CRYONICS

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THE 1984 INDEX IS IN THE CENTER OF THIS ISSUE

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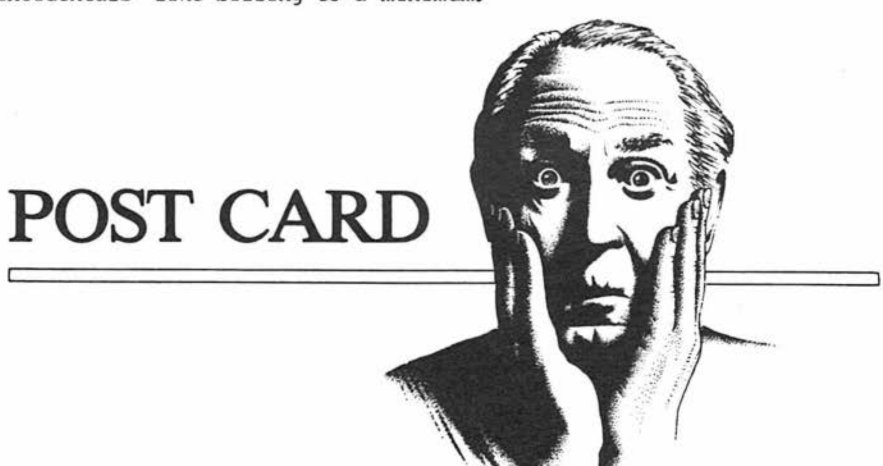
Editorial Matters

We are pleased this month to publish Art Quaife's paper **Heat Flow in the Cryonic Suspension of Humans.** We have been after Art, who is the President of Trans Time, to allow us to run this work, as we feel that it is a valuable contribution to the literature of cryonics. To some extent, our feelings about being able to publish it are mixed, since it means that Art was unsuccessful in attempting to publish it in the regular scientific literature. We feel that this is unfortunate to science as a whole, since his work is likely to be quite useful in organ and limb preservation, and we are not aware of any workers in those fields who are subscribing to CRYONICS. We realize that many of our readers may not share our enthusiasm, as they attempt to make sense of what is a rather abstruse piece of mathematics. Notwithstanding, it **is** important. The cylinders and spheres Art talks about approximate **your** arms, legs, body, and head, and that's important to all of us.

We are also happy to say that the 1984 Index to CRYONICS, compiled by Steve Bridge, is in the center of this issue. It has been sitting in our "IN" basket for nearly three months, an embarassingly long time.

Renewing Your Subscription

About a month before your subscription to CRYONICS is due to lapse you will receive a Post Card letting you know that it's renewal time. In the past, we have sent out only **one** renewal notice. This has caused a problem for a few people when the US Mail loses their renewal notice. We use post cards and send out only one renewal notice primarily because it is **expensive** to send out multiple notices (or even one notice, for that matter) in first class envelopes. In fact, each such letter costs about $1.ØØ (in postage, paper products and time) to produce and mail! Since subscriptions to CRYONICS are only $15.ØØ a year, and we are already losing money on publication, we've had no choice but to keep "incidentals" like billing to a minimum.



For the same reason we cannot "set back" subscriptions if you fail to renew on time (such as by starting a subscription two or three issues back). Our postage costs are about 6 cents per issue if we bulk mail and over 40 cents per issue if we mail First Class! The Postal service is very picky about bulk mailings--all items must be identical...and they DO check! It is simply not economically possible for us to mail back issues out as part of a normal subscription. When we **were** doing this several years ago it became a significant financial and administrative burden.

So, what can be done about people who miss their subscription renewal? Well, we have decided to send out **two** notices for renewal, even if this does mean some added cost. But, there's also something **you** can do. If you don't get your magazine and you're wondering about your subscription status, an easy way to find out is to look on any recent back issue of CRYONICS which you have and check the upper right hand corner of your mailing label. That number, which the computer put on, tells you when your subscription expires(ed).

If you **have** missed some issues and you want to purchase them, they are usually (we are now permanently out of stock on some back issues) available and all you need to do to get one is send us $2.00 for each back issue you want. Also, when you see that renewal Post Card in the mail, remember that you have only one month to renew or you'll start missing issues!

LIABILITY INSURANCE DEBACLE

QUESTION: What do a gynecologist in Fullerton, a Jaycee's organization in Michigan City, Indiana, a chemical company in Des Moines, Iowa, a day-care center in Anaheim, the town of Tehema, California and the ALCOR Life Extension Foundation have in common?

ANSWER: An insurance crisis. About 6-months ago Cryovita Laboratories, where ALCOR shares quarters, was faced with what amounted to a potentially disastrous crisis. In order to occupy the industrial bay in which we are located and in order to do business in the City of Fullerton, we are required to maintain a liability insurance policy to cover possible injuries or accidents that might occur on our premises. Not only do we have volunteers and guests come through our facility, we also have delivery people, consultants, and occasionally contractors work at or visit our premises. Every business is required to provide insurance to cover the contingency of accident or injury. The ugly fact of the matter is that even if someone breaks into our building and trips and falls over an extension cord—we're probably liable to some degree!

In order to keep our lease and our business license we **have** to have that coverage. Period. In the past liability coverage has cost us about $300.00 per year. Not a trivial sum for an organization as small as ours. You can imagine our surprise when we were told that 1) it was very unlikely that we could get any coverage at all and 2) if we did get coverage it would probably cost upwards of $2,000! (Yes, that right — two thousand, **not** two hundred!)

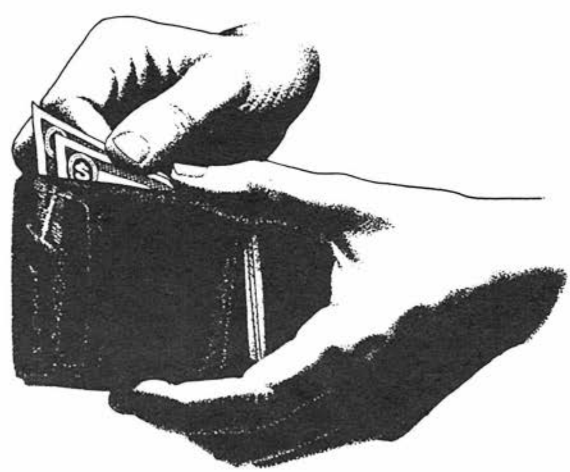
Our insurance agent turned out to be wrong on both counts. We did finally find coverage and it didn't cost upwards of \$2,000 — it cost upwards of \$3,000! Our agent phoned a few days ago to inform me that it was very unlikely we will be able to get coverage at all next year. At any price. When I asked him what we were going to do, he asked if we had half a million dollars to post a bond or self-insure! Helpful advice!

The only comfort in all this is that we are not alone. Liquor stores, charity picnics, even the Southern California Rapid Transit District have been unable to get coverage. All across the United States many hundreds of businesses are closing or, where the law permits (and even where it doesn't) are "going bare"—in other words going without liability insurance.

Like ALCOR and Cryovita these businesses are "high risk." If a suspension patient's family sues us, if an animal rights terrorist throws a brick, bottle, or bullet through our window and someone is injured, the insurance company may find itself in court. Leave aside the fact that liability insurance for personal injury and property damage has nothing to do with liability for suspension services. All the insurance companies know is that they may find themselves in court—and as anyone who has been in court can attest, even if you win, you lose.

Who's to blame for this?: a suit-crazy segment of the American people and the nation's trial lawyers. Litigation has become the easy path to revenge and "riches". In assigning blame we come down hard and heavy on irresponsible trial lawyers who litigate at the drop of a hat for damages that are of **Alice in Wonderland** proportions. In our book, such trial lawyers and the green slime of decomposition go hand in hand. Cryonics has a long and unfortunate history of litigation. In large measure this has been due to the presence of lawyers whose advice has hamstrung, paralyzed, and even led cryonics organizations into situations certain to produce contention, strife, and ultimately, litigation.

Where does all of this leave ALCOR? Frankly, we don't know. We are in the process of trying to prepare an alternate facility (in an unincorporated area) which will be owned by cryonicists. Failing this, we may very well find ourselves out on the street and out of business next year when our policy comes up for renewal. That is, if we don't get cancelled mid-year! According to the California Department of Insurance, many carriers have started cancelling policies and returning the unused portion of the premium. A pleasant thought. Oh well, nobody said living forever was going to be easy. They said it was going to be impossible.



ALCOR COORDINATOR PROGRAM: ANOTHER TRY

In cryonics the distance between interest and participation is often vast. Many times we receive requests for information which constitute "good leads" but we lose the person because there's no opportunity for follow-up and no way that individual can get involved on a local, grass-roots level. Sometimes the situation is an urgent one and the caller needs information immediately—particularly access to printed materials and personal contact from someone who is thoroughly knowledgeable about cryonics, and that someone just isn't there.

A little over a year ago we attempted to solve this problem by establishing a Cryonics Coordinator program. Sadly, we received little interest, and the idea was shelved. This is unfortunate because a Coordinator Program is a **good** idea, even a potentially life saving idea. It is particularly frustrating to us to see people who are living in the same city as subscribers or members--and they don't even know about each other. Obviously there's a lot of untapped talent and resources which could be put to use on a local level if only someone was willing to exercise the responsibility and leadership of "putting it all together."

We **know** that there are ALCOR Suspension Members scattered across the U.S. who have the talent and ability to handle this job. We are frustrated and disappointed that few of them have been willing to step forward and take some responsibility, and would like to remind **all** our members that ALCOR is a voluntary self-help organization. The share of ALCOR's burden that each of us carries varies, and we accept this, within reason. It is good, however, to know that you are not the only one out there with your shoulder to the wheel, making sure this ALCOR of ours gets to its desired destination. And it is **not** good to have the feeling that one is being taken advantage of in this respect.

We would like to see a program of ALCOR Coordinators. Coordinators would initially act as a local resource to refer information requests to and, when the level of local interest seemed to justify it, to try and set up meetings and get an informal or formal local group going. Literature and leads would be supplied by ALCOR, as well as advice on handling the media and/or pursuing local publicity—should the Coordinator choose to do so.

