nickel on Impact Strength of Steel.

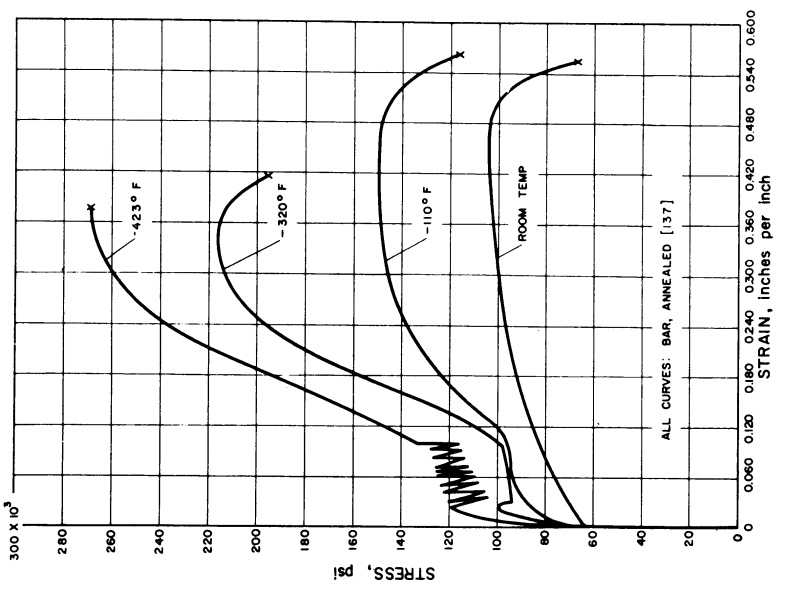


Figure 16. Stress-Strain Diagram for AISI 347 Stainless Steel.

the question arises as to where one looks for information regarding these properties. The sources of information are many but the focal point of such information is the Cryogenic Engineering Laboratory of the National Bureau of Standards, located at Boulder, Colorado. More than ten million dollars has gone to support this laboratory over the past ten years. Perhaps you would be interested to know what this money has accomplished.

The Cryogenic Engineering Laboratory was organized in 1954 as a separate division of the NBS. Prior to this time a considerable amount of low temperature research and engineering had been done within the Heat and Power Division. The mission of the laboratory is: determination of low temperature properties of solids and fluids; investigation of basic problems and phenomena associated with cryogenic engineering technology; research in cryogenic metrology and fluid transport processes; consulting services in these fields to Government agencies; making technical information of this kind available to the public.

The majority of the work of the laboratory is research and specialized engineering done at the request of, and financed by, other agencies such as the AEC and the Air Force. The development of the fusion bomb and advanced missile technology necessitated such activity. In 1958 the laboratory organized the Cryogenic Data Center with the following mission: Procurement and coding of all cryogenic information for storage; retrieval of information and preparation of bibliographies; evaluation and compilation of cryogenic data; and supplying technical information to laboratory staff and the cryogenic industry.

The Cryogenic Data Center has an operating budget of over $200,000. This sum is not adequate for complete and exhaustive literature surveillance but it is felt that at least half of the current literature is reviewed, pertinent articles obtained, and appropriate references coded for storage. About 6000 new entries can be processed each year. References are coded, a punch card is made for each one, and the information is stored on magnetic tape.

The storage tape is searched by looking for the appropriate code designated by an IBM 7090 computer. The search program permits as many as 99 simultaneous queries to be processed at once. Searches are usually made with several variations of each query so that all applicable reference will be retrieved. The computer prints out a list of reference numbers for each search. This must then be manually processed against a numerical list of catalog cards for final selection of the bibliography. The cost of each search is $15 and the print out of each reference is 15 cents each.

The preparation of bibliographies is a most useful function of the Data Center. Copies of the references, however, are not available through the data center; these must be obtained from the usual sources. The Data Center does issue reprints, reports, charts, and data sheets which evolved from activities of the Cryogenic Engineering Laboratory. Some 400 have been issued over the past few years. The documents distributed by the Data Center are sold at a price sufficient to cover printing and handling costs.

The discussion today has covered a considerable range, from miniature refrigeration systems to tonnage liquid hydrogen plants, from properties of materials at low temperatures to the activities of the Cryogenic Engineering Laboratory of the NBS. It is hoped that with such a wide range of subject matter, you will be able to fit almost any query or comment that is on your mind.

