## THE MECHANISM OF HEAT TRANSFER ACROSS METALLIC INTERFACES

by

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#### PREFACE.

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Permission by the Atomic Energy of Canada Limited, to make use of the author's previous work as an Appendix, is gratefully acknowledged; its title :"A Review of Literature on Heat Transfer between Metals in Contact and by Means of Liquid Metals", is abbreviated, for reference, to "Review".

Sincere gratitude is expressed to Prof. D.L. Mordell who, as Director of Research, kindled the author's interest in this field, and to Prof. A.R. Edis, Director of Research from 1952/53 on, for their valuable advice.

An attempt was made to avoid repetition of the material presented in the Review, and therefore a general reference to it (Appendix II) is made here.

Jakob's system of reference /p.730, Jakob(1949)/ was adopted, for flexibility of the list: "In the text the name of the author and the year in brackets.... refer to items in the bibliography". The few exceptions are listed both under the short title adopted and by the author, or editor.

#### SUMMARY

Heat transfer is discussed on the basis of coupled atomic oscillators vibrating both longitudinally . and transversally, and of electron gas obeying the kinetic theory. It is shown how this gas is retained in metals (and how the fundamental mechanism of electric motors follows).

Circumstances at the metal-film, film-film, and film-fluid interfaces are shown to cause a splitting and merging of heat transfer paths.

The conclusions are:

a) a better electronic conductivity is achievable by the use of pure annealed metals;

b) constriction resistance can be eliminated by wetting;

c) roughness voids can be reduced by plating with soft metals;

d) surfaces will be free of films and liquid metals will not become "diluted" if gases will be kept out of liquid-metal systems;

e) non-wetting is not responsible for the 20-40% lowerthan-predicted heat transfer results.

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## NOTATIONS.

	:	Angstrom unit(s) = $10^{-10}$ m
a-spots	:	Asperities actually touching the opposite member.
Btu	:	British Thermal Unit(s)
C	:	Degree(s) Celsius (Centigrade)
em	:	Centimeter(s)
D	:	Electrostatic flux density vector
E	:	Electrostatic field intensity vector
٤	:	Dielectric constant
ft	:	Foot (feet)
F	:	Degree(s) Fahrenheit
gcal	:	Gram-calorie(s)
hr	:	Hour(s)
in.	:	Inch(es)
k	:	Thermal conductivity,Btu/(hr ft <sup>2</sup> F/ft) or,gcal/(sec cm <sup>2</sup> C/cm)
m	:	Meter(s)
mV	:	Millivolt(s)
800	:	Second (s)
v	:	Volt(s)

l gcal/(sec cm<sup>2</sup> C/cm) = 241.9 Btu/(hr ft<sup>2</sup> F/ft)

#### 1. INTRODUCTION

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Heat transfer across metallic interfaces may seem to be a subject of minor importance /p.56,Review/. The perusal of some examples /pp.57,58,ibid./ may help to change this attitude.

The most well-known example is soldering, an art which is older than the science of it. The ancient plumber found from experience that when the copper bit became covered by a crust of exides he was unable to get sufficient heat across this interface to melt the solder. By trial and error he discovered that sal ammoniac would clean away the crust and let some tin to adhere to the bit, and that tin would not so easily develop a crust. Also he found out that certain "fluxes" would clean the metal surfaces to be soldered so that tin would spread on them. It will be seen later that this is exactly the procedure to be followed when making use of the scientific information available: To obtain the smallest resistance to heat flow across a solid-liquid interface one has to attain wetting by scrupulously cleaning away all exides and other films.

### 1.1. Historical Note

Reference: pp. 54-55, Review.

Wiedemann and Franz, in 1853, announced that for all metals the ratio of the two conductivities, thermal and electrical, is a constant. Lorenz, in 1872, introduced the absolute temperature into the expression. Drude (1900) p.577, advanced the theory that this relationship is explainable by free electrons in metals behaving themselves as a gas. Debye (1912) p.802, paid attention to the vibrations of the lattice structure of solids, and successfully explained, on this basis, the expressions for specific heat, etc. Meissner, in 1935 /p.100, Jakob(1949) / compared a crystal with a chain of many slightly damped electric oscillators, which are tuned to the same frequency and coupled very loosely. The wave mechanics, grown from Planck's quantum theory and the Schroedinger equation, explained many puzzling things not explainable by classical mechanics. Seitz (1940) and Slater (1951) went into much detail in their books, and Slater (1954) continues to publish quarterly reports on contemporary work at the M.I.T.

A history of the work on electrical contacts is presented by Holm (1946) on pp.349-359. He mentions Browning as having, in 1906, launched the idea of constriction resistance.

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#### 1.2. Some Notes on the Structure of Matter.

For simplicity chemists make use of the interatomic distances in crystals found by means of x-rays, and assume these distances to be the sums of the corresponding effective radii of the atoms/p.22,Arkel (1949)/, i.e. they picture the atoms as hard, elastic, spherical balls touching their neighbours when assembled into molecules. For more exact calculations certain corrections are applied/pp.21,216,Arkel (1949)/. Electrons are not pictured separately. This model tends to shift the attention from forces to (non-existent) physical contact.

Wave mechanics leads us into rather abstract pictures replacing electrons by probabilities to find at a certain distance from the nucleus a certain distribution of charge density, etc.

Bohr's model, although superseded by the wave mechanics for calculations, is most useful for qualitative description. It is an elaboration of the Rutherford') model and should be called the Rutherford-Bohr model. For our purposes it may be described as having a positive nucleus and an array of negative electrons moving in certain orbits of which the outermost usually are not filled to capacity; the noble gases have filled orbits which makes the distribution of charges spherically symmetrical/p.21,Arkel (1949)/.

The diameter of the nucleus is of the order of  $10^{-12}$  cm and the overall diameter of the atom is of the order of  $10^{-8}$  cm. Thus, atoms are exceedingly empty, and

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<sup>&#</sup>x27;) Lord Rutherford was active at McGill University from 1898 to 1907, and suggested the "empty" model of atom in 1911.

this impression must be obtained from a scale model, to be properly appreciated. Enlarging a hydrogen atom approx. 0.5x10<sup>12</sup>times, i.e. making the proton pea-size and the electron pin-head-size, we would need for the orbit an auditorium, e.g. Moyse Hall, since their distance should be of the order of 30 m or roughly 100 feet. The other means for envisaging the emptiness of matter is the consideration of the specific gravity of a nucleus. For the nucleus of mercury it is of the order of 8x10 grams/cm, or approx.1,400,000,000 compared with 13.6 g/cm or 0.000245 t/in. for tons/in. liquid mercury. Thus, the impenetrability of matter is not due to the space being already occupied ') but to large electrostatic repulsive forces preventing the atoms from penetrating each other/p.444, Slater and Frank (1933)/. Actual atoms are neither spherical (some of the electron orbits being elliptical and intersecting at an angle), nor with a definite diameter, because the interatomic distances adjust themselves until the forces acting on the atoms are in equilibrium.

The forces acting upon the particles and keeping them in some aggregation have been subjected to detailed mathematical treatment, however so far the author has not come across an accepted explanation of the cause of

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This situation, however, is probably approached in some superdense dwarf stars where a collapse of atoms has greatly reduced the empty space, and augmented the specific gravity to 60,000 g/cm, or so.

gravitation ') or of the nature of the elementary electric charge of an electron.

Gravitational forces, on the atomic scale, are negligible/p.144,Lapp and Andrews (1948)/.

Nuclear forces do not act beyond the boundary of the nucleus/p.145,ibid./.

Coulomb, or electrostatic, forces can both be repulsive or attractive depending on the sign of the charges. When one atom penetrates another/p.442,Slater and Frank (1933)/ there is first an attraction, then a repulsion, with an intermediate position of equilibrium. Ions of opposite signs attract each other.

Electrostatic forces arise also from any asymmetry of molecules. According to Dele (1935) p.4, at the immediate vicinity of the positive and negative ends of the permanently asymmetric water molecule forces are active equivalent to a field of 70 million volts/cm. Temporary asymmetry is caused by an electric field which separates the charges, creating a dipole.

A variety of electrostatic forces, van der Waals' forces, arises from the fact that an atom is neutral only on the average. Instantaneously it is not spherically symmetrical, and therefore is a dipole, producing polarization in a second atom or molecule, so that the two asymmetric electrical systems attract each other/p.440,

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<sup>&#</sup>x27;) Approx. four years ago (according to newspapers) Einstein published a "...general theory of gravilation... as it tends to explain, by mathematical equation, the reason for behaviour of particles and planets." Does it answer our question ? Or is gravitation again just a property of four-dimensional space?

Slater and Frank (1933)/. Arkel (1949) mentions their peculiar property: They always strive to bring like atoms together, i.e. to surround each particle with the highest possible number of like neighbours (p.177).

Valence attraction is based on the distortion of one atom by the other when they share electrons/p.443, Slater and Frank (1933)/ which, according to Pauli's exclusion principle, form pairs with opposite spin.

Thus, no matter what their name, the forces between atoms are electrical, differing insofar that their decrease is expressible in larger or smaller inverse powers of distance /p.441,ibid./.

Each of the 98 elements differs from the others by the number of electrons (and nucleons) in its atoms, and books are filled with reasoning how their configuration explains the experimentally observed chemical affinity /p.226, Arkel (1949)/.

Told in a few sentences the story seems to be:

- Atoms have a tendency to obtain filled electron shells.
- b) Chemical reactions proceed spontaneously if the final system has a lower potential energy than the original one; the excess energy is released.
- c) A system of higher final potential energy can be formed from one of lower initial potential energy, if the difference is supplied.

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 Additional supply of (kinetic) energy raises the rate of reaction.

The first shell becomes filled with two electrons, and therefore two hydrogen atoms have no choice but to lend their electron for a short while to the other, to fill its shell, ie. they share this pair of electrons and form a molecule.

No sharing is necessary when such atoms meet, one of which can supply the other's deficiency. Sodium lets its single 3s electron fill the vacancy in chlorine's 3p shell, which now is as full as that of the inert gas argon, and this move of charge makes them ions which are held together by electrostatic attraction. Since the ions are satisfied by their transaction, they do not revoke it even when they separate themselves if circumstances provide a great reduction of the electrostatic force. This happens when their compound is put into a liquid with a high dielectric constant, because  $\underline{E}=\underline{D}/\underline{c}$  i.e. the electrostatic force is reduced to  $1/_{\mathcal{E}}$  of its value in vacuum when the space is filled with a fluid whose dielectric constant is E. The dielectric constant of pure water is 80, and therefore in water the sodium ion attracts the chlorine ion only with a 1/80th of the force in wacuum. The ions literally "fall apart", and this is the mechanism of dissolution and of electrolytic dissociation.

It seems to be strange that wwo oppositely charged bodies in contact do not discharge to become neutral. Arkel (1949) p. 27, explains: "The total potential energy of a Cl atom and a Na atom at the shortest distance of separation is greater than that of a positive Na ion and a negative Cl ion, also at the shortest distance from each other." Thus the "discharge" could not be effected without returning to the system the formerly released energy, i.e. pulling the ions apart.

Larger numbers of electrons can be moved or shared within the limits of the "valence".

It is interesting to know why some metals oxidize faster than others, and even burn, and others do not tarnish at all. The answer seems to be: The atoms somehow feel which combinations of them will produce the smallest clusters of particles so that the largest quantity of energy will become released, and seek corresponding partners. i.e. the electrostatic attraction forces differ between pairs of different atoms; consequently their final kinetic energy, when they collide, will differ widely from pair to pair. Quite often it may not suffice to bring about their interpenetration (against the repulsive force arising at their contact) and regrouping of the valence electrons. From the necessity of a spark for some reactions one can deduce that a threshhold value of kinetic energy must be reached. Apparently the valence electrons have to reach a region where the positive nucleus is less shielded by its own electron shells and is able to pull them out of the attraction of the other nucleus. In some cases even the

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slowest moving molecules may attain this minimum, and then the reaction will proceed fast, even explosively, depending however on the facilities for a large number of participants to meet each other.

## 1.3. Surfaces and Interfaces.

References: pp.59, 78-89, 110-113, 122-124, 129, 132-133, Review.

Apart from geometrical surfaces, one could obtain a reasonably smooth physical surface by splitting a perfect block of mica or a similar crystal, along a cleavage plane.

Metallic surfaces would be machined and finished to some extent. Machining causes chips to be separated from the metal at places where the lattice structure gives way. The result is a visible roughness pattern due to the feed and a finer one which partly follows any imperfections of the atomic lattice. The atomic roughness would be changing due to the vibration of the atoms '), radio-activity, emission of electrons, evaporation, condensation, adsorption, oxidation, etc. The latter usually becomes visible.

Roughness would affect the Mechanism '') quantitat-

a) reducing the area of actual contact of two surfaces;

b) causing a constriction of the paths leading to the contact spots; Reference: pp.71-77, Review.

") Abbreviation for the full title of this work.

The fact that positive ions form the metallic lattice will be emphasized only where the structure of the lattice will be detailed.

e)

holding more adsorbate and/or a thicker oxide film in the valleys than on the peaks.

Fluid in the pockets formed by two rough surfaces in contact would add fresh elements to the Mechanism.

In amplification of the footnote, p. 85, Réview: Noble gases are not entirely inert. Although they are non-polar and have spherically symmetrical electronic structure /p.20, Arkel (1949)/, this symmetry is not present at every single instant/pp.440, Slater and Frank (1933)/. Therefore their atoms attract one another/p.174, Arkel (1949), and they may become adsorbed.

According to Holm (1946) a monomolecular oxygen layer quickly deposits on all metals in air (p.81), e.g. in 20-120 seconds on copper (p.148), and is bound to the metal very strongly by van der Waals forces, only allowing slow vaporization in vacuo (p.95); the molecules dissociate into atoms which soon become negative ions by drawing free electrons from the metal, and combine with the positive metal ions to form an oxide film, which would evaporate only at degassing temperatures (p.96). The formation of sulphides, chlorides, etc. is similar (p.96).

Adsorption and chemisorption seem to be due to the same electrostatic attraction only arising in different degree between pairs of different atoms or molecules. ') Even the "chemical forces"/p.14, Arkel (1949)/

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<sup>&#</sup>x27;) On pp.213/214 Arkel explains the author's difficulty in getting 150-mesh and finer sand screened: "Water molecules can be adsorbed on a surface when their dipoles are attracted by the ions on the surface....The high charge of the positive ion in SiO<sub>2</sub> results in a strong adsorption of water molecules; this adsorption is so strong that dry finely divided SiO<sub>2</sub> is frequently used as a drying agent".

are electrostatic in nature.

Higher temperature may, on one hand, exponentially increase the rate of oxidation, and higher pressure works in the same direction providing a larger number of gas molecules, but, on the other hand, higher temperature will also increase the rate of evaporation or even of dissociation. Holm (1946) brings in Fig. 52.01, p.278, a relation between dissociation temperature of metal oxides and the pressure of oxygen. Arkel (1949) mentions, p.18, that at temperatures above 4,000 C no chemical compounds exist at all.

Some films may protect the metal from further oxidation/p.151,IMH (1952)/; several examples are mentioned on pp.95-106 of Holm (1946) where he presents a theory of tarnishing. The growth of the oxide film may stop or may continue depending upon the affinity and the sizes of the atoms an molecules involved, and upon the circumstances for their encounters. Holm describes, p.97, that the metal ions are smaller and more mobile than the oxygen ions, and therefore diffuse through the existing oxide layer to its surface while "in the interface between oxide and air, oxygen atoms catch electrons and thus become ions reacting with the metal ions from the diffusion current."

Multimolecular films cannot stand the high local pressure at a-spots, however monomolecular layers of liquids endure the pressure and the spots covered by a monomolecular

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film of a lubricant are considered hard/pp.7-8, Holm (1946)/.X)

Cleaning of surfaces by mechanical means is not sufficient. Holm says, p.9, that scratching with a clean knife is better than using emery cloth because "rubbing with emery always leaves contaminations." Probably the contaminants are collected in the spaces between the emery grains and redistributed over the area being cleaned. Any solvent should be selected on the basis of the dissolution mechanism described in Section 1.2. Pickling acids and fluxes (e.g. zinc chloride) should be chosen with a view to the chemical reactions expected. Vacuum alone lessens the chances of fresh or repeated attachment of gas molecules to the surface, but high temperature may be needed to provide the adsorbed molecules with higher kinetic energy so that they could easier leave the surface, or it may be needed for the dissociation of the molecules. In analogy with evaporation of liquids, vacuum and temperature should be provided for a sufficient length of time (many hours). Another effect of temperature is mentioned by Holm on p.149: "In strongly heated contacts another process seems to take place. The tarnish films coagulate, i.e. coalesce to grains, thus increasing the metallic contact areas. It is very probable that soldering paste assists this process."

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It should be interesting to determine which adsorption effects cause a rasor, heated in hot water, to cut much easier.

The cold welding of clean metals is called by IMH (1952) pp.145, 151, "diffusion bonding", and is mentioned as a limiting factor in heat-transfer systems, particularly those employing alkali metals. Cold welding as a (patented) commercial technique is described by Aitken (1952).

## 1.4. Wetting.

Reference: pp.84-89, 95-96, 135-142, Review. Illustrations: pp.135, 136, Review.

If a liquid spreads out on a solid surface, this means large forces of attraction between the molecules of the liquid and of the solid as compared with the cohesion of the liquid molecules. Films usually intervene. Quittenton (1952) p.9, quotes the range of measured oxide film thicknesses: 30 Å to 5000 Å, and on p.26,(1953) he mentions an adsorbed film of 6 Å thickness found in his electromagnetic flowmeter. On p.10 (1952) he states that "the complete lack of signal from an electromagnetic meter is caused by the presence of a gas film, indicating non-wetting conditions, for the electrical resistance of an oxide film alone should not generally be high enough to prevent current flow entirely". There he also quotes Seban's statement that the experimental results would agree with theoretical predictions if 0.0001 inches of air or nitrogen would cover his heat transfer surfaces, and finds it unlikely. He observes that an equivalent oxide film should have a thickness of 1,400,000 o A and considers this also beyond expectation. Quittenton (1953) p.26, disagrees with other authors who believe that roughness valleys would hold more adsorbate.

Wetting agents remove the oxide films /pp.144, 167-9, LMH (1952)/. Vacuum and high temperature remove gas, causing wetting /p.207,ibid./

With liquid alkali metals in the system certain minimum temperatures seem to be required to produce a perceptible rate of a cleaning reaction. Quittenton (1952) p.8 observed with sodium in a cleaned 304 stainless steel pipe that there was no wetting (no signal by the flowmeter) at temperatures up to 575 F, wetting occurred at 800 F, and did not cease at 300 F. Miller et al (1947) p.16, reported that sodium wetted nickel at 355±5 C and low carbon steel at 37015 C. From the diagram 7.8 on p.242 IMH (1952) it is seen that sodium started to wet stainless steel schedule-40 pipe at 752 F, reached steady state after 6 hours at 842 F, and continued to wet at 296 F. The rising curve, Fig.7 p.119, Tidball (1951), gives reason to believe that steady state (complete wetting) was reached in 10 weeks. Repeating the reasoning of p.138, Review, one could think that adsorbed dissolved and entrained gas was finally consumed (and the

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roughness valleys deprived of oxides), however the ll-th and following weeks seem to indicate a worsening of the situation.