Groups formed in this way could do much, even in the early days to improve their chances. Just the presence of vocal, well informed people at a location remote from ALCOR in California or Florida could be a tremendous advantage if an emergency situation were to develop. If a group of even two or three forms, it will probably be able to very quickly afford to maintain a local heart-lung resuscitator (HLR) and emergency drug box--greatly speeding response time should the need arise. We estimate that a local resuscitation/stabilization capability, including HLR, medications and other basic equipment could be put in place for under $1,ØØØ! This should be easily in reach of even a very small local group. And keep in mind that hospitals typically do not have HLRs or many of the medications used in a suspension, and may be unwilling or legally unable to administer them even if they do. In that situation, which is the all too common one, the member will be faced with a wait of many hours until we can arrive on the scene. A wait that would have been unnecessary if help and equipment had been available on a local level.

So, we are going to give the Coordinator program another try. We want to hear from you ALCOR members out there and we want to see you meet us half way. We are willing and ready to go all-out for you, but we can't do it alone.

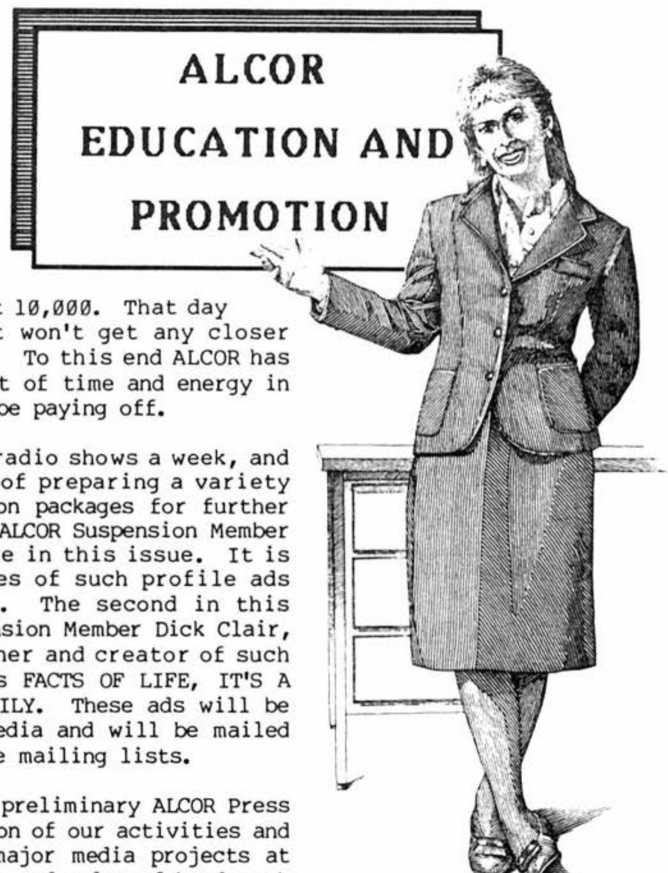
The requirements for being an ALCOR Coordinator are simple. You must be an ALCOR Suspension Member, you must be willing to take referrals and talk to people who are interested in cryonics, and you must spend some time talking with us, so that we can pass on our experiences and evaluate your ability to do the work. We ask that we be allowed to list your name, city and address (a P.O. Box is fine) periodically in CRYONICS. This is important, since we know from experience that many people will contact someone locally much more readily than they will send off to California for information. Don't let this opportunity slip by. Let us hear from you! If you would like to be an ALCOR Coordinator call us or write us today.

A RECORD BREAKING WEEKEND

As we've mentioned several times in the recent past, ALCOR has been signing up new suspension members at the rate of about 3 per month for the past 6 months or so. August was an incredible exception to that average: 12 new suspension members were approved by the Board of Directors at its August 6th meeting! As far as we know this is an all time record. Perhaps more exciting is the fact that the overwhelming majority of these new members are people who are "new" to cryonics as well -- they only recently heard of us or they have never been signed up before.

We're realistic enough to know that we probably won't keep signing up people at this rate steadily. There will be ups and downs, and it's important not to plan the future on the basis of something as uncertain as adding new members. On the other hand, one message is coming through loud and clear: we're growing again and the new blood feels good!

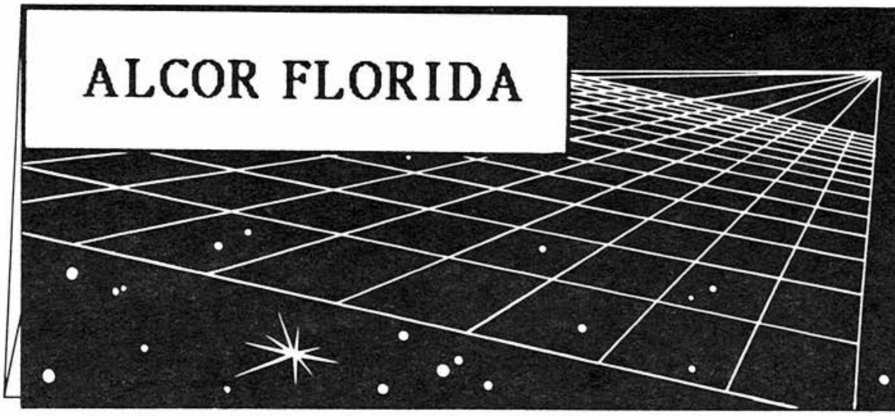
To all you new ALCOR members, Welcome Aboard, the adventure has just begun!



Our growth in membership tells us that we're on the right track, but we know that if cryonics is to succeed we can't sit back and rest on our accomplishments. In any absolute sense what we've achieved so far is but the tiniest fraction of what needs to be done. We need to be signing up not merely 10 members a months, but 10,000. That day is a long way off, and it won't get any closer without a lot of hard work. To this end ALCOR has been investing a fair amount of time and energy in promotion—and it seems to be paying off.

We are doing several radio shows a week, and we are in the final stages of preparing a variety of ads and media information packages for further promotion. An ad featuring ALCOR Suspension Member Saul Kent appears elsewhere in this issue. It is as an example from a series of such profile ads which we will be running. The second in this series features ALCOR Suspension Member Dick Clair, three time Emmy Award winner and creator of such popular television series as FACTS OF LIFE, IT'S A LIVING, FLO, and MAMA'S FAMILY. These ads will be run in a variety of print media and will be mailed out as flyers to appropriate mailing lists.

We have put together a preliminary ALCOR Press Kit to use in media promotion of our activities and we are working on several major media projects at the current time. With luck and a lot of hard work you should be hearing and seeing more of us in the media over the next year or so.



Mike Darwin spent 8 days in Florida, July 18 to July 26, conducting another training session and touching bases with members there. This was a particularly productive trip from both a working and promotional standpoint. Mike was on several local radio shows, including the 3-hour Allen Burke Show. Burke is a nationally known talk show host (who at one time challenged Johnny Carson for supremacy of the evening airwaves) known for his acidic treatment of guests. Mike managed not only to hold his own, but to actually control the interview. As a result, South Florida got a three hour long introduction to cryonics and ALCOR.

On Friday night, the day prior to the first training session, Bill Faloon and Tina Lee hosted a get-together in their home. This was a pleasant evening with some people driving in from as far away as West Palm Beach and Cocoa Beach. It was a great opportunity for people to get to know each other in a "nontechnical" setting. And, as you might guess, the philosophical discussions went on into the wee hours of the morning. Fortunately, the training session was not scheduled to start until noon the next day, so team members had a little extra time to recover.

The two-day training session was used to review medications, I.V., and respiratory support techniques as well as serve as an intoroduction to perfusion operations. Mike Darwin took the opportunity to "solo" on initiating femoral bypass with a bubble oxygenator and the Florida crew got an introduction to sterile technique and bypass procedure. We're happy to report that the training animal, a beautiful shepherd/huskie mix with a lovely disposition, weathered three hours of bypass (and a lot of intubation practice) and cooling to 22°C beautifully. The dog was adopted by Bill Faloon and Tina Lee and has been christened "Sandy." We understand she is now running the Faloon/Lee household and dining exclusively on cooked steak!

The Florida team continues to make progress, although several people were unable to make this training session. This is cause for some concern, since training sessions with personnel from California present are less frequent than is desirable to maintain a high level of skill. Under these circumstances, every session counts, and its important not to miss even one training session.

There was also a lot of discussion about the future of cryonics in Florida. Long-term strategies for facilities acquisition, marketing, and growth were laid down, and contacts were established which will help substantially in expanding operations in the future. All in all it was a great trip.

MOVING INTO THE VAULT: A BUSY WEEKEND

The day following Mike Darwin's return from Florida, work began in earnest to gear up for moving the patients into the Cephalarium Vault. A few recent contributions pushed Frosty Thermometer over the top, and at long last the time and money were there to increase patient security to an all- time high.

On Friday, July 26th, the five ALCOR neuropatients were transferred out of the A-2542 storage dewar into two back-up dewars. Ten days prior to the transfer Hugh Hixon had "fired up" the backup dewars and carried out boil-off evaluations to make sure they were in good working order and safe to use. The A-2542 was then drained of liquid nitrogen, warmed up, and cleaned out. It's simply amazing how much water vapor and particulate debris accumulates in a working dewar after almost four years of continuous operation! Another reason for a warm-up and clean-out of the A-2542 is to get rid of the liquid oxygen (LOX) which tends to accumulate in the liquid nitrogen with time.

No sweat. The top of the vault is lifted off with Jerry Leaf aboard. Hugh Hixon at the controls of 6,000 lb forklift/crane.

Once the A-2542 was cleaned out, it was bolted to a shock absorbing platform and readied for placement in the vault. On Sunday an ALCOR crew consisting of Hugh Hixon (the team leader), Jerry Leaf, Scott Greene, Brenda Peters, Mike Darwin, and a massive, rented forklift with a "slip-on" crane plucked off the top of the vault (which weighs a mere 1,500 pounds!) and lowered the dewar/support platform into the vault. Brenda served as photographer with some help from Scott Greene (who divided his time between snapping photos and assisting with the moving operations). Brenda's pictures turned out great! A few of them appear with this article and the technical article on the vault which we will publish later. These pictures are somewhat unusual in that Hugh Hixon appears in them. Usually he is both a worker and the photographer, and hence invisible to the camera.