R. E. Carroll:

Thank you, Professor Lady. A very interesting presentation and you have kept us on time too. Do we have some questions for Professor Lady at this time?

Question:

I am interested in the refrigeration with solid hydrogen that you mentioned. This system was going to maintain a temperature of 11°K, did you say?

E.R. Lady
Answer:

Yes.

Question:
(cont'd) For a year? About how much hydrogen is involved in that, do you happen to know?

E. R. Lady
Answer:

We calculated about 75 pounds of hydrogen. The heat load that we had to absorb from the electronic component was equivalent to 20 or 30 pounds of hydrogen and the other heat that had to be absorbed was that leaking in from the outside. This assumed, of course, a good insulation, the multi-layer insulation. We had the advantage of a fairly low environment 200°K and not 300, which makes a big difference. Our work was just a theoretical calculation and design study, but apparently Aerojet is doing the same thing. Now the advantage of using solid hydrogen as opposed to a liquid, is, in addition to having a lump so that you don't have to worry about fluid going out the vent pipe, that you have a greater latent heat effect. You have the latent heat from solid to vapor which is the sum of the heat of fusion as well as the heat of vaporization. I am sure it has some problems in the operation since one must pull a vacuum on the block of hydrogen to keep the temperature and pressure down. This way we remove a lot of hydrogen and we have to refill and top-off before blast-off, pull the vacuum and then seal it while the rocket shoots through the atmosphere until it can vent.

S. H. Autler
Question:

At Westinghouse we have been thinking of running a superconducting magnet imbedded in solid hydrogen. Eventually we'd hope to get to lower temperatures than 11°K and we are thinking of actually freezing the hydrogen in liquid helium at first. Do you foresee any problems with this?

E. R. Lady
Answer:

One problem is whether the hydrogen would be frozen in the right place or whether the hydrogen pipes would be plugged up. I visualize having a container with liquid hydrogen, reducing the pressure and therefore self-cooling until the triple point is reached, then solidifying it. Fortunately hydrogen is like most substances and it shrinks when it solidifies, not like water that expands. And so you have some voids and you could even dump in some more hydrogen at that time. We also have the problem of heat transfer. We must transfer heat from the element that we want cooled to this block of hydrogen.

S. H. Autler
Question:

That's what worries me.

E. R. Lady
Answer:

With an electronic component the heat transfer rates are low. I visualize some sort of a metal spider such as aluminum inside this block which would, by conduction, make sure that heat was transferred throughout the volume. The metal spider would be fastened to the component that you want cooled. So no matter where the hydrogen block was it can't get too far from the conducting metal spider. Now we have to allow for the temperature drop between hydrogen block and the element to be cooled.

S. H. Autler
Question:

We are just dabbling with this idea in connection with some of NASA's problems, perhaps wanting to apply a superconducting magnet possibly imbedded in solid hydrogen, there wouldn't be any heat dissipation from the magnet once a field was set up, but during the period you are running the field up the material is exposed to a changing magnetic field, there would be some heat dissipation that we would have to get rid of.

E. R. Lady
Answer:

I think with proper engineering design this can be done because hydrogen is a good conductor of heat, and we do have a definite gas pressure there to conduct the heat. It would have to be designed on the basis of conducting through layers of gas. We could not assume that the solid is in contact with the thing you want cold.

Question:

What is the heat load, by the way, at 75 lbs. of hydrogen?

E. R. Lady
Answer:

I don't know the number. The specified heat load was 200 milliwatts, but then there was the additional calculated heat load by heat leak. I could look that up.

Question:

Well, is it on the order of 200 milliwatts?

E. R. Lady
Answer:

The total heat load when you take in heat leak is of the order of 500 milliwatts.

R. E. Carroll:

Thanks very much Ed.

R. E. Carroll

Well for the last talk of the afternoon we turn back again to the field of electronics, super-conductors. We are going to hear from Dr. John Lambe. Dr. Lambe received his B.S. and M.S. degrees from the University of Michigan, Ph.D. in Physics from the University of Maryland. He worked for some time in the Solid State State Physics area at Willow Run Laboratories, the University of Michigan, and of late has been in the physics section of the Scientific Laboratory, Ford Scientific Laboratory, and he is going to give us a review of the work they have been doing on the devices based on quantum interference and superconductors. Dr. Lambe.