The gradually increasing readings of an electromagnetic flowmeter/p.10, Quittenton (1952)/ need not be due to "partial rupture of a gas film, or the absence of a gas film and presence of a heavy oxide film", if the tunnel effect and the coherer effect/pp.106-143, Holm (1946)/ are considered. The latter is introduced by the puncturing of the film, and this agrees with Quittenton's observation, that a potential of 1.7 mV generated in the flowmeter was unable to break the adsorbed film of a 6 Å thickness while producing a field of 25,000V/cm which is not far from the 30,000 V/cm breakdown voltage of air. At the red heat temperatures of some liquid metal systems one could expect some thermionic emission of electrons, should the work function be sufficiently low.

#### 2. THE MECHANISM OF HEAT TRANSFER

Reference: pp.58-64, 93-97, Review.

According to Encyclopaedia Britannica, "mechanism is a general name for a theory that natural phenomena can be and should be explained by reference to matter and motion and their laws".

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### 2.1. General Considerations.

From the point of view of mechanism, "chemical" energy is rather mechanical energy because the components of a system "fall" to positions of lower potential energy, vibrate around their new mean positions and pass some of the vibrational energy on to the neighbours; "mechanical" energy of friction is due to electrostatic forces, e.g. the pressure of a journal is taken up by the electrostatic repulsion forces between the atoms of the bearing and the atoms of the journal attempting to penetrate them; this elastic deformation leads, when motion starts, to vibrational energy/p.204, Holm (1946)/; "electrical" energy is mechanical energy arising from collisions of electrons with the lattice structure; "nuclear" energy, apart from the conversion of some mass into energy /p.70, Glasstone and Edlund (1952); "little is known of the nature of such forces", p.8, ibid./, is mechanical energy since it comes as the kinetic energy of fission fragments plus some vibrational energy: "radiation" energy is again vibrational energy.

Atoms and molecules continue to share energy even during a (statistical) thermal equilibrium. Theoretically even the finest thermocouple wires distort the temperature field. Eichelberg (1939) p.463, made a thermocouple" on a 25 times larger scale" to investigate where is located the temperature which corresponds to the millivolt reading; he does not mention, however, whether it was designed according to the Fourier law of thermal similarity /p.422, Fourier (1822)/ which is discussed in more detail on pp.443-444 of Hutte I(1942), where a dimensionless Fourier number Fo is used. Fourier also discussed (pp.4,19,21,26,31-35,284, 357-362) sources of error in thermometry. From a test by the author (Appendix I) it appears that a small error is involved if the thermometer is not tapped lightly, as the mercury sticks to the glass and comes down in jerks.

#### 2.2. Solids

"Nearly all substances are crystalline", remarks Arkel (1949) p.22. This means that the atoms interpenetrate somewhat until the repulsion forces balance the attraction forces, and vibrate around this equilibrium position. These mechanical oscillators are coupled to each other because any displacement alters the forces between them so that a disturbance is propagated along the array. Owing to several types of forces (Sec.1.2.) one could imagine several "springs" of differing stiffness in parallel, or in more complicated combinations. Planck (1900), p.69, mentions such oscillators, however only "somehow connected with the atoms". Debye (1912) p.790, already identifies the atoms as the masses, and remarks that their lowest frequencies of wibration are those of sound.

The atomic oscillators extend in all directions, and therefore one can expect both longitudinal waves /p.l, Jakob (1949)/ of the soundwave type, and transversal waves of the light-wave type. Since the "masses" are electrically charged particles, and their acceleration changes during the vibrations, they must emit a spectrum of electromagnetic waves/p.100,ibid./ This radiation, since the days of Planck (1901), is assumed to come in packages, quanta, each containing hy units of energy. Thus on the atomic scale, there are no continuous changes of energy; there are only jumps from level to level. Within solids this radiation is absorbed within 1 mm depth/p.26, Jakob (1949)/ and only "a few minerals like salt (NaCl) can be used as windows in measurements on heat radiation". It can excite atoms to forced vibrations of such an amplitude, **that interpenetration** (chemical reaction) occurs, e.g. ignition by lens-concentrated sun rays.

According to Debye (1912) the vibrating atoms influence each other to such an extent that the vibrations are very far from being harmonic, and could be expressed by a Fourier series only (p.790). As an approximation, he assumes that each of the atoms, having 3 degrees of freedom, will have 3 natural frequencies, totalling up to 3N natural frequencies for a body of N atoms with 3N degrees of freedom. On this basishe derives an expression for the specific heat and obtains numerical values, within a certain interval, in good agreement with experimental values. On p.100 Jakob (1949) quotes Debye's expressions for thermal conductivity derived

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on a similar basis in 1914. He also quotes an expression by Bragg "that the advancing region of wave agitation has to fight its way towards the cold end of the body through a fog of waves which it isself produces".

## 2.3. Liquids.

The author's idea of several "springs" in combination is based partly on the fact that the change of state involves latent heat, or an input of energy which goes entimely to the breaking of one type of springs, leaving softer ones intact (liquefaction); next time the latent heat goes to the breaking of next softer springs, leaving only very soft ones intact (the van der Waals forces between molecules of vapour.) The increase of potential energy only, without change in the kinetic energy (temperature), signifies that the molecules in liquid state are at larger distances from each other than in solid state, and removed practically "to infinity" in gaseous state.

From some remarks /p.22, Arkel (1949) one could deduce the x-rays have revealed some structure in liquids. The slowest molecules probably try to assemble again in lattice formation, however they do not succeed very much bacause the fastest molecules do not leave them alone, and break up the clusters.

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In addition to the oscillatory motion there is in liquids some translatory motion /p.190,LMH (1952)/ and therefore some direct transportation of kinetic energy. However this gain seems to be upset by the large general disorder of motion which reduces the importance of the oscillatory mechanism. The springs are weaker and therefore there is less energy in the oscillators. The damping is larger. The heat conductivity of liquids, therefore, is smaller than that of the corresponding solids.

### 2.4. Gases

Direct transportation of kinetic energy is supplemented by drift currents (convection) and a large transparency for radiation except in narrow bands where resonance occurs. Input of energy may result in such large amplitudes of rotation and vibration that "the attractive forces between the atoms in the molecule will cease to be sufficient to hold it together and it will split into atoms or dissociate /p.18, Arkel (1949)/. Later, electrons, having attained higher velocities, may begin to leave the atoms, i.e. thermal ionization may occur.

#### 2.5. Metals

Reference: pp.58-64, Review.

Whether an element displays "metallic" properties depends upon the configuration of electrons in its atoms, especially whether there is an incompletely filled band/p.7, Eshelby (1951)/ into which an electron could jump were a quantum of energy imparted to it. Apparently when no such vacancy exists the quantum of energy would be received by the atom as a whole (non-metals), while otherwise the electron can receive and disburse energy independently from the rest of the atom, except for a recoil (metals). This additional mechanism in metals may "in some cases increase this apparent conductivity by a factor of more than 100"/p.192.IMH (1952)/.

In metals the valence electrons/p.58, Fig.13. S-hockley (1954) / are completely detached from every atom. leaving positive ions behind. Electrostatic attraction keeps the structure intact/p.280, Slater and Frank(1933)/. This theory of an electronic gas in the metals was developed by Drude (1900) applying "the concepts of the kinetic theory of gases", p. 570. He showed how by these means the Wiedmann-Franz relation can be derived, how the Joule'an heat follows from collisions of electrons, discussed the Thomson-effect, the contact potential difference, thermo-electricity, the Peltier-effect, etc. He also assumed that the concentration of free electrons differs from metal to metal(p.611). For copper Coulson (1948) p.77, states the number of these conduction electrons as being about  $2x10^{22}$  per cm<sup>3</sup>, the time -13 between successive collisions as 2 x 10 sec, and the distance between collisions as 2 x 10 cm. He assumes their random velocities about  $10^{7}$  cm/sec, however observes that

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their drift velocity, producing for example a current 2 of one ampere in a wire of 1 mm section, is surprisingly small: of the order of one cm/sec. In the recently developed transistor their number is predetermined by manufacturing methods/p.65, S-hockley(1954)/.

The free electrons, being the sole medium for electric current, explain the striking difference in the possibilities of insulation. If metallic impurities are eliminated, electrical insulators can be made nearly perfect. The ratio of electrical resistivities of silver 12and of quartz glass is 1 : 3 x 10 , while the ratio of thermal resistivities of silver and of air is only 1 : 1.8 4 x 10. This same fact of a single mechanism for electric current and several mechanisms for heat flow explains why the Wiedemann-Franz-Lorenz ratio cannot be a constant. Abnormally large Lorenz numbers are mentioned, p. 113, by Jakob (1949).

Discussing the electrical conductivity of metals, Arkel (1949)p.205, states: "In this connection it is worthy of note that graphite ... has some electrical conductivity which is probably not caused by free electrons... but by the shift **of** the bonds in the layers of carbon atoms, Fig.37."

On the average there is no resultant force on the free electrons by the lattice of the fixed positive ions/p.280, Slater and Frank (1933)/, and therefore they are free to move about, but may not cross the boundary of the metal except when their energy is sufficient for "em-

ission" i.e. exceeds the "work function". Unavoidable or intentional impurities upset the regularity of the metal lattice and offer many stumbling blocks for the Thus an impurity of 0.1% causes the thermal electrons. conductivity of copper, aluminum, nickel, and iron to decrease by about 2 to 3 % /p.111, Jakob(1949), however the thermal conductivity of a single crystal of copper, at -252 C, has been found 23 times greater than that of bulk copper, at -200 C./pp.109,111,ibid./. Annealing, recrystallisation, atomic migration, etc. tend to regularize the lattice, while cold-working, and quenching produce disorder. These effects are demonstrated by Jakob in table 6-23 (p.116, ibid.). One could expect that near the absolute zero there would be little motion of the ions, i.e. widened "corridors", and table 6-18, p.109, ibid. proves it: k for iron is stated, in Btu/(hr. ft F/ft,)as 17.5 at 800 C, 39.5 at 100 C, and 58 at -200 C.

When metals melt, the disorder affects also the electronic conductivity of heat as is evident from pp.115-116, ibid.: the k of liquid eutectic tin-zinc alloy is only 1/3 of the k in solid state.

With liquid metals in circulatory systems, dissolved and entrained gas can dilute the metal, reducing its k /Quittenton, p.10(1952),p.31 (1953)/.

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#### 3. THE MECHANISM OF HEAT TRANSFER ACROSS METALLIC INTERFACES

Reference: pp.58-64, 69-97, 110-118, 122-129a, 132-144, Review Illustrations: pp.95 and 96, Review.

#### 3.1. The Mechanism at the Metal Surface.

Near the surface the heat current becomes distributed between a number of a-spots ending in a monomolecular film, and a corresponding number of valleys where a thicker oxide film may be present, and some fluid would separate the films on the two contact members. An analogy to the first Kirchoff law applies: paths with higher resistance carry less current.

Both the lattice conduction and the electronic conduction suffer a large congestion due to the constriction of the crosssectional area to a small fraction of the apparent area for heat flow. The importance of the constriction resistance is evident from the 16 F temperature 2drop, at approx. 12,000 Btu/(hr ft ), across an aluminumcast-iron bond /p.118, Review/ of which less than 1 F could be attributed to films /p.27, Quittenton (1953)/.

Adsorbed or oxide films grow from the outermost ions of the metal lattice (except that some ions or molecules of adsorbed gas must be skipped due to their nonmatching size/ and therefore a good deal of direct contact still exists, so that the heat conduction along the coupled oscillators meets only a discontinuity in the constants but not an end of the row. Even any skipped ions will have some "springs" attached to the nearest "masses" of the film, in parallel to those of their neighbours. Part of the energy will, therefore, be reflected from this discontinuity /p.156, Slater and Frank (1933)/.

The barrier for the free electrons results from an effect which has some similarity with surface tension. While an electron is to the inside from the last row of ions in the lattice, it is pulled in all directions without a net resultant force. As soon as it tries to sneak out between two ions, it begins to feel their special attraction directed inward, becomes decelerated (pulling the ions somewhat outward), and is compelled to return into the metal. Any near-by atoms of the film would resist penetration and thus help to bring the electron home.

Thus there will be always a number of electrons staying outside of the last layer of ions, forming the negative layer just outside the surface/p.84, Review/, and exerting a pressure similar to gas pressure upon the wall of a container. Possibly the contact potential of two metals is due to the difference of these pressures, or to something like an osmotic pressure. If the electrons are deflected from their paths by a magnetic field, as in a current-

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carrying wire of an electric motor '), they will increase the bombardment on one side of the wire while reducing it on the opposite side, and thus producing a resultant force tending to move the wire. Removal of the deflecting agency will return their motion to randomness; the resultant force would become zero, and the motion of the wire would cease.

Due to the potential barrier for the electrons (except for those which may use the tunnel effect) the path of the electronic conduction merges, at the metallic surface, with the path of vibrational conduction.

It is then mostly vibrational energy, including "radiation", which emerges from the metal. For pure metals /p.45, Jakob(1949)/ the total radiation has been found to increase with the 5th power of the absolute temperature. Since it is absorbed in metals within a depth smaller than the wavelength /p.26, Jakob (1949)/(which for infrared radiation  $^{-5}$  is between 0.3 cm and 7.6 x 10 cm), it may emerge already from a few atomic layers underneath the surface.

There are several electric effects at metallic surfaces and interfaces, such as photoelectric emission, thermionic emission, thermoelectric effect, contact potential, Nernst voltage, etc., however they do not seem to make appreciable contributions to heat transfer. At interfaces carrying an electric current (e.g. electric welding) there is a Peltier effect and a Thomson effect. Holm (1946)pp.32-34,

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<sup>)</sup> Prof. R.A. Chipman mentioned to the author that a question had arisen during a discussion, what is the fundamental mechanism of the electric motor. This opportunity is used to present an attempt of explanation.

discusses their influence on electric contacts.

The Wiedemann-Franz-Lorenz relation has been found valid also for liquid mercury, with a small discontinuity at the melting point/p.331,Holm(1946)/. This signifies that the electronic conductivity of heat is present also in liquid metals.

As the liquid metal is able to fill, if under pressure, the valley s of the roughness, the constriction effect will be much smaller. Any monomolecular film on the solid member will definitely prevent wetting (pp.139, 142, Review) until it is removed by some means. It will however let some electrons pass, by the tunnel effect.

Obviously there would not be any crushing of roughness peaks of the solid member by the liquid metal nor any local squeezing of its oxide film, except any changes occurring from corrosion or abrasion. The film on the liquid surface would however be broken up when the liquid starts to penetrate the valleys of the roughness. Therefore on the solid metal side the film would be comparatively thick, with possible clogging of the valleys by the film material from the liquid metal if the latter is in motion. This would prevent any tunnel effect from taking place.

On the liquid metal side the breaking of the oxide film would open up clean metal surface. Were there any gas in the system, adsorption and oxidation would soon

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mend the film, but its thickness would differ from place to place. The vibrational energy thus finds a discontinuity worse than on the solid member, but the electronic conduction has a little better chances.

The only remaining cause for some resistance at a perfectly wetted interface is the nonmatching of the ion lattice and the rudimentary, if any at all, lattice in the liquid metal, as well as the large general disorder of molecular motion. The first discontinuity effect will cause the reflection of some vibrational energy, and the second discontinuity effect will cause many free electrons to rebound.

## 3.2. The Mechanism Within the Film.

The electronic conductivity would not continue into the film were it absolute non-conductor of electricity (which would prove absence of free electrons). It is known however[that oxides do conduct electricity to some extent; apparently they contain some metallic impurities which provide some free electrons. (In an analogous manner the impurity of one atom of arsenic in 100 million atoms of germanium makes a transistor/p.65, S-hockley(1954)/). Therefore usually some "channels" will be present in the film along which the electrons could proceed, although with some difficulty.

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The two monomolecular films at the a-spots would provide "channels" for the electrons on a different basis: The vibration of their molecules may at times be in opposition of phase, and the resultant larger separation may reduce the height of the potential barrier so that electrons may leak through by the tunnel effect, and reach the other metal. In thicker films this effect could happen if a larger separation of molecules would occur, by chance, simultaneously in all molecular layers involved.

The vibrational conductivity would be the main channel for heat transfer across the film.

The thermal conductivity of oxides is very much lower than that of the corresponding metals. Magnesium metal, at 400 F, has a k = 85 Btu/(hr ft<sup>2</sup> F/ft) /p.3-14,Kent, Power (1950)/, and magnesite (mostly MgO) at the same temperature has a k = 40 Btu/(hr ft<sup>2</sup> F/in)/p.3-37,ibid./. The ratio is 25.5 : 1 . Chromium has a k of 0.165 gcal/ (sec cm<sup>2</sup>C/cm) /p.1-143,Eshbach(1952)/ which corresponds to 39.9 Btu/(hr ft<sup>2</sup> F/ft). For Gr<sub>2</sub>O<sub>3</sub>Quittenton uses k=1. The ratio is 39.9 : 1. Besides he has calculated a 0.03 F temperature drop through such a film of 5,000Å thickness, at 20,000 Btu/(hr ft<sup>2</sup>). On p.25 he states the thickness of an oxygen film (one chemisorbed atomic layer with an adsorbed molecular layer on top) as 3.8 Å, assumes its k=0.02, and obtains a 0.0012 F temperature drop through

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it, at the same 20,000 Btu/(hr ft).

Radiant energy emitted by the metal surface will not be absorbed very much within the film as the thickness of the latter would be small compared with the 1 mm depth for complete absorption /p.26,Jakob(1949)/. The emissivity (and the absorptivity) of the film substance itself would be several times higher than the emissivity of the clean metal surface, as can be seen from tables 7-2 and 7-4, pp.123-125 of Jakob(1949) who remarks that "heavily oxidized and very rough surfaces approach the behaviour of the black body".

# 3.3. The Mechanism Across the Interface.

The two monomolecular films meeting at an a-spot would not have an exactly matching structure, however the high local pressure would bring the molecules into a very close contact. Therefore it would seem that only insignificant discontinuity would exist between them, and it could not add much to the resistance presented by the films themselves.

Within a small distance of an a-spot the films would usually separate and hold some fluid between them. Assuming that the a-spots constitute 1/10,000 of the apparent area of contact and the remaining 9999/10,000 would hold the fluid, the effects of conduction would be of equal order of magnitude if the thermal conductivity of the metal would be 9,999 times

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that of the fluid. Comparing steel with oil and air, for example, we find, in  $Btu/(hr ft^2 F/ft)$ , 26, 0.10 and 0.044 respectively, or as 2,600 : 10 : 1.4. Thus the effect of conduction through the fluid is fairly important.