Jerry Leaf did a superb job managing the forklift and Mike Darwin performed

Article continued on page 31.

HEAT FLOW IN THE CRYONIC SUSPENSION OF HUMANS

SURVEY OF THE GENERAL THEORY

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ABSTRACT

Procedures used in the successful freezing and thawing of diverse human cells and tissues are known to be quite sensitive to the cooling and thawing rates employed. Thus it is important to control the temperature descent during cryonic suspension of the whole human body. The paper surveys the general theory of macroscopic heat flow as it occurs during the cryonic suspension of human patients. The basic equations that govern such heat flow are presented, then converted to dimensionless terms, and their solutions given in geometries that approximate the human torso, head, and other regions of the body. The solutions are more widely applicable to the freezing of tissues and organs.

1. INTRODUCTION

Cryonic suspension is the freezing procedure by which human patients are preserved, after pronouncement of legal "death", in hopes of eventual restoration to life and health. The procedure attempts to preserve the basic information structures that determine the individual's identity. These include the memories and personality as encoded in the macromolecules and neuronal weave of the brain, and the genetic information stored in DNA.

HEAT FLOW IN CRYONIC SUSPENSION

The author has previously formulated a mathematical model of the heat flow and the diffusion of cryoprotectant that occurs during the first phase of this procedure, in which chilled blood substitutes and cryoprotective solutions are perfused through the vascular system [9]. The present paper treats the general theory of heat flow, particularly at sub-zero temperatures after perfusion has ceased and the body has solidified.

The author has written a computer program that calculates most of the solutions given below, and in subsequent articles intends to present tables and graphs comparing theoretical projections with experimental data. Other problems for subsequent analysis include change of phase, and thermal stresses from temperature gradients within the frozen tissue.

2. NOMENCLATURE

We first describe the typographical conventions to be used. Beginning in Section 4, all dimensioned variables, constants, fields, and operators will be converted to dimensionless counterparts. Therefore we will use ordinary roman type font for dimensioned real quantities (x), with roman boldface to represent dimensioned vectors (**r**). Dimensionless real quantities will be represented in italics (x), while dimensionless vectors will be in boldface italics ($\boldsymbol{r}$). Dimensioned constants in greek along with the gradient operator will be unemphasized (∇), while their dimensionless counterparts will be in boldface ($\boldsymbol{\nabla}$).

The variables and fields used to describe heat flow within a solid region R (such as the frozen human body) bounded by a surface S (such as the skin) are:

Variable	*Description*	*Unit*
r	position vector	m
t	time	s
T(**r**, t)	temperature scalar field	K
q(**r**, t)	heat flux vector field	$\mathrm{J/(m^2\,s)}$
g(**r**, t)	rate of heat generation	$\mathrm{J/(m^3\,s)}$

where we use the standard abbreviations for SI units: m = meters, kg = kilograms, s = seconds, K = degrees Kelvin, J = Joules [= kg $\mathrm{m^2/s^2}$].

HEAT FLOW IN CRYONIC SUSPENSION

The constants needed to describe heat flow within a solid are:[1]

Constant	*Description*	*Unit*
V	volume of (finite) region R	m^3
A	area of (finite) surface S	m^2
k	thermal conductivity	$J\ m/(m^2\ s\ K)$
ρ	density	kg/m^3
c	specific heat at constant pressure	$J/(kg\ K)$
h	heat convection at the boundary	$J/(m^2\ s\ K)$
α	thermal diffusivity $= \frac{k}{\rho c}$	m^2/s

The total heat flow $F_{\boldsymbol{n}}(\mathbf{r}, t)$ [J/m^2] per unit area up to time t, in the direction of unit vector $\boldsymbol{n}$, is given by:

$$F_{\boldsymbol{n}}(\mathbf{r}, t) = \int_0^t \boldsymbol{n} \cdot \mathbf{q}(\mathbf{r}, s)\, ds \tag{2.1}$$

Equation (2.1) may be integrated over a surface S having normal vector $\boldsymbol{n}$ to obtain the total heat flow across the surface.

The average temperatures within the region R and on the surface S are given respectively by:

$$<T(t)>_R = \frac{1}{V} \iiint_R T(\mathbf{r}, t)\, dV \tag{2.2}$$

$$<T(t)>_S = \frac{1}{A} \iint_S T(\mathbf{r}, t)\, dA \tag{2.3}$$

The heat energy Q [J] contained within the region R, with respect to a reference temperature T_∞, is determined from the above constants by:

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[1] k, c, and to a small degree ρ, generally depend upon temperature. By consulting tables showing their temperature variation within the specific medium, we can determine the temperature range within which the "constant" approximation is appropriate.

$$Q(t) = \iiint_R \int_{T_\infty}^{T(\mathbf{r},\,t)} \rho c(T)\, dT\, dV \tag{2.4}$$

Here we have explicitly shown the temperature dependence of c upon T, but except for the solution presented in Section 11, we will otherwise assume c to be a constant independent of temperature. In this case,

$$Q(t) = \rho c V(\langle T(t) \rangle_R - T_\infty) \tag{2.5}$$

We also use the differential operators:

Operator	*Description*	*Unit*
∇	gradient	$1/m$
	$= \boldsymbol{i}\,\dfrac{\partial}{\partial x} + \boldsymbol{j}\,\dfrac{\partial}{\partial y} + \boldsymbol{k}\,\dfrac{\partial}{\partial z}$	
∇^2	Laplacian	$1/m^2$
	$= \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2}$	

when these operators are expressed in rectangular coordinates.

3. EQUATIONS GOVERNING HEAT CONDUCTION

For a homogeneous, isotropic solid (a solid that has the same thermal properties at every position, and in which the thermal conductivity is the same in every direction), Fourier's law of heat flow is:

$$\mathbf{q}(\mathbf{r}, t) = -k\,\nabla T(\mathbf{r}, t) \tag{3.1}$$

This law simply states that heat flows from positions of high temperature to positions of low temperature, and flows in the direction in which the temperature decreases most rapidly, in proportion to the rate of decrease.

In addition we have the *continuity* equation:

$$\nabla \cdot \mathbf{q}(\mathbf{r}, t) - g(\mathbf{r}, t) + \rho c\,\frac{\partial T(\mathbf{r}, t)}{\partial t} = 0 \tag{3.2}$$

Equation (3.2) simply expresses the conservation of heat energy. This is most easily seen by integrating the equation over a fixed region, and using Gauss's divergence theorem to change the volume integral of the divergence (the leftmost term) into a surface integral. Then the equation just states that whatever heat flows across the boundary must come from internal heat generated (such as from metabolism within the human body or from change of phase), or from heat liberated from storage in the solid within the contained region.

Substituting equation (3.1) into equation (3.2), we obtain:

$$\nabla \cdot [k \nabla T(\mathbf{r}, t)] + g(\mathbf{r}, t) = \rho c \frac{\partial T(\mathbf{r}, t)}{\partial t} \tag{3.3}$$

We will make two simplifying assumptions to this general heat flow equation:

A. We assume no heat generation within the solid, i.e. $g(\mathbf{r}, t) = 0$. Our model is designed to treat heat flow in the *frozen* human patient, where heat flow from metabolism has already been arrested, and where liberation of heat from freezing to the solid phase has already occurred.

B. We assume the thermal conductivity k to be constant (i.e. independent of temperature).

Then equation (3.3) simplifies to the usual heat flow equation (Fourier's equation):

$$\nabla^2 T(\mathbf{r}, t) = \frac{1}{\alpha} \frac{\partial T(\mathbf{r}, t)}{\partial t} \tag{3.4}$$

For steady state heat flow, where the time derivative on the right side vanishes, this reduces to Laplace's equation:

$$\nabla^2 T(\mathbf{r}, t) = 0 \tag{3.5}$$

which is one of the most thoroughly investigated and solved equations in all mathematical physics.

4. DIMENSIONLESS VARIABLES

It is natural and useful to express all equations in terms of *dimensionless* variables and parameters. Such presentation simplifies the equations, expresses the variables on a scale which is appropriate to the problem, and permits the solution of diverse problems by use of standard graphs and tables, simply remultiplying by the appropriate scale factors. When possible, we will normalize variables to range between 0 and 1.

Dimensionless Position

We let:

$$\boldsymbol{r} = \frac{\mathbf{r}}{L} \tag{4.1}$$

where L is a characteristic linear dimension of the solid.

In simple geometries such as spheres or cylinders, we use the obvious choice:

$$\mathrm{L} = \mathrm{Radius} \quad [\mathrm{m}] \tag{4.2a}$$

In a solid of finite volume but arbitrary shape, we assign a characteristic linear dimension as:

$$\mathrm{L} = \frac{\mathrm{V}}{\mathrm{A}} \quad [\mathrm{m}] \tag{4.2b}$$

In heat flow within an infinite or semi-infinite solid, there is no natural standard of length to use. Here, to continue presenting our equations in terms of dimensionless variables, we arbitrarily assign:

$$\mathrm{L} = 1 \quad [\mathrm{m}] \tag{4.2c}$$

In this case $\boldsymbol{r} = \mathbf{r}$ (or in one dimensional heat flow $x = \mathrm{x}$), in magnitude but ignoring the dimension [m].[2]

In each case, the mapping $\mathbf{r} \rightarrow \boldsymbol{r}$ immediately induces mappings $\mathrm{R} \rightarrow R$ and $\mathrm{S} \rightarrow S$, which have corresponding dimensionless volume V and area A.[3] Note that when L is determined by (4.2b), we have:

$$V = A = \frac{\mathrm{A}^3}{\mathrm{V}^2} \quad (\text{if } \mathrm{L} = \frac{\mathrm{V}}{\mathrm{A}}) \tag{4.3}$$

Having defined L, we immediately obtain the *dimensionless gradient operator*:

$$\boldsymbol{\nabla} = \mathrm{L}\nabla \tag{4.4}$$

Dimensionless Time

Dimensionless time is given by:

$$t = \frac{\alpha \mathrm{t}}{\mathrm{L}^2} \tag{4.5}$$

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[2] The precise choice of L in different solids varies with the literature source; e.g. some sources use equation (4.2b) to determine L in all solids. For a sphere, L from (4.2b) = 3 × L from (4.2a). For the infinite cylinder, L from (4.2b) = 2 × L from (4.2a). Other normalizations are possible, such as choosing $\mathrm{L} = \mathrm{V}^{1/3}$, which would make $V = 1$. Each choice simplifies some equations at the expense of others.