DEVICES BASED ON QUANTUM INTERFERENCE IN SUPERCONDUCTORS

John J. Lambe

Physicist, Scientific Laboratory
Ford Motor Company

DEVICES BASED ON QUANTUM INTERFERENCE IN SUPERCONDUCTORS

Well, we've had quite a varied program, so get ready to switch your minds around again. What I'm going to try to do is give you a very simple idea about superconductivity. It's not really a new idea but it's an idea that the experimenters have finally gotten at, and I think if you get the simple idea, it will be something you can keep in mind. The interesting idea about superconductors that we are most familiar with is the loss of resistance; that is they are perfect conductors, and this is a rather marvelous and intriguing property. However, there is another rather marvelous property that goes hand in hand with this and only lately has become realized experimentally. When a superconductor is passing electricity we should not think, as we would for a piece of very low resistance copper, that we have simply a bunch of electrons sort of bobbing along in a wire. Rather the way one must think of this current is as a wave. What I want to point out very briefly is that this wave nature has now been fairly well established experimentally and one's mind can immediately foresee various types of devices.

I'll mention briefly a simple device that is already at hand, namely a very sensitive magnetometer. This wave property of superconductivity was postulated many years ago, actually by Fritz London, but it has been a difficult property to get at. If I have a piece of superconducting wire in liquid helium and it's carrying a current, I must imagine this is really a piece of wave guide and I'm propagating a wave down this wire. The nature of this wave is very difficult to understand in any classical sense, but it is the same type of wave problem we have when we realize that particles can also be thought of as waves. In the case of the electron, for example, there is the Debroglie wave idea which is very important in early quantum mechanics.

One of the remarkable properties of superconductors is that one has fairly long wave length waves running down wires. If we want to measure the phase the problem is now that we can't see this wave; it's really a wave in a quantum mechanical sense and it's very difficult to get at. Recently, however, a man named Josephson in England, a theoretician, pointed the way to get at the phase property in the superconductor. It's this rather remarkable property that we now can carry out experiments on. What you do is to take a piece of wire or a thin film and make what we call a junction. By a junction I mean we bring up another piece of superconducting material very close to this wire but not quite touching, and by not quite touching I mean distances on the order of 10 Angstroms. The way one does this actually is by a thin oxide film between the two superconductors. The remarkable fact is that if we try to pass current this way, our ability to do so through this system will essentially be dependent on the phase. Now we have a way, in a sense, of getting at the phase of the wave.

The other fact you have to know to see the whole picture is this. We are certainly used to the fact that a traveling wave has phase. Sound waves are very familiar to you, as well as electromagnetic waves, and all these things are familiar wave-like things. However, these quantum mechanical waves have another remarkable property; their phase often depends on magnetic field. As a matter of fact to be very technical it depends on the vector potential from which you can derive magnetic fields. So the superconducting wave has, 1) this property of being a wave, and 2) its wave length depends on magnetic fields. Now we can see that if we can make these phase measurements, for example, we can perhaps carry out an experiment to sense magnetic fields.

What experiment is very central to wave-like nature? If you'll recall back in the history of physics the famous Young double slit experiment was a very crucial one in deciding that light had a wave-like nature which went against Newton's corpuscular ideas, but this is a very important criterion for really saying "Ah ha! this is a wave, it has wave-like properties." These simple facts permit us to carry out a rather simple experiment which is a complete solid state analog of the double slit optical experiment. What I'm telling you is that superconducting currents will behave in many respects as optical waves do so we can think in terms of optical analogies to superconducting currents. Figure 1 shows what the solid state analog of the double slit optical experiment looks like. What we see here are two of these little junctions that I mentioned. On the bottom, B is a superconducting strip, at point 1 and 2 we have tied on some junctions, and strip A is another superconductor. The current that will pass between A and B is dependent upon essentially the wave lengths that will be formed around the continual strip. If you can imagine this current coming down, I have to show the waves conducting current to the sample, splitting up into the two junctions, then we want to see what would happen when they come back together.

Figure 2 shows the results of such a measurement and you may immediately recognize that this is essentially a double slit diffraction pattern, and it is completely correct to think of this this way. What we are plotting here is essentially a way of detecting a magnetic field. If you were doing an optical experiment you might stick some dielectric in or maybe you would look at different positions along a screen. So here what we do is scan a magnetic field, because I told you one of the mysterious things about these quantum mechanical waves is that they are sensitive to magnetic fields. We have a nice built-in way of changing wave lengths without really having to do anything internally.