Convection within the voids would be possible if the interface would be vertical, or the hotter half of a horizontal interface would be at the bottom. Cell sizes between 1/64 and 1/32 of an inch /p.88,Jakob(1949)/ have been instrumental in obtaining lowest conductivity of Styro-foam. The roughness voids would be much smaller, so that no convection effects could be expected.

Radiation across the voids can become substantial, because of the 4th-power dependence on the absolute temperature (5th power for pure metals), if the temperature at the interface is high, and also because the usual fluids filling the voids would be transparent for it. An exception would occur if the fluid would have strong absorption bands within the region, so that by resonance with the frequencies of the interatomic oscillation and of molecular rotation /p.52,Jakob(1949)/ the amplitudes of the forced vibration would reach (nearly) maximal values, causing considerable absorption of energy. It would, however, be only a detour of the energy flow, as the absorbed energy would become distributed between the molecules within the enclosure and therefore would finally reach the cooler side.

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Should the voids of the interface be filled with a liquid, its fairly good thermal conductivity would reduce the overall thermal resistance a good deal /p.lll Review/. The mechanism of absorption of radiant energy, probably, would differ somewhat from that described for gases (if at the high temperature the liquid would not have boiled away) because there would be much higher damping of molecular rotation and vibration, and no narrow resonance bands could be expected.

With liquid metal as one member, and without wetting, the surface tension of the liquid metal would keep it out of the roughness valleys unless there would be a hydrostatic pressure. Then any gas in the pockets would be compressed to a layer of smaller thickness and of smaller area, as the liquid metal would drive it into the bottom of the valleys. The conductivity of a solid-liquid interface would thus be increased slightly by pressure. Changing the blanketing gas and making observations (p.142, Review) of the change in the heat transfer rate, one could estimate the amount of gas staying in the pockets. The same effect of reducing the volume occupied by gas would increase the area of the interface touched by the liquid, and this would mean a considerable increase of the overall conductance, particularly with well conducting liquid metals.

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With flowing liquid metals there would be a tendency to fill the valleys of roughness with the oxides covering the liquid metal, however that would mean some improvement against gasfilled valleys.

At the interface between the film and the fluid in the voids, the mechanism would not include electronic conduction unless the fluid is a liquid metal. A transfer of vibrational energy would occur as well. Of course the electronic conduction can occur only if there is a tunnel effect in the film.

Vibrational energy would cross this interface also with other liquids in the voids, however little of it could be transferred to gases in this form. The vibrating molecules of the film would rather impart to the molecules of the gas some translatory motion with some rotational motion superimposed if the molecules would have the dumbbell shape or a similar one.

Would there be perfect wetting of the solid metal by the liquid metal, there would not be any voids, and the only effect on the Mechanism would be the discontinuity of atomic properties of the metals which would cause a reflection of a part of the energy transferred both by the mechanism of coupled oscillators and by the mechanism of the electronic gas.

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#### 4. CONCLUSIONS.

Single crystals may have thermal conductivities about 20 times as large as bulk metal (p. 23 ). Therefore metals should be used in pure and annealed state, to obtain better electronic conductivity.

The constriction resistance (p. <sup>24</sup> ) seems to be the largest component of the thermal resistances at interfaces, and should be eliminated, as far as possible, by these means: a) Reduction, by finishing methods, of the roughness and of the waviness of the surfaces; b) Cleaning, and wetting of the surfaces with a layer of mercury, lead, tin, cadmium, or other soft metallic protective coating. The evasive mercury would, probably, facilitate the squeezing out of intervening gas, when the members are assembled. Evacuation of the joint may be helpful; c) Exclusion of gases from liquid metal systems, by the use of a membrane to take care of thermal expansion, a preceding heating and evacuation of the system, and the use of wetting agents.

The thermal resistivity of oxide films is about 30 times, and of gas films - about 2000 times, as large as that of the metals (p. 31). Although the films are thin, in cases of constriction the small cross-sectional area

may cause objectionable resistance. Non-immersed thermometer

bulbs need, therefore, tinfoil wrapping etc. to increase the area for heat flow. Thermocouples can be profitably welded in position by condenser discharge.

(For spot-welding and condenser-discharge-welding the existence of oxide films is advantageous because then more localized Joulean heat is developed.)

The temperature drop across the usual oxide films is small, and the smooth surfaces of experimental tubes do not provide any pockets for an accumulation of thick layers of oxides. Therefore non-wetting conditions alone cannot be responsible (p.139, Review) for the 29-40 % lowerthan-predicted heat transfer coefficients. Quittenton's explanation that entrained and dissolved gas "dilutes" the liquid metal, reducing its k , awaits direct experimental confirmation.

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## APPENDIX I

A Test of Thermometer No. 45953.

The cooling rate of a Parr Peroxide Bomb Calorimeter was observed by R. Putnaerglis on February 26, 1952, without disturbing the thermometer. Mixing was continuous from 12.55 to 13.55, and intermittent at other times. Room temperature rose from 72.95 F to 73.55 F (at 13.24) and then dropped to 73.48.F.

Time	Temperature, F	Time	Temperature,F
12.27	78.93	13.10	78.65
12.34	78.89	13 <b>.12</b>	78.64
1 <b>2.</b> 37	78.84	13.145	78.60
12.40	78.83	13.16	78.60
12.425	78.815	13.18	78.60
12.435	78.81	13.20	78.58
12.47	78,79	13.215	78.58
12.475	78.78	13.24	78.56
12.54	78.75	13.27	78.55
12.55	78.74	13.295	78.53
12.575	78.70	13.315	78.51
12.59	78.70	13.35	78.50
13.00	78.70	13.40	78.45
13.02	78.69	13.45	78.42
13.04	78.68	13.48	78.40
13.06	78.65	13.52	78.39
13.08	78.65		



### A Review of Literature on Heat Transfer Between Metals in Contact and By Means of Liquid Metals

Part I - Heat Transfer Between Metals in Contact

Gas Dynamics Laboratory

Report No. R. 34

By

R. Putnaerglis

Department of Mechanical Engineering McGill University, Montreal

February 1, 1953

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File No. 215 - 1 - 12.

#### PREFACE

Part One of this Review appears as a separate Note in order to let it reach the readers as early as possible.

Since the emphasis was on Sodium for Heat Transfer, no effort was spared to locate and obtain as many publications on it as possible (most of them never arrived). As became apparent on Dec. 2, 1952, (when at last the Liquid Metals Handbook was received), the writer had been searching the needle in a haystack. He has found two needles (the 3 papers on heat transfer by sodium listed in the LMH pp. 211-212 and 5 more, not listed by LMH) at the expense of finding and recording by number, subject, and alphabet some 700 publications on heat transfer

This expense of time limited the span available for writing the Review to less than two months, and will partly explain its imperfections.

The temporary reference numbers are preceded by a space reserved for the final numbers from the alphabetical list of references. Since this list was not complete when the cutting of stencils for Part I was finished (in fact, References No. 1296 to No. 1502 were recorded after the official end of the work on Sept. 30, 1952), the final numbers will have to be inserted later.

The advice of Professor Mordell, to list the pertinent references at the end of each chapter, with the general bibliography at the end of the Review, could be followed only to the extent of splitting the then existing list into 15 separate lists (partly overlapping) without attempting to shift less pertinent references to the general bibliography. ii

From the literary point of view many inefficiencies will be found in this work: abrupt changes, inconsistencies, repetitions, reference to later pages written earlier, long quotations, unfinished chapters, double entries of identical references, etc. etc. However, the writer's feeling was that it is more important to collect more of the necessary information that to iron out the defects remaining after insertion of later material.

The writer is still busy bringing in at least part of the material collected. However at this time (February, 1953) the chapters on mercury, lead-bismuth, and lithium still remain unwritten. and, of course, "of making many books there is no end" (Eccl. 12, 12).

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Deep gratitude is expressed to all the libraries for fine cooperation and generous borrowing privileges. Most of the pertinent publications have been borrowed from the Atomic Energy of Canada Ltd. Library. The following libraries have been visited (especially McGill libraries) in search for material (alphabetically):

Canadian Industries Limited Library,

Ecole Polytechnique Library,

Engineering Institute of Canada Library,

Fraser Library,

International Civil Aviation Organization Library,

McGill: Engineering Library,

Gas Dynamics Laboratory Library, Macdonald College Library, Physical Sciences Centre Library, Redpath Library Mechanics Institute Library,

Montreal Municipal Library,

National Research Council Library (through Interlibrary Loan) Université de Montréal Library.

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# ABBREVIATIONS

The following expressions have been, at times, abbreviated:

Heat Transfer	to	H Tr
Nuclear Reactor	Π	NR
Submarine Intermediate Reactor	Ħ	SIR
Breeding Nuclear Reactor	n	BNR
Nuclear Fuel	Ħ	NF
Temperature	TT .	to
Liquid Metals Handbook	Ħ	LMH

#### ABSTRACT OF PART I

In the Introduction some nuclear processes are discussed which have a bearing on heat transfer problems in nuclear reactors, where both metallic interfaces and liquid metals often are in the path of the heat flow.

The Mechanism of heat transfer across an interface is discussed on the basis of atomic structure. The electronic conduction of heat within the metals, and the absence of it in the non-metallic films of oxides, adsorbed gases, etc. is emphasized.

The three theoretical treatments of heat transfer across contacts by Alcock, Karush, and Cetinkale & Fishenden, are discussed and compared. Experimental methods are discussed and numerical results of experiments listed. Roughness of the surfaces in contact is discussed and found to be the obstacle to correlation of results and prediction of performance, until an adequate method of designating the surface roughness is developed. Contamination of surfaces is found to provide the reasons for some unexplained observations.

Some casual notes on rubbing contacts bear out the importance of knowing the physical condition of the surfaces in contact.

Discussion on solid-liquid metal interfaces is centered around the wetting of solid metals by liquid metals. Here again perfect cleanliness (including removal of oxides and adsorbed gases) is generally found to assure wetting and consequent reduction of thermal contact resistance. Experimenters, however, report contradictory results, so that Liquid Metals Handbook (p. 207 of 2nd ed., June 1952) recommends to divide the predicted h by approximately 2.

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#### Introduction

The two problems, a) and b) above, obviously are the two parts of the general problem: How to extract efficiently the heat generated in the NR (Nuclear reactor).

Two examples are: a) Uranium fuel rods are in contact with aluminum sheaths or cans (p. 146, /1211); b) liquid sodium is a practical heat-transfer medium to remove heat from the SIR (submarine intermediate reactor) power reactor, transfer it to steam and hence drive a turbine ( /973).

Some aspects of the processes in a NR (Nuclear Reactor) will now be discussed, as far as they have a bearing on heat transfer.

A number of writers go into detailed considerations of the general problems of nuclear power, for example Daniels ( /1201) Goodman ( /1209), Ohlinger ( /1202), Koshuba ( /1177), Cockcroft ( /1204) etc.

Special manuals have appeared, like: Manual of Pile Engineering ( /1203), Liquid Metals Handbook ( /958) etc. Others discuss the heat transfer problems in connection with NR's, for example: Lyon ( /800), Gilliland ( /1143) Bonilla ( /1111) etc.

320 abstracts on Heat Transfer, mainly from Nuclear Science Abstracts, have been reprinted in TID - 3022 ( /1226). <u>Heat Production</u> in a NR is somewhat peculiar. Heat in a NR is a byproduct of a nuclear reaction known as "fission" (p. 347 /1199) which remotely resembles combustion or explosion.

From the point of view that it is generated within the metallic (not necessarily) fuel, it bears resemblance to the generation of heat in electric resistances.

<u>Fission</u> may occur when a neutron of appropriate speed enters the nucleus of the NF (nuclear fuel), for example of 92 U 235 or 94  $Pu^{239}$  or 92 U<sup>233</sup>, and causes a great perturbation, the theory of which was developed by Bohr and Wheeler (p. 353 /1199), picturing the nucleus, as a drop of liquid held together by nuclear short-range forces, and acted upon by long-range Coulomb repulsion forces, which finally succeed in splitting the nucleus.

According to Heisenberg (p. 122 /1200), when a 8 Mev ("fast") neutron hits a nucleus, the kinetic theory of gases predicts an increase in its temperature by about ten thousand million degrees centigrade. If the nucleus is thought of as a drop of extremely hot liquid, set into violent vibration, the idea of evaporation lends itself, i.e. the drop will disappear and fast moving smaller particles will emerge from this point. Observations have shown that  $U^{235}$  splits into two nearly equal heavy fragments and emits from one to three neutrons (pp. 352-353 /1199).

The total weight of the fragments is less than the weight of the nucleus plus the neutron. According to Einsteins equation  $E = M C^2$  (p. 24 /1199) the deficiency of mass appears as an excess of energy, roughly 200 MeV or 200 X 4.45 X 10<sup>-20</sup> kwh = 8.9 X 10<sup>-18</sup> kwh (p. 17-03 /1227).

The fragments depart from each other with very high velocity, pushed by Coulomb repulsion forces. Collisions with other molecules serve to slow them down and distribute their energy among all participants, thus raising the temperature of the NF.

According to Feld ( /1207), at a power of one watt,  $3 \times 10^{10}$  U<sup>235</sup> nuclei undergo fission each second. In one year, the consumption at U<sup>235</sup> is  $3 \times 10^{10}$  X  $3.15 \times 10^7 = 9.5 \times 10^{17}$  atoms per year per watt. Since the total number of U<sup>235</sup> atoms in the pile described is  $6.4 \times 10^{25}$ , the rate of depletion of U<sup>235</sup> is 100 X  $\frac{9.5 \times 10^{17}}{6.4 \times 10^{25}} = 1.5 \times 10^{-6}$  % per year, per watt.

Etherington (p. 1275 of /1217) points out that nuclei account for only  $\sim 10^{-14}$  of the total volume occupied by matter. Thus they are exceedingly small targets and neutrons can move through matter with considerable freedom. The geometrical cross-section area of a nucleus is approximately  $10^{-24}$  cm<sup>2</sup>. For comparison of nuclear reactions (some of which occur more often than others)  $10^{-24}$  cm<sup>2</sup> has been made a unit, one barn, and the nucleus is given a fictitious target area, in barns, that a neutron would have to hit in order to effect a particular nuclear reaction. It may be smaller or larger than the geometric area.

The two or three neutrons released in the fission process are extremely important. They are responsible for the sustaining of the chain reaction (p. 388 /1199) started by the first stray neutron hitting a  $U^{235}$  nucleus. As few as possible should be lost in a NR<sup>\*</sup>. Neutrons are not only escaping through the surrounding matter (which is surprisingly empty) if they happen to proceed without coming too close to other molecules, but they are also captured by those molecules which happen to be in their way, like flies on a sticky flycatcher. The chances for a neutron to be captured are pictured by ascribing the nuclei smaller or larger cross-

\* Fortunately they are lost in the natural deposits of U. Thus, a chain reaction is impossible in a Uranium mine. Moreover, no atomic bomb can produce a chain reaction in the surroundings.

sections (different from their geometrical cross-sections) in funny units: "barns". Thus, the extreme probability that a nucleus of gadolinium will capture a thermal (1/30 ev) neutron is pictured by ascribing to Gd a nuclear cross-section of 38000 barns, the acceptable probability for sodium - as 0.5 barns, the desirable probability for carbon - 0.0045 barns, and the undesirable for iron - as 2.5 barns. Cadmium, with 2500 barns, therefore is popular for control purposes. (pp. 17-18 and 17-19 of /1227). This peculiarity of NR imposes heavy restrictions on materials for heat transfer purposes.

However, a material unacceptable in a NR "operated" by thermal neutrons may prove to be suitable for use in a NR where neutrons of different speed are employed. For example, mercury is unsuitable for a thermal NR, however can be used in a "fast" NR. ( /1202).

Materials for NR's had to be chosen with respect to several viewpoints, and particularly that of neutron capture. At the same time other properties of materials were checked for, possibly, a different range of temperatures, different applications, corrosion, etc. New materials were developed for specific needs.

The metal requirements for NR's are discussed by Koshuba & Calkins (p. 97 /1177).

Cockcroft ( /1204) draws attention to the fact that in the "fast" NR's the materials are subjected to much more intense irradiation than in the graphite-moderated reactors.

Flagg ( /825) describes some effects of irradiation on materials.

The selection of materials for heat exchangers in NR is Limited very much by their interaction, corrosion, which is favored by the comparatively high temperature.

First of all the NF itself must be protected from corrosion by the coolant. Smyth ( /1211) describes the search for a suitable sheath, or can, for the metallic uranium, to keep the coolant out and the fission products in, including the gases.

He mentions also research on corrosion-resistant alloys of Uranium, much on the same lines as with stainless steel.

A special investigation of materials for use in heat transfer systems containing molten lead alloys has been conducted by Shepard, Parkman, Lewis and French:

Ref. 308 /1226,

Ref. 306 /1226, on stress-corrosion attack by Pb-Bi eutectic Ref. 309 /1226,

Ref. 307 /1226, on unstressed corrosion tests; stress-rupture tests of Mo, Ta, Nb, and type 446 stainless steel at 1500°F; solubility of Fe and Mo in molten Pb; wetting of solid metals by molten Pb and Bi.

The solubility of metals and alloys in lead-bismuth eutectic, up to 2200°F, has been investigated by Collins & Stephan ( /1009), and in pure Bismuth by Collins ( /1010).

Static corrosion tests have been conducted by Everhart & Van Nuis: ( /1026), (Ref. 7 /1226), (Ref. 8 /1226). Volumetric changes of the Pb - Bi eutectic upon freezing have been determined by Everhart & Van Nuis (Ref. 7 /1226).

Thermal conductivity has been investigated:

Theoretically by Loeb (Ref. 180 /1226)

" by Trice (Ref. 232 /1226)

of 347 stainless steel and of Zirconium by Vianey (Ref. 182

/1226)

of pure  $Al_2O_3$ , by Norton et al. (Ref. 190 /1226) of sintered  $Al_2O_3$  and sintered MgO, by Norton (Ref. 191 /1226) of 18 materials, by Schwartz (Ref. 234 /1226) of Be<sub>2</sub>C by Trice, Neely & Teeter (Ref. 233 /1226) of liquids at high pressure, by Lawson (Ref. 75 /1226) of gases, by Lindsay and Bromley (Ref. 290 /1226) of gas mixtures, by Lindsay and Bromley (Ref. 289 /1226).

Thermal diffusivity (named by Kelvin; Maxwell's name for it is "thermometric conductivity") of refractory oxides was measured at 1400°C by an unsteady-state method, based on a radiation boundary condition, by Levine (Ref. 3 of /1226).