[3] For the infinite cylinder, which is really a two dimensional problem, we only carry out the mapping in the radial direction and not in the axial direction.

where t is also known as the *Fourier number* (Fo), and contains the constant of proportionality necessary to render (3.4) dimensionless. t measures the ratio of the average temperature of a slab to a constant temperature difference maintained between its two faces, when heat flows through one face separated from the opposite insulated face by a distance L.

Other Dimensionless Variables

Of the remaining principal SI units, we have no need for a dimensionless mass variable. Mass only appears in our equations in the product ρc, from which it cancels out.

Dimensionless temperature is given in (5.3) below.

5. INITIAL AND BOUNDARY CONDITIONS

Solutions to equation (3.4) are subject to initial and boundary conditions, which describe the initial temperature distribution within the solid and on the boundary, and the rate of heat flow across the boundary. In the real world, these conditions encountered can be perfectly arbitrary. But in describing a particular physical configuration, they can become too complex to permit a tractable analytical solution to the problem.

For our purposes, we will restrict consideration to heat flow from an instantaneous point source; across a plane; from a highly insulated solid; from a sphere; or from a cylinder; under the following initial and boundary conditions:

Initial Conditions

We let:

$$\mathrm{T}_0 = \text{uniform initial temperature in R (K)} \tag{5.1}$$

$$\mathrm{T}_\infty = \text{uniform initial temperature on S (K)} \tag{5.2}$$

from which we define the *dimensionless temperature scalar field*:

$$T(\boldsymbol{r}, t) = \frac{\mathrm{T}(\mathbf{r}, \mathrm{t}) - \mathrm{T}_\infty}{\mathrm{T}_0 - \mathrm{T}_\infty} \tag{5.3}$$

Our initial conditions become:[4]

$$T(\boldsymbol{r}, 0) = 1 \quad \text{in } R \tag{5.4}$$

$$T(\boldsymbol{r}, 0) = 0 \quad \text{on } S \tag{5.5}$$

[4] Some sources, such as [4] in certain equations, adopt the reverse convention by using the scalar $T' = 1 - T$.

HEAT FLOW IN CRYONIC SUSPENSION

Boundary Conditions

In the case of greatest interest, we consider cooling or warming the human body with an external heat conducting fluid (liquid or gas). For example, we may cool the body by surrounding it with liquid isopropyl alcohol cooled by dry ice, or by liquid nitrogen, or in the vapor phase of liquid nitrogen.

Let $\boldsymbol{n}$ be an outward normal vector from the boundary surface. We consider solutions to (3.4) under the very general boundary condition:

$$\boldsymbol{n} \cdot \nabla T = -Bi\ T \quad \text{on } S \text{ for } t > 0 \tag{5.6}$$

If we let n measure dimensionless distance along the outward normal vector, the left side of (5.6) reduces to $\partial T / \partial n$.

In the above equation,

$$Bi = \frac{\mathrm{Lh}}{\mathrm{k}} \text{ is the } \textit{Biot number} \text{ (dimensionless)} \tag{5.7}$$

The Biot number measures the rate of heat convection at the surface divided by the rate of heat conduction across the enclosed region.

In the cases treated in Sections 7 and 11 where L is determined from (4.2b), we will use the symbol Bl for the Biot number, to distinguish it from the value Bi that would be obtained from (4.2a).

A solution to the problem is required to satisfy the heat flow equation (3.4) inside the region R for $t > 0$, and to approach the initial and boundary conditions (5.4) - (5.6) as pointwise limits.

Special Cases of Boundary Conditions

A. In the case $Bi \to \infty$, wherein the heat flow at the boundary is very large compared to that across the solid, (5.6) reduces to:

$$\mathrm{T}(\mathbf{r}, \mathrm{t}) = \mathrm{T}_\infty \quad \text{on S for t} > 0 \tag{5.8}$$

i.e., we maintain the boundary at a constant temperature.

B. The case $Bi \to 0$ is that of rapid heat flow across the solid as compared to convection at a highly insulated boundary. In the limit $Bi = 0$, (5.6) reduces to:

$$\boldsymbol{n} \cdot \nabla \mathrm{T} = 0 \quad \text{on S for t} > 0 \tag{5.9}$$

Using (3.1) and (2.1), we have that:

$$\mathrm{F}_{\boldsymbol{n}}(\mathbf{r}, \mathrm{t}) = 0 \quad \text{on S for t} > 0 \tag{5.10}$$

so this limit represents a perfectly insulated boundary, across which no heat flows. The temperature within the solid just remains at the constant initial value T_0 as in (5.1).

6. DIMENSIONLESS HEAT FLOW EQUATIONS

We can now define the *dimensionless heat flux vector field* by:

$$\boldsymbol{q}(\boldsymbol{r}, t) = \frac{\mathrm{L}\,\mathbf{q}(\mathbf{r}, \mathrm{t})}{\mathrm{k}\,(\mathrm{T}_0 - \mathrm{T}_\infty)} \tag{6.1}$$

from which we immediately obtain the total *dimensionless planar heat flow* in the direction of unit vector $\boldsymbol{n}$ as:

$$F_{\boldsymbol{n}}(\boldsymbol{r}, t) = \int_0^t \boldsymbol{n} \cdot \boldsymbol{q}(\boldsymbol{r}, s)\, ds \tag{6.2}$$

and define *dimensionless heat generation* by:

$$g(\boldsymbol{r}, t) = \frac{\mathrm{L}^2 \mathrm{g}(\mathbf{r}, \mathrm{t})}{\mathrm{k}\,(\mathrm{T}_0 - \mathrm{T}_\infty)} \tag{6.3}$$

The *dimensionless average temperatures* in the region and on the surface are given by:

$$< T(t) >_R = \frac{1}{V} \int\int\int_R T(r, t)\, dV \tag{6.4}$$

$$< T(t) >_S = \frac{1}{A} \int\int_S T(r, t)\, dA \tag{6.5}$$

while the *dimensionless heat energy* contained within a region is given by:

$$Q(t) = \frac{\mathrm{Q(t)}}{\rho \mathrm{c} \mathrm{L}^3 (\mathrm{T}_0 - \mathrm{T}_\infty)} \tag{6.6a}$$

$$= V < T(t) >_R \quad \text{from (2.5)} \tag{6.6b}$$

so that the dimensionless heat content initially has the value V and over time falls to 0 (if $Bi > 0$).

If length, time, temperature, and energy are measured in new units defined by (4.2b), (4.5), (5.3), and (6.6a),[5] then our fundamental constants take on values $V = A = \mathrm{A}^3/\mathrm{V}^2$, $k = \boldsymbol{\rho c} = \boldsymbol{\alpha} = L = 1$, and $h = Bi$.

[5] This choice of units dictates that if we had need for dimensionless mass, it is given by:

$$m = \left(\frac{\alpha}{\mathrm{L}}\right)^2 \frac{\mathrm{m}}{\rho \mathrm{c} \mathrm{L}^3 (\mathrm{T}_0 - \mathrm{T}_\infty)}$$

Assuming the constants k, ρ, and c are independent of temperature, the basic heat flow equations (3.1), (3.2), (3.3), and (3.4) can be expressed in terms of dimensionless variables as:

$$\boldsymbol{q} = -\nabla T \tag{6.7}$$

$$\nabla \cdot \boldsymbol{q} - g + \frac{\partial T}{\partial t} = 0 \tag{6.8}$$

$$\nabla^2 T + g = \frac{\partial T}{\partial t} \tag{6.9}$$

$$\nabla^2 T = \frac{\partial T}{\partial t} \tag{6.10}$$

7. GLOBAL REFORMULATION OF EQUATIONS

We can obtain additional insight into the differential heat flow equation (6.10) and the differential boundary condition (5.6) by reformulating them in global terms. Let R' be an arbitrary subregion of R, and S' be its surface. Integrating (6.10) over the region R', and applying Gauss's divergence theorem to the left side, we have:

$$\int\int_{S'} \boldsymbol{n} \cdot \nabla T \, dA = \int\int\int_{R'} \frac{\partial T}{\partial t} \, dV \tag{7.1}$$

Pulling the time derivative outside the integral and using the definitions (6.4) and (6.5), we have:

$$\frac{d < T(t) >_{R'}}{dt} = \frac{A'}{V'} < \boldsymbol{n} \cdot \nabla T(t) >_{S'} \quad \text{for all } R' \subseteq R \tag{7.2}$$

Since all of the above steps are reversible, (7.2) is an equivalent formulation of (6.10).

Special Case: Heat Flow in the Whole Region

If we let $R' = R$ in (7.2), use (4.3) and substitute the boundary condition (5.6), we obtain:

$$\frac{d < T(t) >_R}{dt} = -BI < T(t) >_S \tag{7.3}$$

so that the average temperature in the region decreases at a rate jointly proportional to the Biot number and the average temperature on the surface. In the presence of (7.2), this is an equivalent formulation of (5.6).

Special Case: Heat Flow at a Point

If we contract the linear dimensions of the subregion toward 0 about a point $\boldsymbol{r}$, we obtain:

$$\frac{\partial T(\boldsymbol{r}, t)}{\partial t} = \lim_{V'/A' \to 0} \frac{A'}{V'} \langle \boldsymbol{n} \cdot \nabla T(t) \rangle_{S'} \tag{7.4}$$

which gives the time derivative of T in terms of the limiting value of the net flux of ∇T through a small surface about the point.

8. USEFUL MATHEMATICAL FUNCTIONS

We define several functions that will be used in the subsequent solutions. First let

$$N(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \tag{8.1}$$

be the *normal (Gaussian) probability density function with mean* μ *and variance* σ^2.