So here's what you've seen. We are watching the current passing through these two points as we put magnetic fields in the hole between the superconductors. You see that it has essentially a fractional part which is the gradual modulation, and an interference part which is the rapid wiggles. Those rapid wiggles are determined by the area enclosed between the junctions. In other words, the sensitivity of this thing to magnetic fields is essentially this, if you want to know how much field you are going to have to apply to get one wiggle or one fringe, you just take the formula $B\ A = 10^{-7}$ gauss. Now just speculate about areas. Suppose we could make an area of one centimeter, then we would have a sensitivity of one-tenth of a microgauss which would be the world's best magnetometer. We have achieved areas of about 1 millimeter square, in other words we have seen interference patterns that essentially correspond to 10 microgauss per interference fringe.

All I want to do then to summarize these ideas but I don't want to go into a lot of detail, although to me the detail is interesting. We have seen, very explicity, a demonstration of the wave-like nature of superconducting currents. It's my belief, and many other people's, that this wave-like nature can be utilized in many of the devices that people have hoped for in superconductors although I think only time will tell what the reality to that situation will be. Thank you very much.

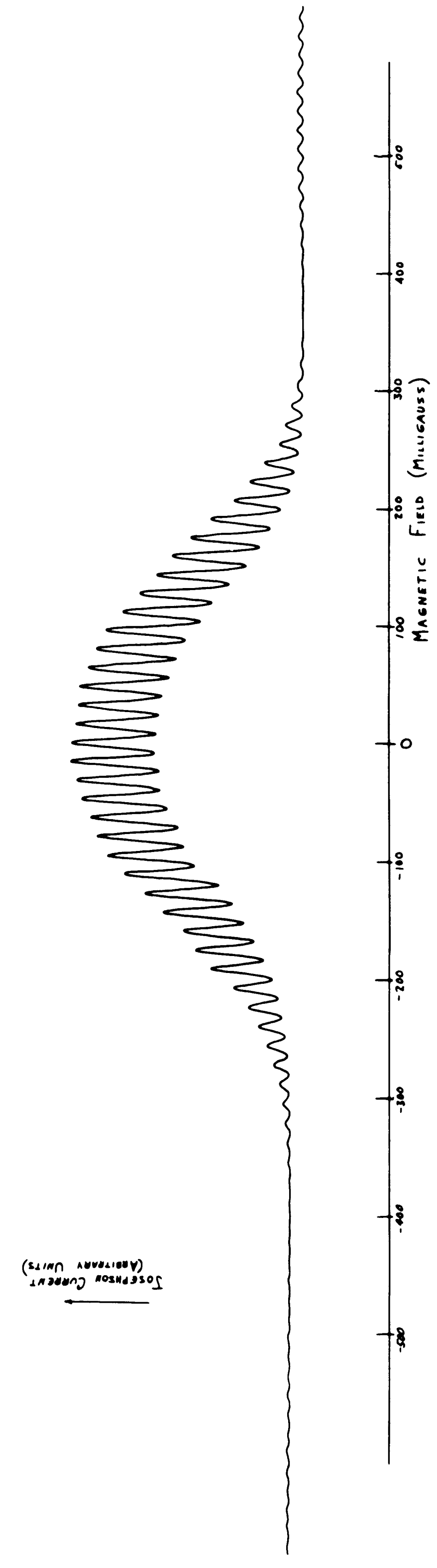

Magnetic Field (Milligauss)
Josephson Current (Arbitrary Units)
-500
-400
-300
-200
-100
0
100
200
300
400
500

Figure 1.