High thermal gradients cause high thermal stresses. Theoretical investigations have been made:

for common geometrical configurations - by Carter (Ref. 25 /1226) for split hollow cylinders - by Karush & Monk (Ref. 29 /1226) for long thin-walled cylinders - by Horvay & Manger, (Ref. 129 /1226) for infinitely long solid cylindrical rod - by Duffy (Ref. 279 /1226)

There is a peculiarity with NR's found to a slight extent only in foundries (and then only a matter of time and not of danger): During construction the NR is not dangerous (besides the toxicity of Plutonium). Once the chain reaction is started, and the highly radioactive fission products accumulate, the NR gets so "hot", in the sense of radioactivity, that extreme shielding by fathom-thick concrete walls, and remote controls are necessary to handle a fuel element, or a pipe from a primary heat exchanger. In addition a cooling time of 100 or 200 days may be necessary (p. 11 /825). To avoid such trouble, a heat exchanger for a NR has to be <u>designed</u> for trouble-free service of 10 years, or so.

2

Instead of visible light, produced in every furnace, extremely dangerous invisible radiations fill the NR and its vicinity. Nuclear forces are so much stronger than chemical valence forces, that the produced "light" is of extremely short wavelength, or of very high frequency. According to Planck, light comes in packages, or quanta, whose energy The fundamental Planck constant  $h = 6.6 \times 10^{-27} \text{ erg sec}$ is E = h v. /1199), and  $\vee$  is the frequency. The frequency of the (p.3  $\chi$ -rays, radiated from a NR, is about a million times higher than the frequency of visible light. No wonder then, that it hits a million times harder than, say ultraviolet light (which may produce dangerous sunburn). Walls many feet thick are necessary to protect the personnel.

The very difficult servicing of the primary heat exchangers in NR's requires extremely careful design. Within, say, 10 years of service no leaks should develop, no fouling of tubes, no scale deposit, no rust, no corrosion, no bursting of pipes in freezing weather, no explosions, no fires, nothing!

Although the temperature within the bounds of one fissioning nucleus reaches literally astronomic figures, an astronomic number of fissions is needed to produce a macroscopic effect: according to Flagg (p.8 /825) 3.1 X 10<sup>10</sup> fissions would release energy equivalent to one watt-second.

Dr. Flagg states (p. 8 /825) that the complete fission of one gram of  $U^{235}$  would release 24000 kwh, equivalent to the energy produced by the combustion of 3.3 tons of coal. Unfortunately not even in 10 years, all atoms of this one gram of  $U^{235}$  would be fissioned because the rate of fission must be kept comparatively low to prevent the temperature from attaining a dangerous level. (Only in the atomic

bomb the rate is uncontrolled and therefore the more or less complete fissioning takes place in less than one microsecond.)

Still more than unfortunate is the fact, that even complete fission does not release all energy available in the NF. The 200 Mev released correspond to about 1/5 mass unit of which there are 235. It looks like <u>burning 235 pounds of coal to 234 -4/5 pounds of ashes</u>!

<u>Nuclear</u> reactions thus evolve roughly one <u>million times more</u> energy than the same amount of matter in <u>atomic</u> (commonly known as "chemical") reactions, which involve only changes in the electron configuration of the atoms (p. 151 /1200).

In other works, the same amount of heat can be generated in one million times smaller "combustion chamber".

Nuclear heat is extremely concentrated.

Gilliland ( /1259) develops equations for H Tr from NR's and applies them to a NR of 10000 horsepower, or 100 000 000 Btu/hr, of ten feet on a side of the cubical form, assuming a temperature difference 1200 - 300 = 900°F.

AERE ( /1299) probably has released some figures on the quantities of heat available in NR, however the abstract available gives no data.

The abstract of Lucke's report ( /1298) mentions an air flow of the general order of 1 000 000 to 1 250 000 lb/hr, between 400 and 500°F, transferring 100 000 000 Btu/hr to water and steam in the boiler.

The actual rates of heat generation are recorded: by Cockcroft ( /1204) as  $\sim 200$  Kw per ton of U at a normal power level of 4 Mw, by Isbin (p. 13 /1249) as 3800 Kw for Oak Ridge NR, as  $\sim 1000$  Mw for Hanford NR. Cockcroft has proposed a rate of heat generation of one Megawatt per ton, or a consumption of 1 gram of  $U^{235}$  per ton U per day, which in 30 years, at 50% operating time, will produce a burn-up of 1% of the total U fuel.

Bonilla (p. 10 /1111) considers the local <u>rate of heat</u> <u>generation</u>: "It may be assumed that in a uniform rectangular nuclear reactor (taken as an infinite slab for simplicity) without reflector, the local rate of heat generation follows a cosine curve, as illustrated<sup>a</sup>.

He, and other authors, mention different other curves for other configurations.

Ohlinger (p.55 /1202) mentions reflectors and variations in fuel arrangement as means of flattening the cosine curve to obtain better uniformity in heat generation.

The safe rate of heat generation in a NR is dependent upon the capability of structural materials, including the NF, and its sheath, to stand high temperatures. Otherwise the <u>NR could produce any tempera-</u> <u>ture desired</u>, up to the millions of degrees attained in **an atomic bomb**.

Therefore the field of high-temperature materials is the one hinge on which the problem of nuclear power could swing into efficiencies unattainable by any other processes.

Actual operating temperatures are stated: by Cockcroft ( /1204) as 200°C at the surface of the fuel elements

by Isbin (p. 13 /1249) as below 245°C for the Oak Ridge NR,

as 125 to 175°C at experimental

openings of the Brookhaven NR,

as 39°C for LOPO

as 185°F for HYPO

#### as 80°C for Raleigh NR

as "liquid metal used for cooling" for SIR.

Davidson (p. 124 /1300) mentions more temperatures of operation of NR:  $535 \circ R = 75 \circ F$  for water cooling,

750 °R = 290 °F for air cooling,

1 000 °F for steam turbines,

1 500 °F for gas turbines,

and remarks that the rate of reaction does not depend on the temperature in the NR (except through the way of influencing the density of materials).

In addition to special controlling devices, the thermal expansion of the NF with rising temperature produces a slight "automatic regulation" of the rate of fissioning, as the number of molecules in a given volume decreases, if the NF expands, and thus somewhat less heat is generated if the temperature rises.

As a possible temperature of sheathing surface Cockcroft ( /1204) mentions  $350 - 400^{\circ}$ C with aluminum cans for the protection of the NF, and higher temperatures with zirconium or beryllium cans.

The melting temperature of Uranium, about  $1125^{\circ}$ C, does not seem to constitute a temperature limit for NR, as compounds of U of the refractory type are known and Isbin (p. 14 /1249) states that the French NR uses sintered uranium oxide compressed to bars of density 8.4.

Some fear of unexpected temperature distributions reflects itself in the mathematical treatments of heat conduction out of the NF, especially in the earlier ones:
Ref. 280 of /1226: The temperature as a function of space

and time in the exterior cylinder (sheath or can) is determined. Ref. 25 of /1226: The equations for temperature distribution

are developed for the most common geometrical configurations.

Ref. 41 of /1226: temperature distribution surrounding coolant holes in a heat-generating solid.

Ref. 21 of /1226: Upper and lower bounds for the temperature rise under a rib are obtained for both a coated and an uncoated object (NF rod) with surface cooling.

Ref. 16 of /1226: ... owing to these end discs the coating (of the NF) will carry an extra thermal load at the area of conjunction between the discs and the coating.

Ref. 18 of /1226: Thermal contact with a semi-infinite slab is made along a strip next to the boundary. The thermal conductivity of this configuration is computed....

Ref. 23 of /1226: The effect of drawing off heat on one side of a corner.

Ref. 17 of /1226: Temperature rise under uncooled areas of thin plates.

Ref. 27 of /1226: Temperature rise in a heat producing cylinder under a coating defect.

Ref. 22 of /1226: Temperature rise in a pitted surface.

The situation is described by Lyon (p. 308 /800): "... the melting point of uranium is listed as less than 1850°C. Actually the melting point is about 1125°C. Thus we not only did not know how hot the uranium might get in a reactor, but we didn't even know how hot we could allow it to get. This situation is repeated each time new materials are proposed for use in reactors".

There must be some really high-temperature work going on because the Atomic Energy Commission of the USA has had astronomers like Whipple (AECU - 705 = Ref. 97 /1226) work out radiation problems, and specialists like Hottel (NEPA - 979 = Ref. 249 of /1226 = 1283) give lectures on geometrical problems in radiant heat transfer. Likewise the National Gas Turbine Establishment of Great Britain has been concerned about radiation heat transfer (Ref. 220 /1226).

The fact that the <u>heat</u> in the NR, using metallic NF, <u>emerges from</u> <u>a metallic surface</u>, and not from a flame as in ordinary furnaces, reduces very substantially the unavoidable temperature gradient necessary for the heat flow. While in a furnace the laminar gas film on the heating surface may have a resistance to heat flow as high as 300 times the resistance of the boiler wall (p. 85 /792), the contact resistance from the fuel to the sheath, for example, may be equivalent to the resistance of the sheath, and the resistance of the laminar film of a liquid metal may be even smaller than the resistance of the wall.

The form and size of a NR would affect the H  $T_r$  characteristics of it because it would alter the surface to volume ratio.

The first pile was of a door-knob shape (p. 239 /1211). Other forms have been: cubical, cylindrical, spherical, etc.

A number of writers have considered problems in connection with the form and size of NR, for ex. Ref. 94 of /1226, Ref. 251 = 1285, Ref. 34 ibid., Eckert /1124; Ref. 311 of /1226; Ref. 312 ibid.

Cockcroft ( /1204 ) states that a NR can be designed to operate in a two-gallon drum, and that the limit to the core diameter

will be set in fact largely by the need to extract about 50 - 100 MW of heat from the core.

Goodman ( /1209) describes several types of NR's, such as: homogeneous, heterogeneous, etc. He mentions solid fuel mixtures, U or Pu alloys of low melting point, U or Pu compounds in solution,  $UO_2$ ,  $UC_2$  or  $US_2$  slurries, gaseous mixture of  $UF_4$  and  $F_2$ , etc.

A number of design examples of nuclear reactors can be found in:

Smyth pp. 60 and 142	(	/1211)	Chicago and Clinton
Sargent	(	/835)	Chalk River
King	(	/836)	HYPO and SUPO
Boer	(	/837 )	Norwegian - Dutch
Isbin	(	/1249)	"A catalog of NR's"
Iron Age	(	/1004)	A low cost NR.

Pulsed Nuclear Reactors are mentioned in Ref. 34 of /1226 by Lodge. Probably pulsing is used for the same purpose as with pulsed radio-transmitters: to attain a very high power level, which the device would not be able to stand permanently.

It would be interesting to know what kind of nuclear power plant did the Germans have, near the end of the war, of which Dr. Graue tells in the "Weser-Kurier" ( /1301) that it was operating (".... Atommaschine lief").

The concentration of heat production in NR depends upon the <u>NF</u>: whether it is fissioned by slowed down neutrons, or by fast neutrons as produced in the fission process. The former NR are voluminous by necessity, involving a large quantity of a moderator, and thus making the removal of heat easier. The latter are small, even a tiny sphere of about one foot in diameter (p.40 /1202), containing hardly any moderator at all, and in them the concentration of energy may go very . much higher, reaching the peak in the atomic bomb.

The "fast" NR may have a considerably reduced size, as compared to the "thermal" NR however this makes the extraction of heat more difficult, because of the smaller surfaces available.

Should the NR be used for power production purposes only, the geometry of the fuel elements could probably, be shaped to best suit the heat transfer problems, for example as tubes cooled both from inside and outside, or as sheet-metal having a large surface-to-mass ratio.

Cockcroft ( /1204) points out that heavy water brings down considerably the size of the NR, compared to graphite as moderator, however to permit sufficiently high temperatures of operation, the tank should be pressurized and the heavy water circulated through a heat exchanger.

The physical appearance of the apparatus for removal of heat from a NR depends very much upon the form and size of the lumps of NF or other kind of distribution of NF inside the NR. The NF can be solid, liquid, or gaseous; the NR can be thermal, involving much of moderating material, intermediate, requiring some moderator, and fast, without moderator at all; there may be a reflector, etc. Thus, a great number of different combinations can be envisaged. The following examples cover only a few.

In principle there is no difference whether the atoms of the NF are the constituents of a solid, liquid, or gas, provided they are amassed in such a form and quantity that the "critical mass" is reached, id est the chain reaction can sustain itself by producing sufficient fresh neutrons to replace those spent in fission and lost by diffusion or capture. (This process resembles somewhat the feed-back in vacuum-tube oscillators.)

It is interesting to note, that for heat extraction purposes many ingenious designs have been proposed with reference to the NF (p. 14 /1202): for example: rolling NF balls, moving NF chains, moving NF tapes, rotating NF discs or wheels, reciprocating NF rods, dissolving the NF in a liquid metal, preparing a NF slurry, to be circulated, etc.

One of the many forms of solid NF is spherical, randomly packed, leaving sufficient space between the spheres for the passage of the cooling fluid. Ref. 313 of /1226 gives experimental results and some theory. Ref. 14 of /1226 proposes an equation for the heat transfer between a sphere bed and a liquid coolant.

Ref. 244 of /1226 = 1277 mentions some experiments with granular materials and theory, including design charts for use in predicting heat-transfer rates to solids flowing in a settled condition inside vertical pipes.

When Uranium is used in metallic form as NF, it has to be protected from corrosion (and the coolant should be kept separated from the highly radioactive products of fission) by a sheath or can, most often of aluminum.

In addition to film heat transfer coefficients, contact heat transfer coefficients are involved at the interface of U and Al.

Ohlinger (p.45 /1202) mentions that oxides and carbides of the fuel metals are refractory materials and thus would permit operation of NR's at elevated temperatures, if the other structural materials would be able to withstand them safely.

From Jaffee's ( /1191) paper on gallium as a liquid metal in the NR "of the thermal type, either as a primary H.Tr. medium or as a solvent for Uranium..." one can deduce that it has been considered to prepare an alloy sufficiently rich in uranium to sustain the chain reaction, and sufficiently low-melting to be liquid at the temperature of operation, and so combine fuel and coolant in one.

Bonilla ( /831) mentions an investigation of the solubility of Uranium in liquid Bismuth. Ether the idea was to have a low-melting alloy of Uranium serving as a NF and a coolant at the same time, or else non-jacketed fuel was considered for use in liquid Bismuth as the coolant.

One form of the liquid NF reactor is the so-called "water-boilertype", in which heat is generated within the liquid, and the liquid is circulated either by natural convection (Ref. 262 of /1226), or by forced convection (Ref. 172 and 268 of /1226), to transport the heat to the place of dissipation.

The "water-boilers" produce not only heat but dissociate water into hydrogen and oxygen too. This explosive mixture is usually flushed out; however, one would wonder why this is not diluted with some other gas and utilized as fuel in an internal combustion engine. Could not the radioactivity be left behind in a scrubbing-tower?

Although Uranium hexafluoride has a vapor pressure of one atmosphere at 56°C (Smyth p. 158 /1211) and thus could be suitable for a gaseous NR, not one gaseous NR is mentioned in the catalog of NR's by Isbin ( /1249). Apparently the gaseous NF would require, for criticality, either an extreme volume or an extreme pressure, both of which are undesirable.

A step toward economy is the Breeder Reactor, mentioned by Cockcroft as being a "fast" reactor, with little or no moderator, having a compact core of  $U^{235}$ , and a blanket of **Thorium**, in which new fuel,  $U^{233}$  would be bred.

Isbin (p. 14 /1249) mentions EBR, Arco, Idaho, as a Breeder reactor, having a blanket of natural Uranium, apparently for the production of Plutonium.

One type of breeder reactor seems to have the NF in liquid form, flowing through the core, and thus easily replaceable, and the solid potential fuel surrounding this core and absorbing the neutrons which remain free, uncaptured by the fissioning fuel.

An exemple of considerations concerning a <u>primary coolant</u> for a NR is given by Jaffee ( /1191) who has investigated the **pertinent** properties of gallium. He considers the 2.2 barns as rather high, the 30°C melting point as good, however rejects gallium because of its corrosive properties.

The primary coolants, and the heat exchangers cannot be protected from the radioactive radiations by shielding. What is the effect of these hard hitting radiations, is not yet fully covered in unclassified literature (Parkins /1221, has been declassified with deletions).

Molten salts are good H Tr medii, however, according to Ohlinger ( /1202) they are subject to decomposition under irradiation.

The same disadvantage of decomposition applies to carbon dioxide and hydrocarbons.

Should a gas be chosen as a coolant, Cockcroft (/1204) recommends to use a gas with good H.Tr. properties, such as helium, and have it under pressure.

A gaseous coolant would provide the advantage that it could be fed directly into a gas turbine, thus avoiding losses in heat exchangers, etc.

Gases as coolants of NR's permit higher temperatures of operation. Therefore a large number of investigations have been made to determine their heat transfer properties in circumstances approaching the performance in the NR.