The *normal probability distribution function* Φ is defined from N by

$$\Phi(x) = \int_{-\infty}^{x} N(u; 0, 1)\, du \tag{8.2a}$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-\frac{u^2}{2}\right) du \tag{8.2b}$$

which has values

$$\Phi(-\infty) = 0, \quad \Phi(0) = .5, \quad \Phi(\infty) = 1 \tag{8.3}$$

A close relative of Φ is the *error function*:

$$\mathrm{erf}(x) = 2\Phi(\sqrt{2}\,x) - 1 \tag{8.4a}$$

$$= \frac{2}{\sqrt{\pi}} \int_{0}^{x} \exp(-u^2)\, du \tag{8.4b}$$

which has the properties

$$\mathrm{erf}(-x) = -\mathrm{erf}(x), \quad \mathrm{erf}(0) = 0, \quad \mathrm{erf}(\infty) = 1 \tag{8.5}$$

and from which we define the *error function complement* as

$$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) \tag{8.6}$$

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This index cover issues #42-53 (January-December) of 1984. Entries list the month of issue followed by the page number of the article --e.g., "May:4." Titles (usually a shortened form) are in quotation marks and are only given where they seem useful. Subjects are in CAPITAL letters. Authors are listed only for major articles.

The error function can be represented by the following infinite series:

$$\operatorname{erf}(x) = \frac{2x}{\sqrt{\pi}} \exp(-x^2) \sum_{n=0}^{\infty} \frac{(2x^2)^n}{1 \cdot 3 \cdots (2n+1)} \tag{8.7a}$$

$$= \frac{2x}{\sqrt{\pi}} \exp(-x^2)\,(1 + \frac{2x^2}{3} + \cdots) \tag{8.7b}$$

useful for small values of x.

The asymptotic expansion of the error function complement as $x \rightarrow \infty$ is given by:

$$\operatorname{erfc}(x) \sim \frac{1}{x\sqrt{\pi}} \exp(-x^2)\,(1 + \sum_{n=1}^{\infty} (-1)^n \frac{1 \cdot 3 \cdots (2n-1)}{(2x^2)^n}) \tag{8.8a}$$

$$= \frac{1}{x\sqrt{\pi}} \exp(-x^2)\,(1 - \frac{1}{2x^2} + \cdots) \tag{8.8b}$$

The expansions presented in this form are particularly useful, since solutions to the linear heat flow equation often contain the term $\exp(x^2)\operatorname{erf}[c](x)$ as in (10.2c).[6]

We now temporarily relax strict rigor in favor of providing an intuitively powerful tool for finding solutions. We first note that as σ becomes small, the mass of N as a function of x becomes highly spiked and localized at the origin. This leads us to formally "define" the *Dirac delta function* as:[7]

$$\delta(x) = \lim_{\sigma \rightarrow 0} N(x;\, 0,\, \sigma) \tag{8.9}$$

Clearly

$$\delta(x) = 0 \quad \text{for } x \neq 0 \tag{8.10}$$

[6] cf. [1] pp. 297 & 298

[7] This function was "invented" by the physicist Paul Dirac in the late 1920's, as part of his reformulation of the basic laws of quantum mechanics. There is no function which has the properties (8.10) and (8.11d) within classical real analysis. The rigorously inadmissible step above occurs in (8.11b) when the limit is passed through the integral sign. But as long as we only use the properties of the delta function while it appears as an *integrand* and limits are taken outside the integral, all is well. Such use of the delta function can be rigorously justified using the theory of distributions later developed by the mathematician Laurent Schwartz.

while its value at the origin is infinite in such a way that:

$$\int_{-\infty}^{\infty} \delta(u)\,du = \int_{-\infty}^{\infty} \lim_{\sigma\to 0} N(u;\,0,\,\sigma)\,du \tag{8.11a}$$

$$= \lim_{\sigma\to 0} \int_{-\infty}^{\infty} N(u;\,0,\,\sigma)\,du \tag{8.11b}$$

$$= \lim_{\sigma\to 0} 1 \tag{8.11c}$$

$$= 1 \tag{8.11d}$$

The delta function can thus be used to represent a point source of unit heat at the origin. More generally, we can formally represent an arbitrary function f as a superposition of point sources:

$$f(x) = \int_{-\infty}^{\infty} f(u)\,\delta(u-x)\,du \tag{8.12}$$

— the integral just picks out the value of f where all the mass of δ is concentrated.

We will now present various solutions to the dimensionless heat flow equation (6.10).

9. BASIC SOLUTION: HEAT FLOW IN ONE DIMENSION

In the most elementary case, we consider heat flow from a very thin flat plate of infinite extent in the y and z directions. We let one (dimensionless) unit of heat per unit area be placed in the plane $x = 0$ at time $t = 0$. Since this source of heat is (ideally) compressed into a plane of zero thickness, this initial temperature distribution can be represented as:

$$T(x,\,0) = \delta(x) \tag{9.1}$$

Then the solution to (6.10) is:

$$T(x,\,t) = N(x;\,0,\,\sqrt{2t}) \tag{9.2a}$$

$$= \frac{1}{\sqrt{4\pi t}} \exp\left(-\frac{x^2}{4t}\right) \tag{9.2b}$$

as can be verified directly by differentiation of this solution. It is also immediate from the definition (8.9) that N satisfies the initial condition (9.1).

Now in the general case, on the x axis we are given an *arbitrary* initial distribution $T(x,\,0)$, $-\infty < x < \infty$. We use (8.12) to represent T as a superposition of point sources:

$$T(x, 0) = \int_{-\infty}^{\infty} T(u, 0)\, \delta(u - x)\, du \tag{9.3}$$

Since equation (6.10) is linear in the temperature T, the same superposition of elementary solutions will be the solution to the general case:[8]

$$T(x, t) = \frac{1}{\sqrt{4\pi t}} \int_{-\infty}^{\infty} T(u, 0) \exp\left(-\frac{(x - u)^2}{4t}\right) du \tag{9.4}$$

where again it is immediate from (8.9) that T satisfies the initial condition (9.3).

10. HEAT FLOW IN A SEMI-INFINITE SOLID

We consider heat flow across the plane surface $x = 0$ from the region $x > 0$. The solution to this problem is particularly useful, since virtually any surface we naturally encounter can be approximated by this planar model, if we confine the approximation to small enough values of x and t. We use (4.2c) to determine L and thus Bi.

The solution to (6.10) under the initial and boundary conditions (5.4) - (5.6) is:[9]

$$T(x, t) = \operatorname{erf}\left(\frac{x}{\sqrt{4t}}\right) + \exp\left(\frac{x^2}{4t}\left(\left(1 + \frac{2Bi\, t}{x}\right)^2 - 1\right)\right) \operatorname{erfc}\left(\frac{x}{\sqrt{4t}}\left(1 + \frac{2Bi\, t}{x}\right)\right) \tag{10.1a}$$

$$= \operatorname{erf}\left(\frac{x}{\sqrt{4t}}\right) + \exp(Bi\, x + Bi^2 t)\, \operatorname{erfc}\left(\frac{x}{\sqrt{4t}} + Bi\sqrt{t}\right) \tag{10.1b}$$

This solution contains three parameters x, t, and Bi, but it may be expressed in terms of any two of the combinations $x/\sqrt{4t}$, $Bi\, x$, and $Bi\sqrt{t}$, useful for graphing the solution.

The heat flow across the boundary per unit area and time in the $-x$ direction is given by:

$$q_{-x}(0, t) = \left.\frac{\partial T}{\partial x}\right|_{x=0} \qquad \text{from (6.7)} \tag{10.2a}$$

$$= Bi\, T(0, t) \qquad \text{from (5.6) with } n = -x \tag{10.2b}$$

$$= Bi \exp(Bi^2 t)\, \operatorname{erfc}(Bi\sqrt{t}) \qquad \text{from (10.1b)} \tag{10.2c}$$

Integrating this equation with respect to t, we find from (6.2) that the total heat flow across unit area in the $-x$ direction is:

$$F_{-x}(0, t) = \frac{1}{Bi}\left[\exp(Bi^2 t)\, \operatorname{erfc}(Bi\sqrt{t}) - 1\right] + \left(\frac{4t}{\pi}\right)^{1/2} \tag{10.3}$$

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[8] cf. [8] pg. 45

[9] cf. [4] pg. 34 or [7] pg. 177

Special Case: Constant Boundary Temperature

If we let $Bi \to \infty$, which entails that the boundary condition (5.6) becomes:

$$T(0, t) = 0 \quad \text{for } t > 0 \tag{10.4}$$

— the boundary is kept at a constant temperature — then the solution (10.1b) simplifies to:

$$T(x, t) = \operatorname{erf}\left(\frac{x}{\sqrt{4t}}\right) \tag{10.5}$$

From (10.2a) we then obtain:

$$q_{-x}(0, t) = \frac{1}{\sqrt{\pi t}} \tag{10.6}$$

and using (6.2) we have:

$$F_{-x}(0, t) = \left(\frac{4t}{\pi}\right)^{1/2} \tag{10.7}$$

The last two equations could, of course, also have been obtained from (10.2c) and (10.3) by use of the expansion (8.8b).

Special Case: Highly Insulated Boundary

If we let $Bi \to 0$, we describe the case where heat flow across the solid is very rapid as compared to convection at its highly insulated boundary. If we carry out the Taylor series expansion of (10.1a) as a function of the parameter Bi, then to first order in Bi we obtain:

$$T(x, t) = 1 - Bi\left(\left(\frac{4t}{\pi}\right)^{1/2} \exp\left(-\frac{x^2}{4t}\right) - x \operatorname{erfc}\left(\frac{x}{\sqrt{4t}}\right)\right) \quad \text{for } Bi << \frac{x}{t} \tag{10.8}$$

From (10.2c) using (8.7b), we see that:

$$q_{-x}(0, t) = Bi \quad \text{for } Bi << \frac{1}{\sqrt{t}} \tag{10.9}$$

and using (6.2),

$$F_{-x}(0, t) = Bi\ t \quad \text{for } Bi << \frac{1}{\sqrt{t}} \tag{10.10}$$

so that the total heat flow across the boundary increases linearly with time.