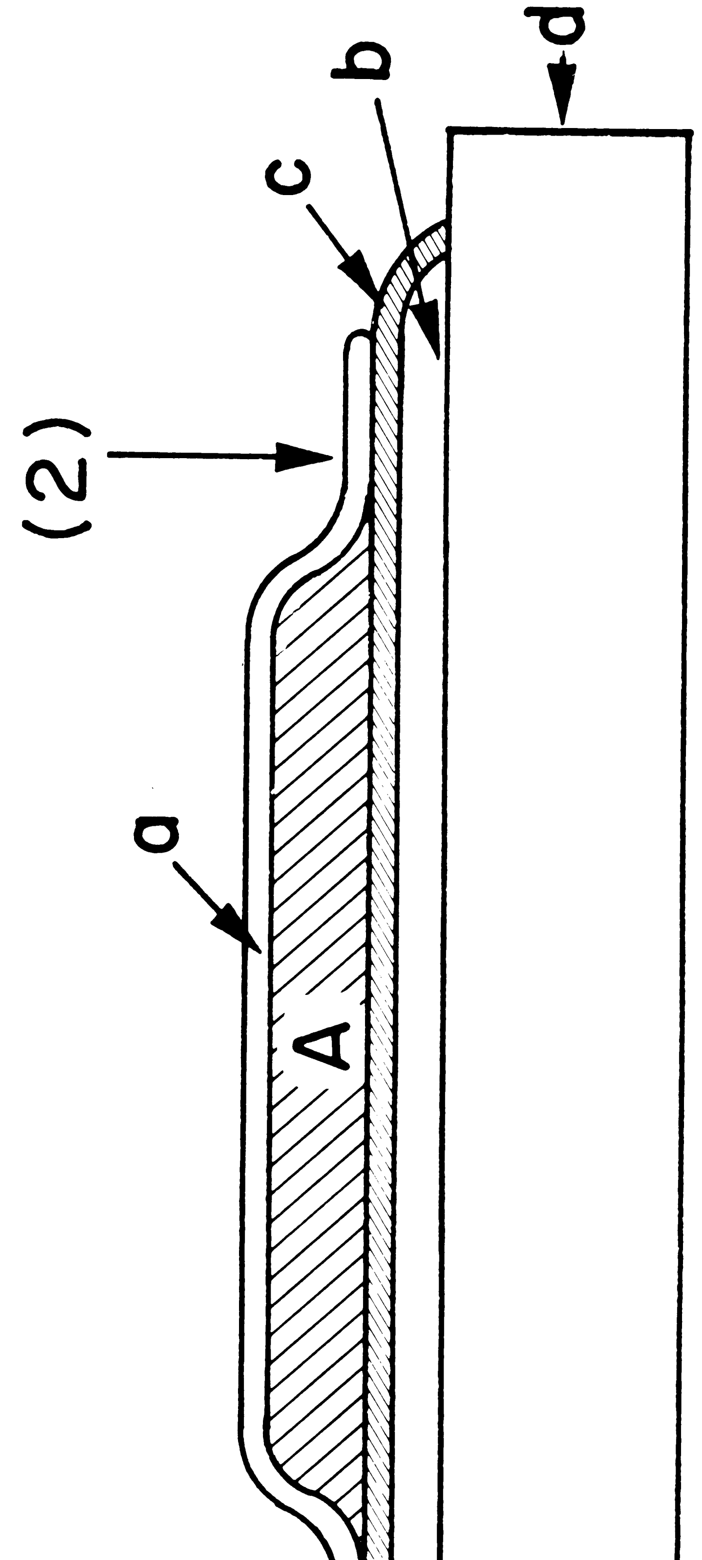


Figure 2.

DISCUSSION

R. E. Carroll:

Thank you very much Dr. Lambe. What are some of the possible uses for this sensitive magnetometer?

J. J. Lambe
Answer:

Well the magnetometer can be used as an amplifier, for example. After all, if you have a radio signal you can easily compute what kind of magnetic fields are involved. And it doesn't take a very sensitive magnetometer to start picking up WXYZ. So it's also an amplifier really. I've just put it in terms of magnetometry. It would be a very useful magnetometer, for example, in conjunction with superconducting magnets. One can beat this diffraction effect and we've seen these wiggles out to 10,000 gauss and you can calibrate a magnet with a fantastic precision.

Question:

With what precision have you established the value of the earth's magnetic field?

J. J. Lambe
Answer:

We have made no good measurement of that type at all. We haven't tried to get a good job on that yet. This, for reason of geometry, we haven't quite licked. We haven't done anything better than what is in the literature. We haven't tried. I think this would be an interesting thing to do.

R. E. Carroll:

Thank you very much.

CLOSING REMARKS

R. E. Carroll

This concludes our activities for the day. You all have credit in the course and if we had any diplomas we'd present them. I hope you have a very pleasant trip back home wherever it is. Thank you for coming and we look forward to seeing you again before too long.