Szczeniowski (	<b>/1190)</b> : ga	s, tube, H Tr
Hebert and Knowles	( Ref. 33	/1226): steam, annulus, H Tr
Morduchow & Libby	(Ref. 43	/1226): $\int$ of energy eq. for Pr = $3/4$
Cor <b>rsin &amp;</b> Uberoi	(Ref. 45	/1226): air jet, H Tr
Boelter et al	(Ref. 46	/1226): exh. gas and air heat exch.
Boelter et al	(Ref. 47	/1226); """""
Boelter et al	(Ref. 48	/1226) 11 11 11 11 11
Boelter et al	(Ref. 49	/1226): " " " " " "
Boelter et al	(Ref. 50	/1226): design manual for e×h. gas-air heat exchangers
Boelter & Sharp	(Ref. 54	/1226): Th. conductivity; air; exh. gas
Boelter et al	(Ref. 58	/1226): air along finned plates
Boelter et al	(Re <b>f.</b> 63	/1226): air along a flat plate with turbulence promoters.
Finamore	(Ref. 88, ibid) :	exp. investigation of the Hilsch tube
Project Squid	(Ref. 90, ibid) :	spark photography of gas flow
n n	(Ref. 91 "):	11 11 11 11
Powell	(Ref. 105 ") :	H <sub>2</sub> flowing through H Tr tubes

(All references list	ed are from	/1226)
Schlinger & Sage	Ref. 121,	flow of natural gas into air
Hough et al	Ref. 122,	flow of fuel gas and air
Corrsin & Uberoi	Ref. 127,	round turbulent jet
Epstein & Roe,	Ref, 131,	2nd. virial coefficients for $\alpha 6 - 12$ pot.
Schey & Rollin,	Ref. 135,	effect of baffles on H Tr of finned cylinders
McLellan & Nichols,	Ref. 136,	diffuser resistance combinations in ducts
Kaplan	Ref. 138,	compressible fluid past a curved surface
Kaplan	Ref. 141,	compressible fluid past a circular arc prof.m
Hicks et al	( /1159)	compressible fluid flow in ducts w/ H Tr
Humble et al	Ref. 145,	air flow with H Tr
Lowdermilk & Grele,	Ref. 147,	air flow with H Tr
Sams & Desmon,	Ref. 148,	air flow with H Tr
Sibulkin & Koffel,	Ref. 149,	chart for calculations for cooling passages
Gray	Ref. 151,	anti-icing of airfoils
Deissler	( /1158)	air flow, adiabatic, turbulent, in tubes.
Lowdermilk & Grele	Ref. 153,	air flow with H Tr (entrance configur.)
Pinkel et al	Ref, 154,	air; passages; H Tr; pressure drop chart
Desmon & Sams,	Ref. 156,	air; platinum tube; high temperatures
Deissler	( /845),	turbul. flow; tubes; H Tr; variable fluid
		properties; Pr = 1
Valerino & Doyle,	Ref. 160,	charts for pressure drop; gases; passages;
		H Tr.
Drezel & MacAdams,	Ref. 173,	air; tubes; ducts; finned cylinders
MacAdams et al,	Ref. 179,	steam at high t°; annulus;

(All references liste	d are from	/1226)
McAdams,	Ref. 189,	air; tubes; high t <sup>o</sup> differences
Stalder & Spies,	Ref. 203,	exh. gas to air heat exch.
Weise	Ref. 205,	conversion of energy in a radiator
Pfriem	Ref. 208,	periodic heat cycle between gas and wall
Schmidt & Wenner,	Ref. 209,	air; heated cylinder; transverse flow
Lelehuck	Ref. 210,	hot air; high velocity; H Tr; flow resist.
Varshavsky (	/1169),	thermal Laval nozzle
Harper & Brown,	Ref. 218,	Eqs. for H cond. in the fins.
Ergen	Ref. 230,	gas; hot tube; H Tr; friction losses
Emmons (	/1071),	recovery factors in moving gas streams
Shapiro & Hawthorne (	( /1282)	steady one-dimensional gas flow
Valerino (	/1286),	aircraft heat exchangers
Kays	Ref. 294,	steam-to-air heat exchanger
Kays	Ref. 295,	effect of fin spacing
Kays	Ref. 296,	strip-fin heat exchanger
Kays	Ref. 297,	plate-fin heat exchanger
Garbett	Ref. 298,	H Tr coefficients by transient method
Johnson	Ref. 305,	finned circular tube heat exchangers
Beatty & Katz	Ref. 318,	steam to air H Tr
n n	Ref. 319,	film coefficients for Trufin tubes

It is apparent from several abstracts (References 24, 73, 183, 188, 278 of /1226) that unusually high pressures of water and steam have been under consideration, so that water could be circulated through the NR without boiling and flashed to steam outside of it. Water pressures of 2500 psia. are mentioned, and thermodynamic properties of steam have been extrapolated to 10 000 psia and 1600 °F.

Boiling can hardly be tolerated inside a NR because of the instability, however it would be involved when hot liquid under high pressure would be flashed to steam outside of the actual reactor. Therefore boiling has been studied anew for the AEC of USA by many investigators with many different fluids:

Kreith (	/1034) n-	-butyl-	alcohol	
Kreith (	/1028) ar	n <b>ili</b> ne		
Kreith (	/1027) wa	ater and	d aniline	+ furfuryl-alcohol
Martinelli et al,	(	/812) #	air, benz	ene, water, oil.
Bromley	(Ref. 288		/1226) ben:	Water, N <sub>2</sub> ,C Cl <sub>4</sub> , ethanol, zene, diphenyl <sup>4</sup> oxide, pentane
Bromley	(	<b>/</b> 1257)	N <sub>2</sub> , wa mercur	ter; suggestions for boiling y.
McGill & Sibbitt	(Ref. 286		/1226)	water, up to 3 000 psig and up to 650 °F
Wigner	(Ref. 270		/1226)	water
Plesset	(Ref. 261		/1226)	Uniformly heated liquid
Cichelli & Bònilla	(	/1019)	Water, n-pente propane	ethanol, benzene, propane, ane, n-heptane, water-ethanol, e-pentane.
Scorah	(	/1273)	water	
McAdams et al	(	/1269)	water	
Clark	(Ref. 198 c	of	/1226)	water?
Clark	(Ref. 197		/1226)	water at 1500 psia
Clark	(Ref. 196		/1226)	water at 2000 psia
Clark	(Ref. 195		/1226)	water at 2000 psia and 600 °F.
Clark	(Ref. 194		/1226)	
Clark	(Ref. 193		/1226)	water at 2000 psia
Clark	(Ref. 192		/1226)	water at 1000 psia

McAdams et al	(Ref. 188	/1226)	water		
Rohsenow	(Ref. 184	/1226) bubb	theory; Re and Nu based on the les receding from the heating surf.		
Rohsenow et al	(Ref. 181	/1226)	water at 2000 psia and 550°F		
McAdams et al	(Ref. 178	/1226)	water		
McAdams	(Ref. 177	/1226)	water at high heat flux		
Sydoriak & Sommers	(Ref. 171	/1226)	helium		
Kaufman & Isely	(Ref. 155	/1226)	water		
Gunther & Kreith	(Ref. 126	/1226)	distilled water		
Kreith & Summerfiel	La (	/1029)	water		
Colburn et al	(Ref. 89	/1226)	water; methanol		
Reinhardt & Foster	(Ref. 42	/1226)	water, ethyl alcohol		
Knowles	(Ref. 35	/1226)	water		
Martin	(Ref. 20	/1226)	mathematical investigation		
Hawkins	(Ref. 72	/1226)	review of literature on boiling		
Condensati	on of vapors has	likewise	been a subject of fresh		
investigation:					
Thompson	( Ref. 128	/1226)	Theory		
Colburn & Carpenter	• (	/1284)	pure vapors; high velocities		
Katz	(	/1287)	6 finned tubes in a vertical		
		row; fr	eon-12, n-butane, acetone, H <sub>2</sub> O		
Beatty & Katz	(Ref. 320	/1226)	steam and water		
Carpenter & Colburn	. (	/848)	effect of vapor velocity		
Mass trans	fer (in other wor	ds: diffi	usion, dissolution, alloying,		
etc.) has been studied particularly with reference to the new heat transfer					
medii: liquid metals	, fused salts, et	с.			

Bonilla	(	/831),	(	/1082),
Bonilla	(	/1081),	(	/1077),
Bonilla	(	/1078),		

There is, according to Thompson ( /1114) a wide variety of <u>nuclear power plants</u>. A general classification is given by Ohlinger ( /1202). Steam-turbine and gas-turbine systems are compared by Salisbury (Ref. 133 /1226), and by Thompson ( /1104 and /1114). A tentative specification for waste heat steam boilers is given by Williams (NSA 2064 = 1314). A discussion of the optimal steam temperature in nuclear power plants is presented by Elliott ( /797).

An interesting example of similarity investigations is that by Riekert et Held (Ref. 206 /1226) on heat transfer in geometrically similar cylinders, stating certain advantages for smaller cylinders, including lower weight per hp.

Although nuclear energy is far from being able to compete with more familiar forms of energy on an economic basis, there are certain fields where other than economic considerations are more important: Nuclear energy <u>rockets</u>: Hsue-Shen Tsien (Ref. 175 of /1226) and Ergen (Ref. 231 ibid.) Nuclear powered <u>aircraft</u> (Isbin, p. 16 /1249) Nuclear powered <u>submarines</u> (""")

Although nuclear reactions are known which resemble very much a combustion process in a furnace ("burning" of hydrogen to helium in the Sun - p. 152 of Heisenberg /1200) it is not likely that these will be applied in the near future (except in the hydrogen bomb). In the familiar type of NR no oxygen is needed (actually it is kept out to avoid corrosion) and the amount of gaseous products of fission is negligible. There is no need for a combustion chamber for the proper mixing of the fuel and air, nor is a chimney necessary for any draft, or for conducting

away the flue gases and smoke. There is a saving in space and a saving in heat which otherwise is lost through the smoke stack.

Even when heat is just a by-product at research and production NR's, the trend is from heating a river (Smyth /1211) to heating a building (Cockroft /1204) or to production of electrical power (Lucke 1298).

Although a Professor of Mechanical Engineering, Osborne Reynolds (p. 967 /585) in 1883 uses the metrical system (for example, in Table V, pressure in metres of water, discharge in cubic metres per second, temperature in degrees centigrade, and velocity in metres per second) and hardly any good reason can be produced for continuing to use non-decimal systems of units (except tradition, antiquity, and keeping out commercial competitors) the fact is that <u>conversion factors</u> are unavoidable. Therefore a few have been collected.

Ingersoll & Zobel (p.7 /802) bring in a table 1.2 the following conversion factors:

1	g/cm <sup>3</sup>	=	62.4 lb/ft. <sup>3</sup>
l	Btu	=	252 cal = 1055 joules = 777.5 ft-1b
1	Watt	=	0.2389 cal/sec
1	KW	=	56.88 Btu <b>/mi</b> n = 3413 Btu/hr
l	Cal	=	4.185 joules
1	Cal/cm <sup>2</sup>	=	3.687 Btu/ft <sup>2</sup>
1	cal/sec	=	14.29 Btu/hr
1	watt/ft <sup>2</sup>	=	$3.413 \text{ Btu/(ft}^2)(hr)$
1	$cal/(cm^2)$ (sec)	=	318500 Btu/(ft) <sup>2</sup> (day)
1	Btu/hr	=	0.293 Watts = $0.000393$ hp
1	Year	=	$3.156 \times 10^7$ sec = 8766 hr.

k in fph = 241.9 k in cgs

k in cgs = 0.00413 k in fph

 $\propto \inf fph = 3.875 \propto \inf cgs$ 

 $\propto$  in cgs = 0.2581  $\propto$  in fph

е	=	2.7183	=	<b>1/0.</b> 36788
Ħ	=	3.1416	=	1/0.31831
# <sup>2</sup>	=	9.8696	=	1/0.10132
<b>√</b> <del>3⊀</del>	=	1.7725	=	1/0.56419
		-		

 $g(45^{\circ} lat.) = 980.6 cm/sec^2 = 32.17 ft/sec^2$ 

Table 64 of Eshbach (/1296) brings the units andconversion factors of specific heat $\begin{bmatrix} L^2 T^{-2} t^{-1} \end{bmatrix}$ 

'To change specific heat in gram-calories per gram per degree centigrade to the units given in any line of the following table, multiply by the factor in the last column."

Unit of Heat or Energy	Unit of Mass	Temperature Scale	Factor
gram-calories	gram	centigrade	1
kilogram-calories	kilogram	centigrade	l
British thermal units	pound	centigrade	1.800
British thermal units	pound	Fahrenheit	1.000
Joules	gram	centigrade	4.186
Joules	pound	Fahrenheit	1055
Kilowatt-hours	kilogram	centigrade	1.163 X 10 <sup>-8</sup>
Kilowatt-hours	pound	Fahrenheit	2.930 X 10 <sup>-4</sup>

Table 65 of Eshbach p. 1-166 ( /1296) contains units and conversion factors of thermal conductivity and resistivity  $\left[MLT^{-3} t^{-1}\right]$  and  $\left[M^{-1}L^{-1}T^{3} t\right]$  (t = temperature).

"To convert thermal conductivity, in gram-calories transmitted per second from one face of a cube 1 cm on edge to the opposite face per degree centigrade temperature difference between these faces, to the units given in any line of the following table, multiply by the factor in the last column.

To convert thermal conductivity in any unit given to any other unit multiply the number of original units by a factor obtained by dividing the factor in the last column for the final unit by the factor for the original unit.

To convert thermal resistivity, in degrees centigrade between one face of a cube lcm on edge and the opposite face per gram-calories transmitted per second between these faces, to the units given in any line of the following table, divide by the factor in the last column.

To convert thermal resistivity in any given unit to any other unit multiply the number of the original units by a factor obtained by dividing the factor in the last column for the original unit by the factor for the final unit.

.

Surface emission resistance in thermal ohms per square centimeter is derived from degrees Fahrenheit per Btu per hour per square foot by multiplying the number of the latter units by 1761."

## Table 65, 1466, Eshbach

Unit of:

Heat	Area Th	ickness	Time	<u>Temperature</u> <u>scale</u>	Factor
gram-calories	cm <sup>2</sup>	cm	second	centigrade	l
Kg-calories	$m^2$	cm	hour	centigrade	3.6 X 104
British Thermal Units	ft <sup>2</sup>	inch	hour	Fahrenheit	2903
Joules *	$m^2$	cm	second	centigrade	4.186
Joules	ft <sup>2</sup>	inch	second	Fahrenheit	850.6
Kilowatt hours	m <sup>2</sup>	cm	hour	centigrade	41.86
Kilowatt-hours	$ft^2$	inch	hour	Fahrenheit	0.8506
* Thermal resistances	in these	units a	are know	n as thermal o	ohms.

## Conversion factors for Heat Transfer

( 1259) Gilliland brings a table 10 - 1 of convers. factors 1 Btu = 252 cal = 0.293 watt-hours 1  $\frac{\text{Btu}}{\text{hr ft }^{\circ}\text{F}}$  = 0.42 X 10<sup>-2</sup>  $\frac{\text{cal}}{\text{sec cm }^{\circ}\text{C}}$  = 0.0176  $\frac{\text{watts}}{\text{cm }^{\circ}\text{C}}$  $\frac{\text{Btu}}{\text{hr ft}^{2} \circ \text{F}}$  = 1.35 X 10<sup>-4</sup>  $\frac{\text{cal}}{\text{sec cm}^{2} \circ \text{C}}$  = 5.7 X 10<sup>-4</sup>  $\frac{\text{watts}}{\text{cm}^{2} \circ \text{C}}$ 

Knolls Atomic Power Laboratory of the General Electric Company had prepared a conversion chart for heat transfer for English units to CGS units (Ref. 134 of /1226, not received).

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#### Heat Transfer Between Metals in Contact

Historical Note.

<u>0.</u>

Attention to metallic contacts has been drawn by advances in lubrication technics and in electrotechnics. H tr (heat transfer) across metallic contacts has not been discussed or experimented upon very much. Bowden & Tabor ( /1212) seem to have started more advanced discussion, in 1939, by emphasizing the discontinuous nature of metallic contacts.

Northrup (/1246) seems to be the first to have measured, in 1913, the thermal conductivity of a copper-copper contact, followed by van Dusen (/1247), in 1922, and Jacobs & Starr (/944) in 1939. Eichelberg (/1248), in 1939, investigated heat flow across wet and dry thermal contacts in engines (his paper of 1923 may already contain part of this information.

Ellerbrock, in 1939 ( / 1151) investigated thermally the bond of aluminum fins and a steel barrel. Then follows, in 1940, a doctor's dissertation of Tampico ( (1198), however thermal resistance of contacts is not his chief concern. Austin, in 1940 ( 792) discusses Jacobs et Starr results and calls attention to alien films covering Ingersoll & Zobel, in 1940 ( metal surfaces. /802) include a short paragraph on contact resistance. McAdams, in 1942, ( /790) mentions in a few sentences the factors influencing contact resistance. Karush, /1057) derives, for the AEC, a theoretical expression for in 1944 ( the metallic part of this resistance and applies his theory to a number of special cases. Holm, in 1946 ( (943) consolidates his earlier publications in a book "Electric Contacts" and brings some scattered notes on thermal aspects of them too, including some theory.\*1 Keller, in 1948 + : P.T.O.

( /945) discusses in detail the different aspects of heat transfer Kouwenhoven & Potter, in 1948, ( through layers of sheet metal. /947) report experiments on the thermal resistance of contacts. Fishenden & Kepinski, in 1948, ( (942) bring this matter before the 1948 Congress of Applied Mechanics. Brunot & Buckland, in 1949, 941) and Weills & Ryder ( /948) bring the results of their ( experiments before the ASME. Several books on lubrication discuss the Moyer & Riemen, in 1951, ( importance of adsorbed films. /1106) report investigations at sodium-stainless steel interface. Cetinkale (893) bring before the joint Conference of & Fishenden, in 1951 ( ASME and IME the most comprehensive (so far) theoretical treatment of the problem and some experimental results. Finally, in 1952, (includes

/1192, 1193, 1194) a book of the ASM: "Metal Interfaces" brings several articles on processes at the interfaces, including adsorption and wetting.

Scattered short notes on contact resistance might be found in other papers too.

0.1

### Classification of contacts

Metals can be solid, liquid and as vapors; consequently contacts can be: 1) solid-solid; 2) solid-liquid; 3) solid-vapor<sup>\*2</sup>; 4) liquid-liquid; 5) liquid-vapor; 6) vapor-vapor. These groups cannot be taken strictly, because vapors and gases are unavoidable com-

\*1. It was not realized at first that Holm's book, printed in Stockholm, would be in English, and available here. Aug. 21, 1952 an attempt was made to locate it and, as a surprise, it was found in Physics Library. The second surprise was to find in it a bibliography of 24 pages, of some 500 references, on electric contacts. A number of these references may cover thermal aspects of electric contacts, however a detailed study has to be postponed until this Review is written, and an Appendix begun.

\*2. Solid-gas contacts will be discussed when contaminated surfaces will be dealt with.

ponents in certain combinations. For example, an evacuated metal vessel is not empty; it is filled with the vapor of this metal and a residue of gas (if the pump was not ideal) plus any contaminants due to the pump, such as mercury vapor, grease vapor, etc.

The contacts of each group can be

A. at rest; B. In movement.

4

Again, case A cannot claim absolute rest, as there is movement in every solid and, sufficiently magnified, every interface would be similar to the water-air interface of a YMCA swimming pool. In addition to this microscopic movement, there would be a macroscopic movement due to expansion, convection, etc. A cylinder liner, when heating up, would expand and compress to some extent the casting. The interface will thus move in a direction normal to its extent, and at the same time increase in area. The same applies to NF (nuclear fuel) and its Some conditions will help to ensure less movement at the sheath. Heat generated at the interface by electric current, will interface. flow away symmetrically, both up and down. Steady-state conditions (their practical approximation) should mean that every adjustment and movement has come to an end. Thus, case A would better be qualified as contacts not intended to move.

Case "B" will not be covered fully because the domain of Friction and Lubrication is too important to be pushed underneath the simple title "Metals in Contact". Actually much more research has been done in this field than in the field of contacts. A remark of Alcock ( /1214) is significant: "..... the very comprehensiveness of the author's survey of those classical HTr problems, radiation and convection, emphasized by contrast the almost universal neglect of that "Cinderella"

of the subject, heat flow between solids in contact (or nearly so)".

Again each of the subgroups can include: a) chemically inert components; b) chemically active components (rusting, corrosion, etc.), which, of course, should be kept apart, if possible.

One could hardly imagine an interface of physically inactive components, as adsorption, migration, electron emission (photo-electric and thermionic), electric contact potential, thermoelectric potential (both Seebeck and Peltier), surface tension, adhesion, cohesion, etc. play a significant role at interfaces.