11. HEAT FLOW FROM A HIGHLY INSULATED SOLID

We consider the case of a solid of arbitrary shape in which heat conduction across the solid medium is very rapid as compared to heat convection at the boundary. Then the temperature within the solid will be nearly the same at all positions. In this case, we use (4.2b) to define L, and consequently BI. For most solids, if $BI < .1$ then the temperature within the solid can be taken as uniform to within a 5% error.[10]

We now allow for the possibility that the specific heat c is not a constant, but depends linearly upon temperature. This is approximately true of ice, whose heat flow characteristics can be used as a first approximation to the frozen human body.[11] We assume

$$c = c_\infty(1 + b\,T) \tag{11.1}$$

In (4.5) we use $\alpha_\infty = k/\rho c_\infty$, so that instead of (6.10) we obtain:

$$\nabla^2 T = (1 + b\,T)\frac{\partial T}{\partial t} = \frac{\partial T}{\partial t} + \frac{b}{2}\frac{\partial T^2}{\partial t} \tag{11.2}$$

By precisely the same argument as was used to obtain (7.3),

$$\frac{d\langle T\rangle_R}{dt} + \frac{b}{2}\frac{d\langle T^2\rangle_R}{dt} = -BI\,\langle T\rangle_S \tag{11.3}$$

But since the temperature has a nearly uniform value $T(t)$ within R,

$$\langle T\rangle_R \approx \langle T\rangle_S \approx T$$
$$\langle T^2\rangle_R \approx T^2 \tag{11.4}$$

so that (11.3) becomes:

$$(1 + b\,T)\frac{dT}{dt} = -BI\,T \tag{11.5}$$

or

$$(1/T + b)\frac{dT}{dt} = -BI \tag{11.6}$$

Integrating (11.6) from time 0 to t, we obtain:

$$\log(T) + b\,(T - 1) = -BI\,t \tag{11.7}$$

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[10] [7] pg. 140

[11] see data in [12] pg. D-138; also [2] Chapter 29.

This equation cannot be solved in closed form for T, but T can be obtained by Newton's method. We let

$$T_0 = 1 \tag{11.8}$$

$$T_{n+1} = T_n - \frac{\log(T_n) + b\,(T_n - 1) + BI\,t}{1/T_n + b} \tag{11.9}$$

and iterate until the T_n's converge to the desired degree of precision.

Special Case: Constant Specific Heat

If we let $b = 0$, we can obtain T explicitly from (11.7):

$$T = \exp(-BI\,t) \tag{11.10}$$

This result could have been seen directly from (7.3). This special case is known in the literature as the *homogeneous billet.*[12]

12. HEAT FLOW FROM A SPHERE

The sphere can be used as a model of heat flow through the head, either during whole body suspension or during neurosuspension. Under the uniform initial and boundary conditions we have adopted, all heat flow must be in the radial direction. We use (4.2a) to determine L, and thus Bi.

The solution to (6.10) under the initial and boundary conditions (5.4) - (5.6) is:[13]

$$T(r, t) = 2\sum_{n=1}^{\infty} \frac{\sin(R_n r)\exp(-R_n^2 t)}{(R_n r)[R_n \sin(R_n)/Bi - \cos(R_n)]} \tag{12.1}$$

where $R_1, R_2, \cdots$ are the solutions to the eigenvalue equation:

$$R_n \cot(R_n) + Bi - 1 = 0 \tag{12.2}$$

The denominator in (12.1) can be reformulated in various ways, using the eigenvalue equation (12.2), so that the expression does not contain indeterminate forms (0/0) when r and Bi approach desired limiting values. We have written (12.1) so that it converges to the proper limit as $Bi \to \infty$.

The solution at $r = 0$ is obtained by taking the limit of (12.1) as $r \to 0$:

$$T(0, t) = 2\sum_{n=1}^{\infty} \frac{\exp(-R_n^2 t)}{R_n \sin(R_n)/Bi - \cos(R_n)} \tag{12.3}$$

---

[12] [5] pg. 139 and [7] pg. 140

[13] cf. [4] pg. 91

The average temperature within the sphere is given by:

$$<T(t)> = 6 \sum_{n=1}^{\infty} \frac{\exp(-R_n^2 t)}{R_n^2 (1 - 1/Bi + (R_n/Bi)^2)} \tag{12.4}$$

Special Case: Constant Boundary Temperature

If we let $Bi \to \infty$, the eigenvalue equation (12.2) simplifies to:

$$\frac{\tan(R_n)}{R_n} = 0 \tag{12.5}$$

whose solutions are:

$$R_n = n\pi \quad \text{for } 0 < n < \infty \tag{12.6}$$

The solution (12.1) simplifies to:

$$T(r, t) = 2 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\sin(n\pi r) \exp(-(n\pi)^2 t)}{n\pi r} \tag{12.7}$$

The solution at $r = 0$ is again obtained by taking the limit as $r \to 0$:

$$T(0, t) = 2 \sum_{n=1}^{\infty} (-1)^{n+1} \exp(-(n\pi)^2 t) \tag{12.8}$$

The average temperature within the sphere is given by:

$$<T(t)> = 6 \sum_{n=1}^{\infty} \frac{\exp(-(n\pi)^2 t)}{(n\pi)^2} \tag{12.9}$$

Special Case: Highly Insulated Boundary

If we let $Bi \to 0$, we describe the case where heat flow across the sphere is very rapid as compared to convection at its highly insulated boundary. In this limit, the first solution to the eigenvalue equation (12.2) becomes approximately:

$$R_1 = \sqrt{3Bi} \tag{12.10}$$

In this case, the nearly uniform temperature within the sphere can be obtained from the first term in (12.4):

$$<T(t)> = \exp(-3Bi\ t) \tag{12.11}$$

We note that if we use (4.2b) rather than (4.2a) to define the characteristic linear dimension of the sphere, then with the revised values of t and Bi, (I12.11) becomes:

$$<T(t_{BI})> = \exp(-BI\, t_{BI}) \tag{12.12}$$

which was the solution obtained in (11.10).

13. HEAT FLOW FROM A CYLINDER

We now consider heat flow from a cylinder that is (ideally) infinitely long, so that all heat flow is in the radial direction. The cylinder can be used as a model of the human torso, during whole body suspension. We use (4.2a) to determine L, and thus Bi.

The solution to (6.10) under the initial and boundary conditions (5.4) - (5.6) is:[14]

$$T(r,\, t) = 2\sum_{n=1}^{\infty} \frac{J_0(R_n r)\exp(-R_n^2 t)}{R_n J_1(R_n)[1 + (R_n/Bi)^2]} \tag{13.1}$$

Here J_0 and J_1 are the Bessel functions of order 0 and 1, while R_1, R_2, $\cdots$ are the solutions to the eigenvalue equation:

$$R_n J_1(R_n) - Bi\, J_0(R_n) = 0 \tag{13.2}$$

and we have again used the eigenvalue equation to formulate the solution so that it converges to the proper limit as $Bi \rightarrow \infty$.

The average temperature within the cylinder is given by:

$$<T(t)> = 4\sum_{n=1}^{\infty} \frac{\exp(-R_n^2 t)}{R_n^2[1+(R_n/Bi)^2]} \tag{13.3}$$

Special Case: Constant Boundary Temperature

If we let $Bi \rightarrow \infty$, the eigenvalue equation (13.2) simplifies to:

$$J_0(R_n) = 0 \tag{13.4}$$

The roots of (13.4) are widely tabulated.[15]

In this limit the solution (13.1) becomes:

$$T(r,\, t) = 2\sum_{n=1}^{\infty} \frac{J_0(R_n r)\exp(-R_n^2 t)}{R_n J_1(R_n)} \tag{13.5}$$

---

[14] cf. [4] pg. 73, [8] pg. 102, and using (13.2)

The average temperature within the cylinder is:

$$< T(t) > \; = 4 \sum_{n=1}^{\infty} \frac{\exp(-R_n^2 t)}{R_n^2} \tag{13.6}$$

Special Case: Highly Insulated Boundary

If we let $Bi \rightarrow 0$, just as with the sphere we describe the case where heat flow across the cylinder is very rapid as compared to convection at its highly insulated boundary. In this limit, the first solution to the eigenvalue equation (13.2) becomes approximately:

$$R_1 = \sqrt{2Bi} \tag{13.7}$$

We obtain the nearly uniform temperature within the cylinder from the first term in (13.3):

$$< T(t) > \; = \exp(-2Bi\; t) \tag{13.8}$$

Again we note that if we use (4.2b) rather than (4.2a) to define the characteristic linear dimension L of the cylinder, then with the revised values of t and Bi, (13.8) becomes:

$$< T(t_{BI}) > \; = \exp(-BI\; t_{BI}) \tag{13.9}$$

which was the solution obtained in (11.10).

14. ANALOGY BETWEEN HEAT FLOW AND DIFFUSION

The basic laws of heat flow (3.1) - (3.4) can be reinterpreted to describe the process of *diffusion* within the human body. To describe diffusion, such as of glycerol or DMSO during cryoprotective perfusion of the human body, we require new fields such as:

$$\mathrm{C(r,\ t)} = \text{concentration of cryoprotectant} \;\; [\mathrm{kg/m^3}] \tag{14.1}$$

Here, *matter* rather than *heat* is moving. So the isomorphism is accomplished as follows, using the diffusion symbols of [4]:

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[15] for example in [1], with shorter tables in [3], [4], and [8]

HEAT FLOW		$\longleftrightarrow$ DIFFUSION	
Quantity	*Unit*	*Quantity*	*Unit*
$\rho c T$	J/m^3	C	kg/m^3
α	m^2/s	D	m^2/s
$\mathbf{q}$	$J/(m^2\,s)$	$\mathbf{j}$	$kg/(m^2\,s)$
F	J/m^2	M	kg/m^2
Q	J	m	kg
$h/\rho c$	m/s	α	m/s

Equation	*Name*	*Equation*	*Name*
$\mathbf{q} = -k\nabla T$	Fourier's law	$\mathbf{j} = -D\nabla C$	Fick's first law
$\nabla^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t}$	Fourier's equation	$\nabla^2 C = \frac{1}{D}\frac{\partial C}{\partial t}$	Fick's second law
$k\frac{\partial T}{\partial t} = -h(T - T_\infty)$	boundary condition	$D\frac{\partial C}{\partial t} = -\alpha(C - C_\infty)$	boundary condition

15. REFERENCES

The list of references below includes several relevant texts that were not explicitly referenced in the article.