## Enumeration of examples

Solid-solid, static /1214): Poppet valve and seat; ( Valve seat insert and cylinder head; Dry liner and cylinder; Threads (e.g. sparking plug); Hot spot between inlet and exhaust manifold of petrol engines; NF and sheath ( /1211) Fins bonded to cylinder ( /1151) /943) Electric contacts ( Fuel injectors and cylinder head ( /923). /1214): Piston ring and cylinder bore; Solid-solid rubbing ( Piston ring and side of groove; Piston skirt and cylinder wall (also /1152); Journal bearing surfaces; Sleeve valve and cylinder; Solid-liquid, "at rest" : Natural convection with liquid metals /1058) , flowing : Forced convection with liquid metals

/962)

<u>0.2</u>

1.

2.

3. Solid-vapor, at rest : Evacuated container

- , flowing : Superheating of metal vapors Condensing of metal vapors
- 4. Liquid-liquid, at rest: Two liquid metals in a container

, flowing: Two liquid metals in a wall-less heat exchanger.

- 5. Liquid-vapor, at rest: Liquid metal in an evacuated container ( /1106) , flowing: Boiling of liquid metal; condensing;
- 6. Vapor-vapor : Two metal vapor streams in a wall-less heat exchanger.
- Note: This list is by no means complete; only examples which were at hand are included.

# 0.3 <u>Mechanism of heat transfer across an interface and</u> general theory.

Austin ( /792, p. 2-7) reminds us of the fact "that no one has seen, felt, heard, tasted or smelled this mysterious something called heat," that the term "flow of heat" persists from the caloric theory, as well as the idea of heat capacity (which implies the capacity of a body to hold the caloric fluid). Since they have a definite usefulness, they are likely to continue to survive, he remarks. Heat "transfer" is no better, however it would be difficult to invent something exact and as pictorescue as that. Electric current, however, is a transfer of electrons from one body to From the Wiedemann & Franz relationship between electrical end another. thermal conductivity (p. 178 (801) one could deduce that electrons would play an important rôle in heat conduction as well, and this is recognized by the modern theory as explaining the large difference between metals and non-metallic conductors of heat ( /892). (There is, however one

exception: The remarkable substance: liquid helium II has an apparent conductivity many thousands of times greater than silver (p.8, /802). /892) explains heat conduction through metals and non-Eshelby ( metals. The writer has not found yet a complete description of the mechanism of heat transfer at an interface. However from odds and ends he has tried to fix this mechanism: Bowden & Tabor ( /1212) have found from measurements that flat steel surfaces touch only at one ten-thousandth of the apparent area. Holm ( (943) calls the points of actual contact "a-points". Both papers agree that the number of such a-point would be not less than three and more likely about ten, this number increasing with ./1192) shows that there are no clean surfaces, Uhlig ( pressure. because of adsorption, chemisorption and corrosion. Thus even at the a-spots the metals do not actually touch each other. Nearly always there is an alien film between them, or two layers of such film. These films seem to be deformed by the high local pressure so that at least a part of their surfaces is within molecular distances. Only in high vacuum truly clean metal surfaces can be obtained, without an adsorbed film. If such surfaces touch, cold welding results and the bond so formed is equal to bonding anywhere else in the metal lattice (p. 325 That would not mean that there would be zero thermal resistance /1192). now at the interface, because the cross-section for heat flow is still contracted: not all elements of one (rough) surface are cold welded to the corresponding elements of the other surface. It is the resistance to bottlenecking of Karush ( /1057) and the constriction resistance of Holm ( (943), dealt with below.

Returning to an a-point with an alien film or two separating the metals:

The main difference between the metal and the film is this: In the metal there is an electronic "gas"; part of the electrons can freely move about between the ions of the lattice. In a non-metal all electrons are attached to definite atoms and can be torn off only by extreme forces Heat (kinetic energy of the molecules) can be to molecule (breakdown spark). transmitted in any material from molecule according to the laws of the kinetic theory. Metals have the great advantage that the regular lattice provides kind of highway for the electrons. Austin says (p. 16, /792): "If it were possible to obtain a perfect crystal composed of but one kind of atom and entirely free from thermal vibration, the mean free path would be increased to an extent that the thermal resistance of the crystal would tend to vanish". Generally the lattice is not ideal, (Fig. 3 of (792) and the electronic conduction of heat is reduced.

According to Eshelby ( /892), at the absolute zero of temperature non-metals have filled energy levels, in contrast to metals, whose levels are only partly filled. For a temperature T other than absolute zero, the distribution function is approximately,  $f = \exp \left\{ -\frac{1}{2} \left( \frac{E_1 - E_0}{6T} \right) \right\}$ 

where  $E_1$  denotes the next higher (excited) energy band and 6 is the Stephan-Boltzmann constant. Hence if the gap  $E_1-E_0$  is large in comparison with 6T the number of occupied levels at  $E_1$  and the corresponding depopulation of levels near  $E_0$  will be negligible, which is the case with non-metals. Metals have the partly unfilled fundamental (non-excited) levels which are attainable with a small excess energy. Therefore at the temperature T many electrons will have moved up in the same band  $E_0$  to slightly higher (formerly unoccupied) levels. (Fig. 11 of /892). In other words: assuming some temperature gradient along the metals in contact, one could imagine the steady flow of electrons through the metallic lattice (Fig. 3

/792) suddenly stopped at the barrier formed by the nonp. 17 of metallic film. The electrons would collide with the electrons, ions, atoms of the film and thus transfer their KE to these molecules, setting them into more intensive motion around their "normal" positions. There being no unattached electrons in the film, the only way of sharing the energy with neighboring molecules is via collisions. On the return swing a few may hit some metallic electrons carrying less KE than they and thus return some KE to the metal (reflection; steps toward thermal equilibrium). Generally there will be a flow of the KE across the film until the other The electrons of it, "loitering" at the boundary, metal is reached. will get struck by the violently oscillating particles of the film and will be sent flying through the lattice until they strike some other particle and deposit most part of their KE. Small forces are needed to bring the light electrons in motion and strong forces are required to set the heavy molecules into oscillations. Thus most of the thermal gradient will appear across the non-metallic film (corresponding to high thermal resistance) and only a small part of the gradient will be found along the metal (low thermal resistance). (Of course a thin film may have smaller thermal resistance than a long bar of metal).

In the wave picture: whether it is a translational, vibrational or rotational movement, every moving particle creates a wave (as does, for example, a 10 gram bullet of 1000 m/sec velocity, producing a wavelength of 6.6 X  $10^{-33}$  cm, (p. 9 /1199), and these waves interfere with each other, strengthening or weakening the resultant wave motion according to their frequency, amplitude and phase relationship, getting absorbed by the medix, reflected and refracted at the interfaces and discontinuities, etc. According to Slater (pp. 19, 316, 348 of /791) the vibrational frequencies of the atoms, as a whole, in molecules

and crystals, are of the order of magnitude of  $10^{13}$  cycles per second, and the corresponding energies depend upon the temperature. For energies less than  $\sim 0.04$  electron-volts quantum theory must be used while for larger energies the classical theory is appropriate. For heavy atoms such energy corresponds to temperatures well below room temperature, whereas for very light atoms these temperatures can be comparable with room temperature or even higher.

If a localisation of high temperature occurs somewhere within a crystal, this would mean that the atoms in that region were vibrating with much more amplitude than the average, sending out a spherical wave, gradually dissipating its energy as this wave traveled outward with the velocity of sound (also p. 8 of /892). If it were a perfect propagation of sound, the energy would spread like radiation, however, and not, as heat does, by diffusion. In actual crystal the waves are scattered by imperfections in the crystal, and this scattering makes the propagation of energy resemble diffusion and satisfy the correct differential equation for heat This suggests that anything which tends to scatter acoustical conduction. waves of high frequency will decrease the heat conductivity of a solid. This is the only mechanism present in insulators, but in conductors the same electrons which carry electric current also can carry heat and this electronic thermal conductivity is much greater than the other type. At each collision with the atomic lattice the electron gives up some kinetic energy or gains some. The recoil of atoms, analogous to the Compton effect, furnishes the mechanism for energy interchange between the electrons and atoms by which effective thermal equilibrium is The specific heat of the electrons is very maintained between them. small compared with that of the atoms, so that we must expect that

almost all the Joulean heat appears as energy of the atoms. Eshelby adds /892), that for metallic conduction the sound waves were regarded (p.8, as the scatterers of the electronic  $\psi$  -waves, but for non-metallic conduct-Ingersoll & Zobel (p.27, /802) ion the sound waves scatter each other. explain the increased resistance at the interface as due to a gas layer on the solid metal. Based on electronic considerations they find a temperature discontinuity at the gas-solid boundary, which greatly increases the resistance. This resistance varies with gas and they mention Birch and Clark, Am. J.Sci., 238, 529-558, as having corrected for it in their rock conductivity determinations by making measurements with nitrogen and again with helium (which has some six times greater conductivity) as the interpenetrating gas at the rock-metal boundary. In the same connection they mention that the conductivity of silica aerogel of 0.00005 cgs or 0.012 fph is actually a little less than that measured /802) although they are not certain that the cause for still air (p.8, is this thermal slip (p. 28).

For those parts of the interface, where the film-covered metal surfaces are at sufficient distance to have some fluid between them, the picture is slightly different. The mechanism of conduction through the fluid would be as described by the kinetic theory. Should the pockets be deeper than 0.1 mm Fabry (p.45 (795) would say that convection has to be accounted for. In cases of comparatively high /790) would suggest temperature level at the interfaces McAdams (p.9) plotting the apparent conductivity as ordinates versus temperature to check whether the curve becomes concave upward, which would be a proof that radiation becomes important. He points out (p.45) that conduction and convection are affected by temperature difference and very little by temperature level, whereas radiation increases rapidly with increase in temperature level. At very high temperatures radiation is the controlling factor. Oxidized metallic surfaces are generally much better emitters (and absorbers) of radiant energy (p.86, /792); Table XIII on p. 393 of /790.

Thus there are several co-nductances for heat in series; in parallel to one of them are the two separate channels across the fluid: radiation and convection (Fig. 8 of /941). Few authors mention all of them. Almost everybody omits some of them, for simplification.

/790	"Contact Resistance" in Heat Transm	nission" p.	24
	by: W. H. McAdams.		

- /791 Mechanism of heat conduction in "Quantum Theory of Matter"
  by: Slater McGraw-Hill book p. 316 1951.
- /792 Relative influence of metallic resistances in thermal circuits in "The Flow of Heat in Metals" p. 82 Fig. 42 by: J. B. Austin.

(book) American Society for Metals October 1941.

- /795 Limits of convection in "Propagation de la Chaleur" by: Charles Fabry 1942
- /801 Smooth and rough surfaces in "Modern Theory of Solids" by: Seitz p. 167, McGraw-Hill book 1940.
- /802 "Heat conduction; 3.13 Contact Resistance"
  by: Ingersoll, Zobel and Ingersoll
  McGraw-Hill book 1948.
- /892 "The fundamental physics of heat conduction" by: J. D. Eshelby,

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- ,/893 "Thermal conductance of metal surfaces in contact" by: T. N. Cetinkale and M. Fishenden in Preprints III Sept. 1951.
- /923 "H Tr in internal combustion engines" by: Alcock Preprints V 1951.
- /941 "Thermal contact resistance of laminated and machined joints" by: Brunot, Buckland.

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/942	"Resistance to heat transfer in gap between 2 paralle					
	surfaces in contact"					
	by: Fishenden, Kepinski					
	in Proc. Intern. Appl. Mechanics Congr. 1949 p. 193.					
<b>/</b> 943	"Electric contacts" by: R. Holm					
	1946, Hugo Gebers Forlag, Stockholm.					
/944	"Thermal conductivity of metallic contacts"					
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<b>/</b> 945	"Heat transmission in strip-coil anncaling"					
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/947	"Thermal resistance of metal contacts"					
	by: Kouwenhoven, Potter					
	in Welding Journal, 1948, Vol. 27 p. 515 s					
/948	"Thermal resistance of joints formed between stationary					
	metal surfaces" by: Weills, N.D., Ryder E.A.					
	in Trans. ASME 1949 Vol. 71, p. 259.					
/962	"Forced convection heat transfer theory and experiments					
	with liquid metals" by: Lyon, R.N.					
	June 1949, Oak Ridge Nat. Lab 361, Tennessee.					
/1057	"Temperature of two metals in contact"					
	by: Karush W. in AECD - 2967; CP-2059. Dec. 22,					
	1944; Decl. Oct. 16, 1950. Ref. 19 in TID-3022.					
/1058	"Heat transfer by natural convection from horizontal					
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- /1106 "Heat transfer measurements at sodium-stainless-steel interface". by: Moyer J.W. and Riemen W.A. in KAPL-567 of June 1, 1951, 19p.
- /1151 "Heat-transfer tests of a steel cylinder barrel with
   aluminum fins." by: Ellerbrock, Jr., H.H.
   in MR Aug. 1939 E-194.
- /1152 "Piston heat-transfer coefficients across an oil film in a smooth-walled piston reciprocating-sleeve apparatus." by: Manganiello, E.J., et Bogart D.

in NACA ARR No. E5K08 = E-110 of Dec. 1945.

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1.	Solid Metals in Contact
1.1	Heat Transfer across a stationary interface of solid metals.
1.1.1.	No complete theory has been found so far by the writer.
	Partial aspects have been analysed theoretically by Karush
(	/1057) and Cetinkale & Fishenden ( /893).
	A number of theoretical solutions for composite slabs have

69

been found (Laplace transform method used by the Anthony - /888 and /889; Random walk method used by Weinbaum - Ref. 109 and 111 of

/1226; Ref. 18 of /1226; etc.), however none of them refer to any gas pockets or oxide films. To the contrary: "It is assumed that the thermal properties of each slab are independent of temperature, time, and position, and that there is <u>perfect thermal contact at each interface</u>" ( /888).

<u>1.1.1.1.</u> <u>Dimensional analysis</u> has been attempted by one\* only author ( /1214), Mr. J. F. Alcock, on page 126 of V. 149 of Proc. IME (1943). Therefore it will be quoted here:

"Consider two similar surfaces in contact, nominally mating, but actually touching at a large number of peaks. The conductance C per unit area would depend upon: Contact pressure P, Thermal conductivity K, Hardness B, and Surface finish factor. The last-mentioned might be separated into two factors, one L, denoting the size of the irregularities, the other, S, their shape.

The dimensions of those factors (using the Lanchester system in which heat had the dimensions of energy  $ML^2 T^{-2}$ , and temperature  $L^2 T^{-2}$ ) were as follows: - Unit conductance C=Heat / (temperature) (time)(area) =  $M L^2 T^{-2} / (L^2 T^{-2} \times T \times L^2) = M L^{-2} T^{-1}$ 

value, since elastic deformation, as well as plastic, must be taken into account)  $B = Force / area in contact = M L^{-1} T^{-2}$ . Conductivity  $K = ML^{-1}T^{-1}$ ; Projection size L = L; Projection shape S: Non-dimensional. Thus C = f(P, B, K, L, S) or, since P and B had the same dimensions,  $C = f(\frac{P}{B}, K, L, S)$ . That left only C, K, L as dimensional factors, and by inspection,  $C \propto \frac{K}{L}$ ; Thus  $C = (\frac{K}{L}) f(\frac{P}{B}, S)$ . In other words the unit conductance varied

directly as the conductivity, inversely as the size of the projections, and as some unknown function of the projection shape and of the pressure/ hardness ratio.

That analysis ignored as negligible heat transfer across gaps, due to conduction or radiation. It also assumed the two surfaces to be similar. If they were dissimilar, the conductance would be a function also of the ratios  $K_1/K_2$ ,  $B_1/B_2$ ,  $L_1/L_2$ ,  $S_1/S_2$  and some factor expressing the extent to which the surfaces interlocked. For example, two grooved surfaces in contact would presumably conduct more heat if the grooves were of equal pitch and parallel than if they were of unequal pitch or crossed".

There are no established dimensionless numbers as yet for contacts. Cetinkale & F. ( /893) include a set in their theory, however do not use them for correlation of the results of previous experimenters. Evidently the latter had not recorded sufficient data for this purpose. The roughness of the surfaces had not been established by the same methods. Kouvenhoven & Potter ( /947) in their conclusions mention that it is probable that for heat transfer purposes the r.m.s. system of designating roughness (introduced by ASA) is inadequate. The Meyer hardness has been determined by Cetinkale & F. themselves only. <u>1.1.1.2.</u> The two theories, of <u>Karush</u> ( /1057) and of Cetinkale & /893), use the same model of contact elements: A circular Fishenden ( cylinder of radius  $r_0$  (Karush) or  $r_e$  (Cetinkale) with a centrally placed circular solid spot of radius r surrounded by fluid of uniform thickness L (Karush) or  $\delta$  (Cetinkale). Karush keeps the "plug", of radius r, resistance and neglects the fluid; Cetinkale keeps the fluid and neglects the plug. Karush's concern seems to be to select such dimensions of the bottleneck, that the temperature of the contact would be essentially that of the heat source. Apparently it is the problem of cooling a sheathed uranium fuel rod so efficiently that its exterior (surface) temperature would not rise much above the temperature of the He does not mention, however, how he would prepare a surface sheath. to have a-spots as per design.

Karush uses a unique "resistance to bottlenecking in cylinder",  $R_1 = \frac{t_1 - \overline{T_1}}{G} - (2)$  where  $t_1$  is the temperature of the base when the flow is not constricted (i.e.  $r = r_0$ ),  $\overline{T_1}$  is the average of the disturbed temperatures at the interface over the area of the plug, and G is the heat flux. He reasons that constricting the flow perturbs the temperature by a harmonic function which vanishes for large Z (which is the coordinate along the axis of the cylinders). His result is  $R_1 = \frac{r_0}{k_1} f(\frac{r}{r_0})$ , where  $k_1$  is the thermal conductivity of metal No. 1. He states without proof that for small  $r/r_0$  ( $\ll$  1) f may be written f  $\frac{r}{r_0} = \frac{8}{3\pi} \frac{r}{r_0}$ , so that  $R_1 = \frac{r_0}{k_1} \cdot \frac{8}{3\pi} \cdot \frac{r}{r_0}$ . Introducing  $\frac{r}{r_0} = \infty$ he further shows that he can fix  $\propto$  at any value and select  $r_0$  so that

the temperature at which the metals make contact becomes t1. Generalizing,

<u>n</u>

he shows how the results may be obtained by assuming that the heat flows across the interface through long parallel equally spaced strips instead of through circular spots, and later, through areas of arbitrary shape. There remains, of course, a function  $p\left(\frac{A}{A_0}\right)$  depending upon the geometry, which he does not define more precisely.

In seven more booklets (Ref. 16, 17, 21, 22, 23, 27 and 29 of /1226) Karush theorises concerning some special cases of fuel/sheath combinations, like defects of coating, influence of ribs, etc. 1.1.1.3. Cetinkale & Fishenden ( /893) find the temperature distribution in the contact element by Southwell's relaxation method ( /951, /952); Brown & Marko (p. 28, /826) and McAdams (p. 16 /790) describe the graphical method of Awbery and Schofield ( /21) for this purpose. Cetinkale & F. then calculate, and tabulate, the solid resistance, fluid resistance, and the total (aggregate) resistance, all in arbitrary units. These results they use as a check on their theory. They approximate the isothermal surfaces by surfaces formed by revolution of a family of ellipses having their foci where the fluid meets the solid spot, and the flow lines by hyperbolas having the same foci. Their theoretical formulas then yield results within 0% to 4.2% of those obtained previously by the relaxation method.

They introduce the following dimensionless numbers: Conductance number  $U = \frac{u \delta}{k_f}$ , where u = conductance per unit area,  $\delta = \text{thickness of the fluid between}$ the contact elements,  $k_f = \text{equivalent thermal conductivity}$ of the fluid;

Constriction number  $C = \frac{r}{r_{e}}$ , where r = radius of the contact spot, re = radius of the contact element; Fluid thickness number  $B = \frac{\delta}{r}$ 

Conductivity number  $K = \frac{kf}{k_s}$ , where  $k_s = equivalent$  thermal conduct-

ivity of the solids, found as the harmonic mean of the conductivities of the two

solids in contact: 
$$\frac{2}{k_s} = \frac{1}{k_1} + \frac{1}{k_2} ---(19)$$

Their contact conductance equation then is:

$$U = 1 + \frac{BC}{K \arctan\left(\frac{1}{C}\sqrt{\left(1 - \frac{1}{U}\right)}\right)} - \dots (28)$$

As both sides contain U, it is necessary to use the iteration method to calculate U, for the first approximation assuming

$$\arctan\left(\frac{1}{C}\sqrt{\left(1-\frac{1}{U}\right)^{2}}-1\right) = \frac{\pi}{2}$$

They derive K, C, and B from known properties of solids, fluids, and surfaces.

Their kf is an equivalent fluid conductivity which includes radiation and takes account of accommodation effect. Unless the distance between the metallic surfaces, S, is larger than the mean free path of the molecules of the fluid between them, and radiation cannot be neglected, the conductivity of the fluid ko, can be substituted for kf. Otherwise their correction formulas (based on the kinetic theory) must be used.

The constriction number C is expressed, for plastic flow,  $C = \sqrt{\frac{p}{M}}$ , where p is pressure, and M is Meyer hardness ( /1241); for elastic flow, when pressure p<sub>max</sub> was attained and was reduced to p:

$$D = \sqrt{\frac{p_{max} - p}{M}}$$

Time\* of the application of the test load must be taken into account, if it exceeds 1/180 hour, by formula (38):  $M = M_0$  (1- $\omega \log_e 180\tau$ ), where M and M<sub>0</sub> are the Meyer hardnesses for  $\tau$  hours and 1/180 hour application of load respectively, and  $\omega$  is a constant. Values of M<sub>0</sub> and  $\omega$ are given in table 2.

To deduce the effect of temperature upon the rate of change of M, it is supposed that an atomic migration process takes 7 hours at temperature T and 7' hours at T'.

Then 
$$M = M_o \left\{ 1 - \omega \left( \frac{T!}{T} \log_e \tilde{\mathcal{L}}' + 35 \frac{T!}{T} - 29.8 \right) \right\}$$
 ----- (40)

where T is the temperature at which  $\omega$  is determined, and M and M<sub>o</sub> are Meyer hardnesses at T' for  $\mathcal{T}$ ; hours and 1/180 hour application of load respectively.

Fluid thickness number depends upon the smoothness of the surfaces. For geometrically smooth planes  $\delta$  would be the distance apart. For rough surfaces  $\delta = \epsilon \beta_c$ , where  $\beta_c$  is the arithmetic-mean distance between the surfaces and  $\epsilon$  a constant - less than unity - depending upon the shape of the surface irregularities.  $\beta_c$  can be expressed as  $\beta_1 + \beta_2$ , where  $\beta_1$  and  $\beta_2$  are the arithmetic-mean distances of surface 1 and surface 2 from the plane through the points of contact.  $\epsilon$  has been calculated by Keller ( /945) for paraboloids of trevolution making point contact at the apices,  $\epsilon = \frac{1}{1.86} = 0.538$ , and Cetinkale & F. \*I would suggest "duration" instead of their expression "time". find this value well in agreement with their result ( $\varepsilon = 0.61$ ) for <u>ground</u> surfaces. They were unable to detect any change in  $\delta$  with pressure up to 800 lb/in2 and assume that  $\delta$  is constant.\*<sub>1</sub>

The radius of a contact element,  $r_e$ , was found (as suggested by dimensional analysis) to be  $r_e = \Psi (\lambda_1 + \lambda_2) C^{\varsigma}$ , where  $\Psi$  and  $\varsigma$  are constants and  $\lambda_1$  and  $\lambda_2$  are the wavelengths of the roughness of the two surfaces (as obtained from absolute profiles of the surfaces, taken using a Talysurf\*<sub>2</sub> instrument). The two wavelengths were combined into  $\lambda_c = \lambda_1 + \lambda_2$  and then  $r_e = \Psi \lambda_c C^{\varsigma}$  -----(42) (In their tests they used surfaces whose  $\lambda$  were from 8600 to 34000 micro-inches, and found, using a planimeter, the mean height,  $\beta$ , from 12 to 570 micro-inches. These data refer to the so-called macro-roughness).

The effective fluid thickness was calculated, using the zero pressure relation  $\delta = \frac{kf}{u}$ , and plotted against  $\beta_c$ . This gave a nearly straight like with the equation  $\delta = 0.61 \beta_c$  (that is,  $\epsilon = 0.61$ ) with a mean deviation of  $\pm 11$  microinches. The value of  $\mathbf{r}_e$  was **claculated**, using the contact conductance equation and the appropriate values of the dimensionless numbers, and log  $\mathbf{r}_e/\lambda_c$  was plotted against log C. These points fell on a nearly straight line giving the relation,  $\mathbf{r}_e = 0.0048$   $\lambda_c \ C^{-\frac{5}{3}}$ , with a mean deviation of  $\pm 4000$  microinches. From this equation  $\Psi = 0.0048$  and  $\mathcal{S} = -\frac{5}{3}$ . The conclusion of Cetinkale & F. is: "The values of  $\epsilon$ ,  $\Psi$  and  $\mathcal{S}$  were found to be independent of the nature of the metal or fluid, and were constant for a given type of surface roughness, for ex, ground surfaces; thus agreeing with the theory. The

\*1 Compare with Fig. 12 of K. & Potter ( /947).

 $*_{g}$  An attempt, with the aid of Prof. V.W.G. Wilson and of Shop Instructor Mr. F. G. Corrick, to locate at McGill some kind of profilometer, was unsuccessful.

contact conductance number,  $U = \frac{u \\ \delta}{kf}$ , is a function of the two dimensionless numbers  $K_{/B} = r_e kf_{/C}k_s$ , and  $C = \frac{r}{r_e}$ , and the relation between them is given by the contact conductance equation. The contact conductance for ground surfaces can be estimated with sufficient accuracy for practical purposes, using this equ. and the experimental values of  $\varepsilon$ ,  $\psi$  and  $\zeta$ ."

The procedure for estimation of contact conductance for ground surfaces seems to be:

1) Use Talysurf instrument to determine  $\lambda_{c} = \lambda_{1} + \lambda_{2}$ ;

2) Use planimeter to obtain the mean height  $\beta_{c}$  of the crests;

3) Use  $\varepsilon = 0.61$  and charulate  $\delta = \varepsilon \beta_c$ ;

4) Obtain k<sub>o</sub>; correct it, if necessary, to obtain kf more exactly;

5) Obtain  $k_1$  and  $k_2$  and find  $k_8$  from  $2/k_8 = 1/k_1 + 1/k_2$ ;

6) Calculate 
$$K = \frac{KI}{k_s}$$
;

7) Obtain Meyer hardness of surface, and pressure; calculate  $C = \sqrt{\frac{p}{M}}; 5$ 

8) Calculate  $r_e = 0.0048 \lambda_c C^3$ ; 9) Use  $r_e$  to calculate B from  $B = \frac{\delta}{r_e}$ ; 10) Use formula (28) and assume  $\arctan\left(\frac{1}{c}\sqrt{\left(1-\frac{1}{U}\right)}-1\right)$ ;

11) Calculate U and reinsert it in  $\arctan\left(\frac{1}{C}\sqrt{1-\frac{1}{U}}-1\right)$  to find the new value of the latter; insert it in formula (28);

12) Recalculate U until convergence is satisfactory.

13) Calculate  $u = \frac{U \ kf}{S}$ : conductance per unit area of apparent contact. For comparison, factors of Alcock, Karush and Cetinkale & F. ( /1214) ( /1057) and ( 893) resp.

are tabulated:

· \* .

## Comparative Table of Theories

Alcock		Karush		Cetinkale & Fishenden				
•				$K = \frac{k_f}{k_s}$	Conductivity number.			
		-		$B = \frac{\delta}{r_e}$	Fluid thickness number.			
				$\mathbf{U} = \frac{\mathbf{u}\delta}{\mathbf{k}\epsilon}$	Conductance number.			
				k <sub>f</sub>	Equivalent thermal conductivity of the fluid.			
		Ratio of "neck" to $\alpha =$ "bottle"	r_ r <sub>o</sub>	$C = \frac{r}{r_e}$	Constriction number.			
Conductance per unit area:	C		h	u	Conductance per unit area.			
Contact Pressure	Ρ		-	p	Pressure.			
Thermal	K		k	ks	(s = solid)			
Conductivity:	Ŕ		-	M	Meyer hardness.			
(Size	L		-	β <sub>c</sub>	Mean height.			
Surface				E < 1	A shape factor.			
factor				λ	Wavelength of the roughness.			
Shape	e S			Ψ Σ	Constants for a definite type of surface.			
For dissimilar K,	/K 2	ж	. Ar.	k <sub>1</sub>	Mean conductivity of solid 1.			
surfaces:	, - <i>K</i>		1/12	k <sub>2</sub>	Mean conductivity of solid 2.			
Factor expressing the extent to whi the surfaces are interlocked.	.ch		-	-				
_		Resistance to bottlenecking the heat flow:	R1	-				
_		Length of plug:	L	8	Thickness of the fluid between the solids.			
For dissimilar								
surfaces: B./B.:								
~1/ 22)					·			

4

 $L_1/L_2;$  $L_1/L_2;$  $S_1/S_2.$ 

é s

Special cases of metals in contact, involving local hot spots, have been treated mathematically by several authors of the AEC of U.S.: References 280, 25, 41, 21, 16, 18, 23, 17, 27 and 22 of /1226. As far as can be seen from the abstracts available, perfect thermal contact has been assumed.

1.1.1.5.1 As mentioned on page 70, the <u>surface roughness</u> is one of the obstacles to correlation of experimental results, and it is not discussed in much detail by any of the above-mentioned authors. According to Broadston (p. 24-28 of /803), surface-roughness measurement and designation standards have been published by ASA for the first time only five years ago, in 1947, as B 46.1 "Surface Roughness, Waviness and Lay".\*

Table I on p. 24-29 states standard roughness height values (Microinches)

1/4	4	13	40	(125)	400	It is recommended
1/2	5	(16)	50	160	500	that the encircled
1	6	20	63)	200	600	values be given
2	8	25	80	250	800	preference because
3	10	(32)	100	320	1000	standard sets of

flat surface roughness specimens for fingernail tactual comparison conforming to these roughnesses are available.

Carter & Thompson (p.438 of /1242) in their table 25 have three more: 4000, 16 000, and 63 000 microinches root-mean height of irregularities Mikelson( /1243) brings a comparative table of two qualifications for the roughness: a) Roughness, average, by a profilometer, or calculated; b) roughness, average, peak-to-valley, by surface analyzer, a profile recorder, or calculated.

a) 4 8 16 32 63 125 250 500 1000 2000

\* B 46.1 was not available in the Engineering Library, nor in E.I.C. lib.

#### b) 15 28 56 118 220 455 875 1750 3500 7000

Mikelson describes how these figures are arrived at: ".... samples are measured both by the profilometer and the surface analyser. Where the range of these instruments is exceeded on the rougher specimens, a profile curve is plotted by a Gen. Elect. profile recorder, and the average roughness value of the profile calculated by dividing the peakto-valley height by a factor of 3.5. Studies of this ratio seem to indicate that for smooth surfaces the ratio may be considerably higher, but for rough surfaces where the profile is relatively simple, the factor of 3.5 is approximately correct".

Broadston (p.24-28 of /803) quotes more detail from B 46.1. "Although both shape and length of the irregularities may affect the overall performance of a given surface, the standard deals only with their height, width, and direction. The standard also permits the maximum allowable roughness width (repetitive units of the dominant surface pattern due to feed) to be specified in inches (adjacent to the lay symbol). For a simple, regular profile, (Fig. 2) where all the peaks and valleys occur at regular elevations, the peak-to-valley height is simply the distance between these elevations, expressed in microinches. For a highly irregular surface profile (Fig. 3) it is customary to use one of two interpretations: 1) the maximum peak-tovalley height, which is the vertical distance between the elevation of the highest peak and that of the lowest valley, or 2) the average peak-to-valley height, which requires a personal factor of interpretation to determine the average elevation of the peaks and the average elevations of the valleys and then the vertical distance between them. .... these measurements ... can hardly be classed as specific or

Futhermore they make no allowance for the duplicable measurements. shape of the irregularities, a vital factor in performance. Height ratings may also be expressed as an average deviation from the mean surface ... located in such a way that the volume of the peaks above it is equal to the volume of the valleys below. The arithmetic average deviation of the surface of the irregularities from the mean surface .... and the root-mean-square average ... are not strictly mathematically equivalent, but general agreement exists that the difference between them is negligible for surface-roughness measurements. It appears (1949) that the arithmetic average deviation from the mean surface should be used in preference to other values since commercial roughness-measuring instruments are calibrated for a similar value, and as future national standards may prefer it because it is simple to define and explain.

Waviness refers to those irregularities which are of greater spacing than roughness irregularities. Waviness heights are usually specified as maximum allowable peak-to-valley heights and with the approved standard values given in Table 2.

(in	inches):	0.00002	0.00008	0.0003	0.001	0.005	0.015
		0.00003	0.0001	0.0005	0.002	0.008	0.020
		0.00005	0.0002	0.0008	0.003	0.010	0.025

Waviness is usually measured by using a sensitive dial indicator. Waviness widths may be specified directly in inches, but no provision for such specification is included in the approved surface-roughness symbol\*.

Finally, the tracer-point sharpness should be mentioned. Williamson (p. 319 /846) has tested the diamond points "of the 0.0005 in. tip radius commonly used in this instrument." (profilometer).

Roughness readings of the specimens were made using standard profilometer equipment including a type  $\int$  tracer and type U "mototrace". The tracing speed supplied by the mototrace was 0.22 ips, and the length of the trace was just less than the 2-in. width of the specimen. Regardless of the smoothness of the piece, a tip radius of 0.0005 in. (500 microinches) Exceptions as in the case of ground glass are bound should be adequate. to occur, and may even be found on metals, although such an exception has never come to the attention of the author". To this the writer would remark that such a tip radius (500 microin.) might be satisfactory for comparative measurements, however for absolute measurements he would expect a tip radius small enough to reach to the bottom of the roughness irregularities.

1.1.1.5.2. Jacobs and Starr ( /944) polished the test surfaces to "optical flatness", which could mean anything between 1/4 and 1/2 microin. /1198) polished the surfaces for 20 minutes with No. K. & Tampico ( 2/0 emery cloth flooded with lard oil and remark, that "a surface polished with 2/0 emery cloth is actually quite rough". One could expect to have them between 2 and 8  $\mu$ -in. Keller ( /945) shows the probable wave form and proportions in Fig. 6-d, where max. peak-to-valley distance is 0.00073"; thus the r.m.s. roughness value could be near to 250  $\,\mu$ -in. /942) worked already to ASA specs. and used the K. & Potter ( Profilometer. "A medium range of roughness was obtained by ruling in a grating engine (machine?), and an extreme roughness range was made by milling". Roughness (r.m.s.) was between 3  $\mu$ -in. and 4 150  $\mu$ -in. The ruled grooves had a 45° inclination of the sides. Brunot & B.

( /941) in Fig. 3 present a photograph of their surfaces ranging from 4 to 2000  $\mu$ -in. "Actual roughness in  $\mu$ -in. was not measured; the

surfaces were cut to match the standard specimens". Weills & R. had /948) ground their test surfaces in one of two roughness ranges; ( 10  $\mu$ -in. (rms) was considered smooth and 50 to 100  $\mu$ -in. (rms) was chosen as the range for the rough surface. Roughness measurements were made either with a profilometer or a Brush surface analyzer. (893) used a Talysurf instrument for roughness Cetinkale & F. ( measurements and report the arithmetic-mean distance between the two test surfaces in contact from 12 to 570  $\mu$ -in. Fishenden & Kepinski\* /942) made two separate cuts, L to the axis, with reciprocating The surfaces could hardly have been better than 1000  $\mu$  -in. saw. 1.1.1.5.3 Since solid spots can be formed only at the crests of the roughness "waves", Centikale & F. measured the wavelengths from 8600 to 34 000  $\mu$ -in. K. & Potter ( /947) do not give their wavelengths, however those could be roughly estimated to be 2(h+y). Keller's Fig.6-d indicates a wavelength of some 3 300  $\mu$ -in. Nothing is known of the wavelength of test pieces of other experimenters. The shape of the irregularities of surface has received attention by Keller ("multiplier is found to be 1.40" or E of Fishenden and Cetinkale in this case would be  $\frac{1}{1.40} = \sim 0.72$ ), by Cetinkale & F. ( $\varepsilon = 0.61$ ), and by K. & Potter The latter, in their effort to have the surface roughness /947). as reproducible as possible, ruled the specimens with a diamond point and assumed that the surface consisted of a series of isosceles trapezoids each having a width at the top of from 0.0005 to 0.001 in. The rough specimens were examined by both comparators and micrometer microscopes. Probably these measurements led them to the conclusion (see page 70) that ASA rms system is inadequate.

\* received September 5, 1952.
<u>1.1.1.5.4</u> Only Weills & R. ( /948) checked the <u>flatness</u> of the surfaces by comparison with a standard surface plate, and found it to be within the accuracy of the dial gage employed or <u>+</u> 0.0001 in.