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[3] Carslaw, H. and Jaeger, J., *Conduction of Heat in Solids*, 2nd ed., Oxford, 1959

[4] Crank, J., *Mathematics of Diffusion*, Oxford, 1956

[5] Eckert, J. and Drake, R., *Analysis of Heat and Mass Transfer*, McGraw-Hill, 1972

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[7] Kreith, F., *Principles of Heat Transfer*, 3rd ed., Harper & Row, 1973

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[11] Timmerhaus, K. ed., *Advances in Cryogenic Engineering*, Vol. 8 pg. 267, Plenum Press, 1963

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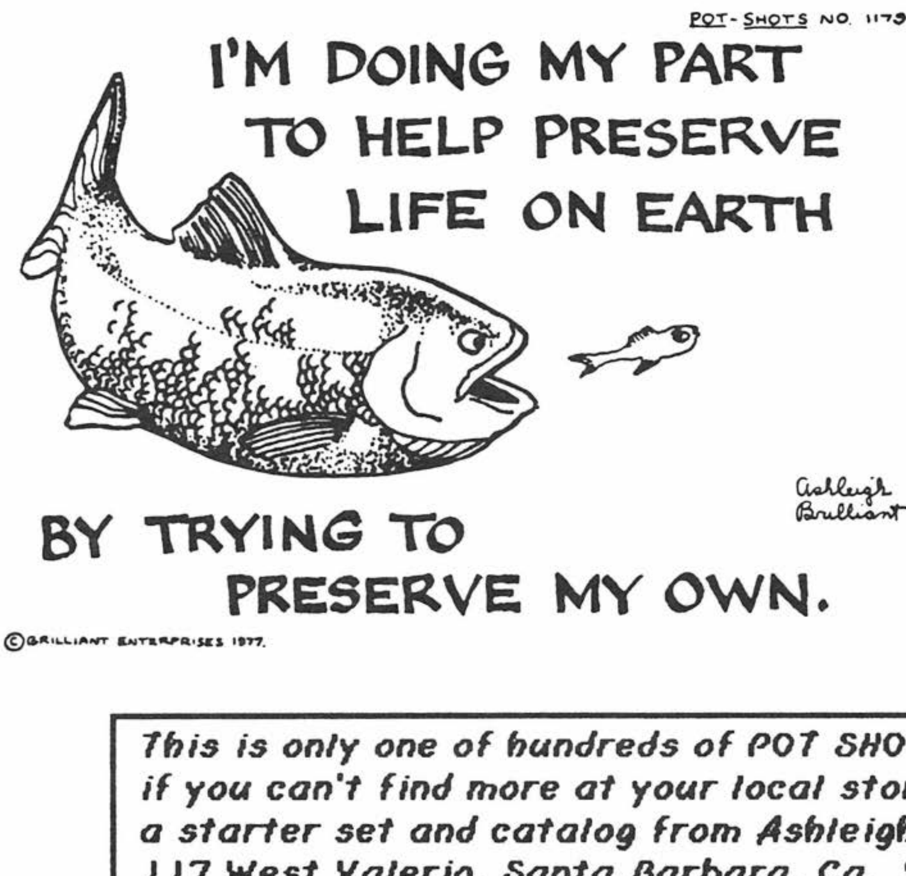
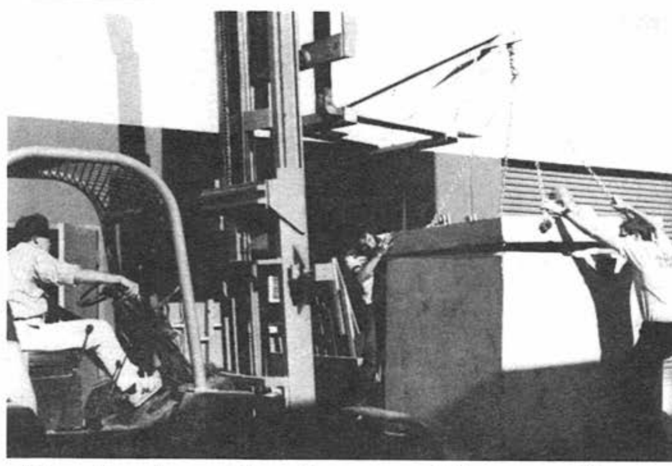


Hugh Hixon preparing to mount the shock absorbers on the dewar feet.

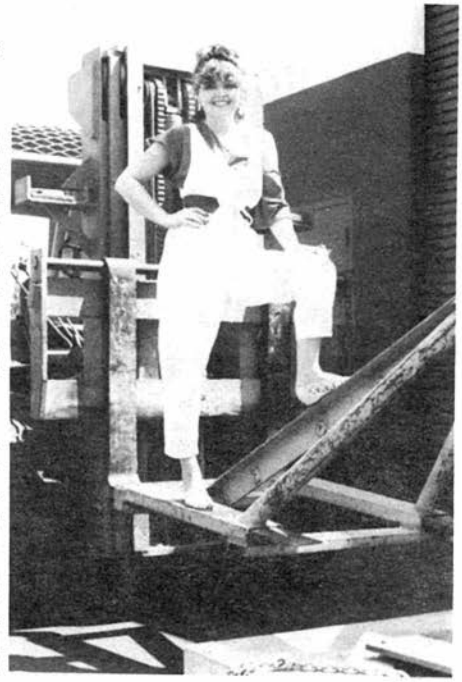
Mounting the A-2542 dewar on its plywood base.

Picking up the dewar on its new base.



Replacing the top on the vault, using the forklift/crane. Jerry Leaf at the controls, Scott Greene and Mike Darwin guiding.

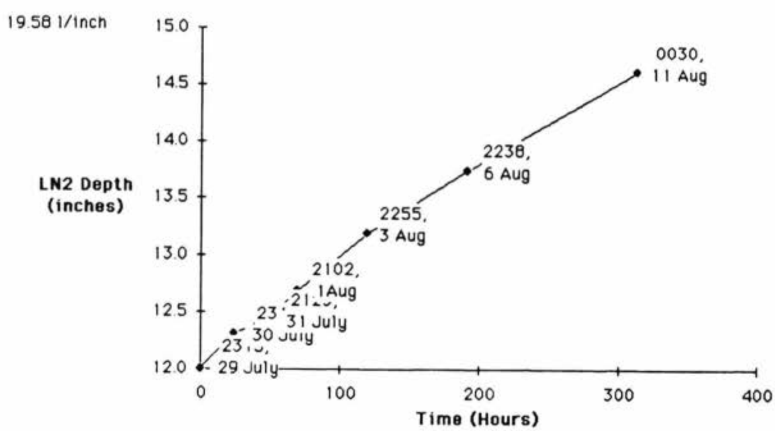
The forklift/crane. (And Brenda Peters, our photographer.)



very well at running around and shouting a lot. But, the real star of the day was Hugh Hixon, who's thoughful planning and ingenious engineering design resulted in a flawless operation from start to finish. Things went so smoothly we even had time to intersperse moving operations with entertaining some guests: ALCOR member Saul Kent showed up with a couple of people from Florida, and we all paused for a little talk and some cool refreshments.

On Monday, the 29th of July, the patients were returned to the dewar and boiloff studies were begun to thoroughly evaluate the health of the A-2542. Over the past few years a precise measurement of the performance of the A-2542 has been all but impossible. This was because there was a tremendous amount of research material in the dewar, much of it irregularly shaped and some of it projecting above the liquid

A-2542 Boiloff



A-2542 Boiloff. LN_2 depth is measured as distance of liquid surface from the top of the neck tube. Each inch of depth equals 19.58 liters of LN_2. Note that as the interval between measurements gets longer, the boiloff rate decreases.

line. Also, since the dewar is being used not only for patient care, but for research as well, small amounts of liquid are occasionally removed and the lid is opened with some frequency. This prevents the careful measurements which are necessary to establish dewar performance from being taken. Thus, it was extremely important to get a baseline on the container's performance.

As you can see from the accompanying graph, the A-2542 is performing superbly. This latest series of measurements indicates that it is boiling off 3.5 liters per day. The dewar is rated from the manufacturer to boil off 3.4 to 3.8 liters per day, so it's right where it should be! This was a little surprizing since our initial evaluation four years ago, when it first arrived, was that it was boiling off 4.5 liters per day. We have now learned the importance of a longer evaluation period and the use of a single individual employing a highly repeatable measuring technique.

All in all, moving into the vault went much more smoothly than expected and we are all overjoyed and relieved to have this big project behind us and to know that our patients are finally getting the kind of protection they both need and deserve!

Letter To The Editors

Dear Mike,

Cocoon, which you reviewed in the August issue of CRYONICS, is indeed a wonderful film which stresses the immortalist philosophy. However, I have some cautions for optimistic readers who may think this heralds the dawn of a cryonics boom. We as cryonicists are hypersensitive to the immortalist ideas expressed in the film and give them greater importance than may most of the general public. Many of my friends here in Indianapolis have seen Cocoon and have praised it highly--yet only one, even with my prompting, recognized the philosophy stated in the film as being "immortalist" or having anything to do with my cryonics involvement. And this is from people who have heard immortalist ideas from me. Most people are viewing the film as pure entertainment. When pressed for a "meaning," the best these people can do is "Old people are a lot livelier than most young people understand" or "It would be great for the aliens to invite us out into space with them." This may be the first great immortalist film, but it won't lead anyone to cryonics.

....UNLESS **we** make the connection for them. Here is my suggestion. When you are talking with people about the film, ask a group "If those aliens landed now and offered you the same conditions as they offered the old folks in the film—that is, you would lead productive lives and learn many of the secrets of the universe, you would never get older, you would never be sick, and you wouldn't ever die; but you would have to leave the time, the place, and the people (except for those coming along with you) you know—how many of you would go?"

You are likely to get several yes's. If so, you can discuss the idea of living and learning forever in space. And eventually you can make the observation that the aliens probably are not coming for us. If we want that kind of life, it will have to be a "do-it-ourselves" proposition. And the opportunity for "do-it-ourselves" is already here in cryonics.

Don't ever think that movies like Cocoon or books like Jitterbug Perfume (reviewed in June issue of CRYONICS) will do our work for us. They merely provide us with a starting point and a climate from which to launch an attempt to change individuals' ideas about immortality; to show them that immortality is not just an entertaining plot device or vague human dream, but that it is a potential reality which can affect their own lives.

Stephen Bridge
Indianapolis, IN

The Scanning Tunneling Microscope: The Door Into Molecular Technology

by Hugh Hixon

Over approximately the past year, the scientific press and journals have been reporting the development and operation of a fundamentally new scientific instrument. Able to resolve distances of the order of one one-hundredth of an atomic diameter, the Scanning Tunneling Microscope (STM) promises to be the precursor of a group of revolutions so far-reaching as to defy accurate prediction.

For cryonics and life extension, what it appears to promise is a particularly rapid entry into the molecular technology (MT) necessary to discover the basic mechanisms of aging within the living cell, and to perform the reconstructive work necessary to perform a reanimation from cryonic suspension.

Among the earliest views made of what has up to now been a world beyond anything but our mental conceptions are atom-by-atom maps of the surfaces of crystals and components of one of nature's own molecular machines, the T-4 bacteriophage. The pictures of the T-4 phage pieces are not easily reconciled with our ideas of them gained from conventional transmission electron microscopy, but this is a problem that will be overcome with developments in experimental technique. The pictures of the crystal surface, however, are unambiguous, so far as our present knowledge of such things goes.

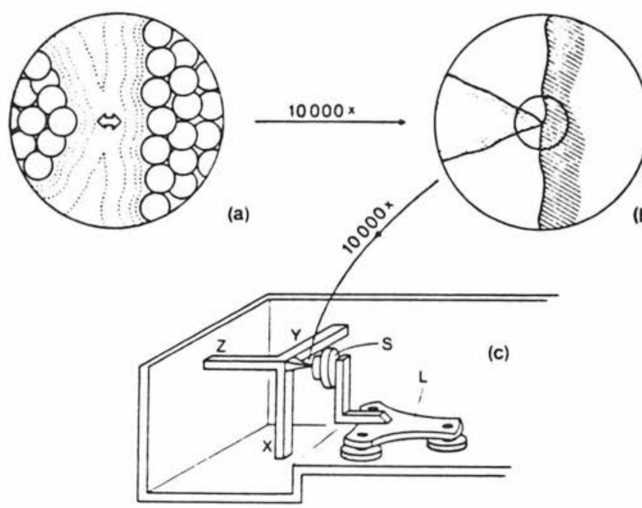
Both conceptually and practically, the heart of the STM is the essence of simplicity. A three-axis drive moves the tip of a needle over the surface of interest, at a distance so small that electrons from the surface bridge the gap by quantum-mechanical tunneling. The resulting current, easily detected by an instrument no more sensitive than a pH meter, is used to control the distance of the needle above the surface, and that control signal is also used to trace a picture of the surface.

What is not simple is getting used to the idea that a device centimeters (10^{-2} meters) in size can regulate its position with an accuracy of hundredths of Angstrom units (10^{-12} meters) a ratio of ten billion to one! By comparison you can think of using a continuous strip-mining machine (10^2's of meters) to observe the components of a microelectronic chip (10^{-6} meters), and still fall short by a factor of 100! The history of the invention has not yet been written, but it will be interesting to read of how the IBM researchers who created the STM overcame the mental barriers to the construction of a device, all of whose components were available by 1900, and whose underlying theory of quantum-mechanical tunneling was defined in the early 1930's.

The STM's inventors are Gerd Binnig and Heinrich Rohrer of IBM's Zurich Research Laboratory. In the August, 1985 issue of **Scientific American,** thay give a brief account of how the STM works, and some good pictures and diagrams of their pioneering instrument. For a description of how the STM works, I quote from Conrad Schneiker's forthcoming paper, **NanoTechnology:**

> ... Roughly speaking, STM's operate by scanning an extremely sharp, electrically conducting needle tip within a few atomic radii of a surface to be imaged. Variations in the spacing between the object being "looked at" and the tip of a few tenths of nanometers (= Angstroms, = 10^{-10} meters) result in observed (quantum vacuum tunneling) current changes of over four orders of magnitude. This permits atomic scale feature resolution under favorable conditions. In addition, **the STM will work in air, water, and oil with some loss of resolution.** (Emphasis added).

Binnig and Rohrer's list of co-authored publications is growing almost daily, as researchers in every field that does microscopic work move to assess the potential of the STM. As of August, 1985, Schneiker lists 32 papers on STM in a draft of his forthcoming paper, **NanoTechnology.** STM's are being built all over the world, and they are simple enough that it is likely that there will be at least one STM project in the 1986 Science Fair (Westinghouse Science Talent Search, which promotes science projects at the high school level).



The STM. The sample "S" is mounted on the positioning platform "L", and moved close to the scanning needle. The needle tip is scanned across the surface of the sample by the 3-axis X, Y, and Z drives. Inset (b) diagrams the needle and surface on a microscopic scale. Inset (a) diagrams the needle tip and surface on an atomic scale.

In detail, the STM consists of: a positioner on piezoelectrically driven legs to move the object to be observed close to the tip without smashing into it; the three-axis piezodrive, which scans the sensing tip over the object in a TV-like raster pattern, and moves it back and forth to follow the surface of the object; the tip, which picks up the electrons emitted from the object. (Depending on the application, the tip may be either ion-milled, where the tip is first sharpened conventionally, and the final sharpening is done by blasting away metal atoms with a directed stream of ions, or simply used after mechanical sharpening, since the sharpening process leaves fine microwires of material projecting from the tip.); the current detector, which measures the quantum mechanical tunneling current between tip and object; and which is connected to a controller, a simple computer which keeps the current constant by varying the voltage to the piezoelement controlling the distance between the tip and object (Z-axis positioner), and which also controls the position of the tip (X- and Y-axis positioners); the shock absorption system, which can be as complex as Binnig and Rohrer's two-stage, magnetically damped, vacuum-isolated workstage, or as simple as a stack of metal plates separated by rubber grommets; and finally, a theory of operation, in this case the quantum-mechanical prediction that electrons may be found away from a surface (although at this scale, the concept of a surface becomes rather uncertain).

As an adjunct to their tip sharpening, Binnig and Rohrer found that, with proper technique, they could move a few atoms, or even a **single atom** from the object to the tip, to make a final point on a scanning needle that is only one atom in diameter! Not only does this give the scanning needle the ultimate sharpness, but it is an immediate demonstration of the possibility of moving single atoms around; i.e. -- molecular engineering. It seems likely that practical engineering tips will be more complex, incorporating molecules like B-12 on the tip (Vitamin B-12 is a complex macrocyclic ring structure with an atom of cobalt in the center. Living systems use it for one-carbon transfers in molecular synthesis).

Researchers have already begun examining DNA molecules under the STM. While we have not seen pictures of the results, it is obvious that a very early goal of this technology will be a DNA reader, able to read a strand of DNA like a piece of punched teletype tape. A somewhat more complex goal will be a molecular machine that can also write, or erase and rewrite, DNA.

In **NanoTechnology**, Conrad Schneiker traces the concept of molecular machines to a speech and paper by physicist Richard Feynman in 1959, outlining a system to produce more and more, smaller and smaller machines. (This reprint is available from ALCOR as part of the package on the Scientific Basis of Cryonics.) It now appears that Feynman's route to molecular devices, making them smaller in stepwise fashion, has been short-circuited. As Schneiker points out, the STM appears to be able to go from something that can be held in one's hand to the smallest machines conceivable, in one step. Feynman is reportedly delighted. Readers of science fiction may attempt a previous credit with Robert Heinlein's 1940's story, **Waldo**, but such a claim seems tenuous. Heinlein used the idea of building smaller and smaller machines only once, and in passing.

To further the development of STM's and molecular machines, Conrad Schneiker has proposed and will fund a series of competitive challenges and prizes to the engineering and science community at large, for progressively smaller STM's. More information on this competition is available in his ongoing paper, **NanoTechnology**, available from ALCOR for $4.00, in its latest iteration.

SEPTEMBER-NOVEMBER 1985 MEETING CALENDAR

ALCOR meetings are usually held on the first Sunday of the month. Guests are welcome. Unless otherwise noted, meetings start at 1:00 PM. For meeting directions, or if you get lost, call ALCOR at (714) 738-5569 and page the technician on call.

ALCOR

ALCOR LIFE EXTENSION FOUNDATION
4030 NORTH PALM #304
FULLERTON, CALIFORNIA 92635
(714) 738-5569

The SEPTEMBER meeting will be at the home of:

(SUN, 8 SEPT 1985)
(SECOND SUNDAY)

Mike Darwin and Scott Greene
350 W. Imperial Highway, #21
Brea, CA
Tel: (714) 990-6551

DIRECTIONS: Take the Orange Freeway (Hwy 57) to Imperial Highway (Hwy 90), and go west through Brea on Imperial Highway. 350 is about one mile from the freeway, and in the third block beyond Brea Blvd., on the south (left) side. If the gate is closed, park on the streets north of Imperial. Be careful crossing Imperial. There is a blind curve to the east and a blind hill to the west at this point.

The OCTOBER meeting will be at the home of:

(SUN, 6 OCT 1985)

Paul Genteman
535 S. Alexandria, #325
Los Angeles, CA

DIRECTIONS: From the Santa Monica Freeway (Interstate 10), exit at Vermont Avenue, and go north to 6th St.
From the Hollywood Freeway (US 101), exit at Vermont Avenue, and go south to 6th St.
Go west on 6th 4 blocks to Alexandria, and turn right. 535 is the first apartment building on the west side of the street. Ring #325 and someone will come down to let you in.

The NOVEMBER meeting will be at the home of:

(SUN, 3 NOV 1985)

Maureen Genteman
524 Raymond Avenue, #12
Santa Monica, CA

DIRECTIONS: Take the Santa Monica Freeway (Interstate 10) to Santa Monica and get off at the 4th Street exit. Turn south (left) on 4th. Go south on 4th to Ocean Park Ave. (4-way flashing stop). Go left on Ocean Park, down ramp to stop and up to 6th St. on Ocean Park. Turn right on 6th. Raymond is the second street. Turn right on Raymond. 524 is on the left. #12 is on the second floor.

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