1.1.1.5.5 Changes in roughness during tests are recorded by K. & Potter, who calculated the flattening of the ridges from a width  $\chi$  to a width  $W = \chi + 2\delta + 2\sqrt{\chi \delta + \delta^2}$ ; they found the values of  $\delta$  (Fig. 12) from Huggenberger tensometer measurements, corrected for the elastic deformation of the solid steel cylinders. Weills & R. applied a preliminary pressure treatment: the test surfaces were pressed together at room temperature under the maximum anticipated load, to smooth out unusual high spots on the surfaces which would produce an abnormally high resistance, then cleaned and reassembled for test runs. Roughness measurements, following pretreatment, indicated a maximum smoothing of the surfaces of about 20%. These only were recorded. An additional decrease in roughness was usually found following normal operation at the test temperature. Cetinkale & F.

( /893), to the contrary, report that no detectable change was found in roughness values taken before and after tests. K. & Tampico ( /1198) mention that there was no appreciable change in total area with pressure in the case of steel specimens. K. & Potter ( /947) left the contacts overnight under full pressure. In the morning the strain gage readings remained the same. They reason that the plastic part of the deformation takes place rapidly and that time is not a factor in this type of measurement at the pressures used.

1.1.1.6 <u>Hardness</u> of the material is recorded, for use in the calculations, only by Cetinkale & F., as Meyer hardness. Weills & R.

( /948) report Shore monotron hardness figures characterizing materials tested.

<u>1.1.1.7</u> <u>Contamination of surfaces</u> has received attention already from the earliest experimenters Northrup (p. 96 /1246), Van Dusen (p. 742 /1247), and Jacobs & Starr ( /944), however not always recognized as a factor in later tests.

Contaminants can come: 1) from the atmosphere, as gas or water vapor; 2) from other objects such as table-tops, containers, wrapping, including hands of experimenters supplying sweat and grease; 3) from impurities in the metals themselves.

Herring ( /1193) states that even the theory of uncontaminated surfaces is still in its infancy, and confines his paper to a merely qualitative exposition of the distribution of electronic density and of surface energy. Uhlig ( /1192) goes more into practical consideration of surfaces and Udin ( /1194) considers wetting phenomena; all three papers appear in the 1952 book "Metal Interfaces".

Herring represents the work function  $\emptyset$  of metallic surface as  $\emptyset = \emptyset_0 + D$  ----(1); only D is considered, because  $\emptyset_0$  concerns the bulk properties rather than the surface properties of the metal. Two double electrostatic layers are shown to explain the phenomena: 1) a negative layer just outside the surface with highest peaks of roughness protruding; a positive layer inside, near the surface; 2) a less pronounced opposite double layer with the positive part adjacent to the positive part of the first double layer and the negative part below it. Actual numerical calculations of D are known only for sodium (Bardeen). In the appendix it is shown how the work function can be measured experimentally: 1) in photo-electric emission, 2) in thermionic emission, 3) in contact potential difference. Surface energy is then considered. The ratio of surface tension to binding

energy is abnormally low for metals: approximately 1/6 as compared to 1/3 - 1/2 for the liquid phases of the simpler substances enumerated. /1194) distinguishes between surface tension (and energy) and Udin ( interfacial tension (and energy). The former refers to a solid or liquid in equilibrium with its vapor in a vacuum or a noble\* gas atmosphere. The latter refers to all other cases because of the gas as a second substance. The surface atoms are at an energy state intermediate between that of the interior atoms and vaporized atoms. This excess energy in the surface supplies the driving force for any process which leads to a decrease in surface area. Uhlig ( (1192) explains that a metal surface constitutes a portion of the lattice where surface atoms may have only half the usual number of neighbors. This means that the strength of each bond per surface atom must be appreciably greater than the average for the Also the attraction of surface atoms to their neighbors in the lattice. surface must be somewhat greater than applies to the inner atoms of the It follows that the characteristic atomic radius must also be lattice. less than the radius assigned from density or X-ray data. A compromise is arrived at: The body of the metal is under compression and the surface This surface tension in solid metals is proved experiatoms in tension. mentally as well. Any adsorbed substance weakens the surface bonds and A metal surface has greater affinity increases the metal atomic radius. for some substances of the environment than for others, in the same sense that chemical affinities are specific. Oxygen, for this reason, is often attracted to a metal surface more than Nitrogen. The range of surface

<sup>\*</sup>Why here noble gases would be different from other gases is not understood by the writer. Jnanananda ( /1244) quotes Bawn's data: "The thickness of the adsorbed film of ...argon was not greater than would correspond to a unimolecular layer." Is not Argon a noble gas? However it affected the surface tension as compared with conditions in vacuum.

forces is rather short, as proved, for example, by crystal cleavage experiments, and is in the order of an atomic diameter (10<sup>-8</sup> cm). Specific affinities of metal surfaces, therefore, can be greatly diminished or cut off by single molecular or atomic layers of the environment. If multiple layers form on metals, those beyond the first are almost always held by much smaller forces, especially for substances strongly bonded to the metal. Jnanananda (p.276, /1244) explains Langmuir's theory: Gas molecules are in ceaseless agitation and strike at random any surface with which they come in contact. The rate at which they strike a surface has a definite value, which is given by expression 1-48 b. According to Langmuir, in almost all cases and at all temperatures the molecules striking the surface do not rebound but are held at the surface by the field of force surrounding it so as to form a film which tends to continue the space lattice of the solid. While this process, which is in a way identical to the condensation of vapors on solid surfaces, continues, evaporation of the condensed layer goes on as an independent process. At highly elevated temperatures, this latter process is rapid, and the surface becomes practically free from the film of gas molecules. If. on the other hand, the field of forces on the surfaces be relatively intense, the rate of evaporation is negligibly small, and the surface becomes completely covered with a layer. Langmuir regards the direct result of such a kinetic equilibrium between the rates of condensation and evaporation as adsorption. In the case of true adsorption, this layer is usually unimolecular, for as soon as the surface becomes covered by a single layer one molecule deep, the surface forces are, so to speak, Uhlig ( /1192) continues that Langmuir showed that saturated. physical adsorption could be represented by an equation of the type

 $X = \frac{abp}{1+ap}$ , where X is the amount of gas adsorbed per unit area of surface, a and b are constants, and p is the pressure (Fig. 4) The substance, called adsorbate, may establish an equilibrium concentration on the surface. If the metal atoms leave their lattice to form the new lattice of a chemical compound (such as a metal oxide), a continuing chemical reaction occurs and equilibrium is not established. Something in between the physical adsorption and the chemical reaction is, according to Uhlig ( /1192), chemisorption or chemical adsorption. While physical adsorption may be reversible (gas comes off at reduced pressure), chemisorption is irreversible (gas cannot be recovered by vacuum). The emount of adsorbed gas decreases with rising to for physical adsorption and increases, within limits, with rising temperature for chemisorption. Physical adsorption is general, and not specific for the surface or for the gas; chemisorption is highly specific. Ph. ads. is rapid; a layer forms in less than a second. Chemisorption is much slower; it may The heat of ph. ads. is about 500-2000 cal/g mol of adsorbed be slow. gas, while for chemisorption it is from 10 000 to 100 000 cal/g mole of adsorbing substance. Examples of the specific chemisorption are oxygen on tungsten and hydrogen on nickel, while oxygen on glass or nitrogen on copper are not chemisorbed. (p.5 /1266) Miller et al. evacuated the system to pressures below one micron with the viscometer at 300°C ... to remove adsorbed oxygen from the surfaces of the glass.

It follows from the above description of adsorption phenomena, that there are no clean metal surfaces while exposed to the atmosphere. To get absolutely clean metal surfaces one has to apply high vacua and high temperatures ( /1244) and sometimes has to heat the metal first in a hydrogen atmosphere, to displace the adsorbed gas by hydrogen,

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and then outges the metal in vacuum, to eliminate the dissolved hydrogen. As mentioned on p. 59, if such clean surfaces touch, cold welding results ( /1192). Shaw & M. (p.500 /1253) quote Bowden: "The observation that the friction of naked metals is very high (some 20 times greater than that of the normally clean metals) makes us realise how fortunate it is that, in engineering practice and, in fact, in many every day affairs, metal and other surfaces are contaminated with oxides and other films. If it were not for the fact that metal surfaces (even when we think that we have cleaned them thoroughly) are coated with comparatively thick layers of oxide, "dirt" and other contaminants, much of our machinery would come to a sudden and disastrous stop".

Application of solvents, for cleaning purposes, is a process analogous to reduction of gas pressure (p. 319 /1192). The amount of solvent applied, therefore, should be such that the concentration of the solute in the solvent would correspond to a gas residue in a high vacuum. A number of applications of fresh solvent may be necessary.

In connection with questions of wetting and corrosion, the following statements by Uhlig (p. 323, /1192) on intentionally "contaminated" surfaces may be of value:

"Stainless steels, defined as ferrous alloys containing at least 12% chromium, are considered on this viewpoint to be covered with a partial or complete monolayer of oxygen chemisorbed on the surface (Fig. 8). This film of negatively charged atoms, analogous to the film on tungsten, is considered responsible primarily for the observed passivity and noble galvanic potential. Some investigators believe instead that a protective oxide film forms which isolates the metal from its

environment, and that this oxide is the cause of passivity. The physical barrier oxide film, however, is not as satisfactorily in accord with the For example, CO, which is an excellent inhibitor (passivator) facts. for the corrosion of 18-8 stainless steel in hydrochloric acid, and which like 02 produces a more noble potential, is not a likely source of any oxide film. Carbon monoxide can, however, readily satisfy surface valence forces because of the known affinity of CO for the alloy components, as exemplified by the metal carbonyls. When an adsorbed oxygen film on stainless steels is responsible for passivity, an oxide may form eventually, especially in the presence of halides or halide ions, or through abrasion or polishing which induces very high local surface temperatures. Such relatively thick films can be detected by various means, or isolated and examined. These oxides, however, are thought to be of secondary importance in accounting for corrosion resist-The primary passive film, according to the writer's viewpoint, ance. is the adsorbed partial or complete monolayer of oxygen, or any other substance of the environment having high affinity for the alloy. Similarly, chromates, which are among the best corrosion inhibitors for iron, are thought to chemisorb on iron as a partial or complete monolayer of negative ions (Fig. 9), thereby satisfying surface valence The passive surface, plus a dipole layer with forces of the metal. negative charge outward, accounts for a marked noble galvanic potential. Again, any thick layer of oxide or metal chromate forming in due course is thought to be a secondary factor in the corrosion protection, rather than the primary cause of passivation."

Already Northrup, in 1913 (p. 96 /1246), mentions "very large surface film resistance which is found at the surfaces of thermal When Van Dusen ( conductors". /1247) stated that mica split into thin layers and subsequently squeezed together has a considerably greater thermal resistance than unsplit material, he had in mind either /944) the air spaces or the surface films, or both. Jacobs & Starr ( found that the slightest trace of grease resulted in an increased conductance at room temperature and a seriously decreased conductance when, at In all cases they found the low temperatures, the grease became hard. thermal conductances much smaller at low temperatures, probably due to adsorbed surface films. For gold and copper contacts progressive decrease of conductance with time, after cooling, was observed. This behavior would also indicate the formation of surface films, as the temperature Their tests were conducted in vacuum, without conduction or goes down. convection losses; a technique which has been used by Eichelberg ( /1248) too.

K.&Tampico ( /1198) washed their oily specimens first in varsol, then in alcohol, then dried them in a desicator, and washed again in alcohol before mounting in the machine. Aluminum specimens were mounted and tested without storing them first, to avoid oxidation of surfaces. They do not mention any observations with reference to any film resistance, which, no doubt, was present.

Keller's surfaces were "as manufactured" ( /945), however he is particularly well informed about gas-films.

K. & Potter ( /942 ) wanted to avoid impurities within  $\overline{}$  the metal specimens differing from those of other metal specimens,

**90**°

so they cut all the samples from the same rod. The finished specimens were coated with a Dearborn rust preventive and packed in ordnance grade Test pieces were washed twice with a solvent, grease-proof wrappers. and no specimen was used a second time. When test pieces were found heavily oxidized at the completion of a run, argon was used as a protective atmosphere, and then the specimens were clean and only slightly discolored after a run. The "unexplainable", appreciably lower, thermal resistances of the contact in argon atmosphere would probably become explained if adsorption phenomena and film resistance would be investigated. The authon, apparently have not paid much attention to this, according to their statement: "Also little is known of the heat conductance of gas Brunot & B. ( films of the order of one mil or less in thickness". /941) are well aware of the "dead air and oxide layers in the space between the surfaces" and use also rusted specimens and multilayer For their 4-rm s (lapped) specimen they suspect aluminum foil shims. "that some other resistance now dominates, such as the oxide film over the entire surface". "For more than 5 layers of foil the effect seems to be slight, and the resistance may be increased as the number of layers becomes large due to resistance between the layers of foil." (p. 326

/1259) Gilliland mentions "In building a nuclear reactor from blocks of graphite, one of the chief resistances to the flow of heat will be the gas films between the blocks, and the materials in the reactor. In such cases it may be desirable to fill the reactor with a gas of high thermal conductivity, such as helium, to improve the transfer across the gaps".

Weills & R. (/948) quote Holm (/943) in that the presence of a film of oxide or other foreign material of low thermal

conductivity could contribute to the thermal resistance of the joint. However their calculations have shown, they report, that except at very low pressures the oxide resistance appears to account for only a small part of the total resistance.

Fishenden & Kepinsky ( /942) did not treat the saw-cut surfaces in any way, nor refer to gas or oxide films, except that they express the contact resistance in equivalent thickness of an air space of about 0.001 inch thick.

Ellerbrock ( /1151) does not explain the nature of the bond between the steel barrel and the aluminum fins nor mentions the unavoidable oxide layer on the surface of aluminum.

Eichelberg ( /1248) and Manganiello & Bogart ( /1152) experiment on internal-combustion engines and report the rates of heat transfer across oil films, however they do not mention Langmuir's monomolecular film on the metals.

Cetinkale & Fishenden ( /893) do not describe in their paper any adsorbed layers or oxide films. However they are aware of the influence of rust on their test surfaces. They kept the contact surfaces coated with a rust preventer, but cleaned them with solvents immediately before a test.

A quantitative investigation of adsorbed layers and oxide films, in connection with heat transfer, remains to be done by future experimenters.

It could be mentioned here that such studies have been done in other connections, such as friction, corrosion, etc., for example by McFarlane & Tabor ( /1220), Rothen ( /1005), Feitknecht ( /1006) and others. Contamination of surfaces by metal transfer from the other surface may not be important, as the transferred quantities, between stationary surfaces, are very small: only of the order of  $10^{-10}$  g in an experiment by Rabinowicz & Tabor ( /1224), who used **autoradiographic** techniques to detect and estimate these small fragments of a side length of about 10000Å.

<u>1.1.1.8</u> Radiaction across the gap has been calculated by Jacobs et Starr and by Keller. The former ( /944) observed that "at zero pressure" the thermal conductance was approximately the same when the surfaces were "just touching" or separated by a few millimeters. This radiation conduction is less, they say, than  $10^{-3}$  watt/cm/°C.

The latter ( /945) represents the 100 layer-per-inch coil as an almost ideal heat insulator (from radiation): its average equivalent thermal conductivity is only 0.0014 Btu/ft hr °F or less than 1/8 of one per cent of the total conductivity of the coil (radially). Were the surfaces oxidized, he says, the percentage would be 2-1/2%.

An interesting application of radiation is found in F. & Kepinski's paper ( /942). The surface of their test rod was coated with deadblack camphor soot, so that its emissivity was known and the 'radiation from it could be calculated as  $1.73 \times 10^{-9} \times 0.96$  ( $T_r^4 - T_s^4$ )  $Btu/ft^2_{hr}$ , where  $T_r$  is the surface temperature of the rod and  $T_s$  the temperature of its surroundings, in degrees Rankine. Since the temperature along the rod did not vary linearly with distance, the surface convection and radiation losses were calculated separately for each one inch length, and added for the total length in question.

1.1.1.9 Conduction across the fluid in gap has received considerable attention, however the "form factor" of Keller (discussion on Weills & R.,

/948), varying from 1-1/4 to as much as 3-1/2 times that which p. 267, would exist if the air-film thickness were entirely uniform, appears only once again, in Cetinkale & F. paper ( /893), as  $\frac{1}{6}$ . Percy in (945) reminds the readers that a discussion of Keller's paper ( should the air film thickness between wraps approach the mean free path of the gas, the laws of conductivity would no longer hold, but the heat transfer would reach a constant minimum. Keller's answer is, that the mean free path for air and similar gases at room temperature is about "2-1/2 microinches, while the minimum gas-film thickness is believed to be about 120 microinches, thus far above the limiting value. It is a pity that K. & Potter ( (947) used argon and air and did not try to find out more about the phenomena involved.

Brunot & B. ( (941) mention the expectance of increased or decreased contact resistance if thegas between the surfaces would be other than air, however have not experimented in this direction. Weills & R. ( (948) experimented with air, oil, and copper plating. Cetinkale & F. ( (893) used air, spindle oil, and glycerol, but report only that the experimental results agree well with the theory, while Weills & R. found inconsistency in the general slope of some curves for oil . Apparently Cetinkale & F. results were good because they traced the actual profile of roughness and found the mean fluid thickness by planimetring; K. & Potter could have done it for the The shape of roughness K. & Potter used was even case with argon. better adapted for this purpose because it was regular. A repeated experiment, using regular shapes of roughness, and checking by volume measurements of the interface voids, might lead to consistent results.

Cetinkale & F. theory should be checked both on such regular profiles and on profiles of random shape. It is regrettable that Cetinkale & F. have not published complete results.

<u>1.1.1.10</u> <u>Convection</u> in the voids of the rough specimens, according to Fabry ( /795) would not be negligible, if the air space would be above 0.1 mm  $\approx$  4000 microinches. The experimenters have not mentioned convection.

<u>1.1.1.11</u> The <u>overall conductance</u> or overall resistance across the contact was, of course, recorded by all experimenters, except Ellerbrock ( /1151). As mentioned on page 64, the writer pictures a contact like that:





In terms of resistances the picture is:

Latest (as far as the writer is aware) pictures published are:



Fig. 1 of Brunot & B. ( /941) Fig. 8 of Brunot & B. ( /941)

Approximately half of the experimenters have preferred the conductance concept and the other half- the resistance concept. When comparing the plotted results one should not forget that the reciprocity of conductance and resistance is reflected in the shape of the curves. Most strikingly the straight line of Jacobs & Starr ( /944), representing conductance, reappears in Austin's book ( /792) as a hyperbola, representing resistance.

Keller (in discussion of Weills & R. /948) has another warning concerning the shape of curves. He points out, that the similarity of forms of the experimental conductance versus pressure curves to those derived from calculation of the true conductance of a single contact (both curves becoming concave upward at higher pressures) does not prove that the experimental data bear out the theory, as claimed by Weills & R. (p. 260 /948). In his opinion the air-film conductance curve can also become concave upward at higher pressures because of the additional (to the film thickness reduction) influence of the increased "form-factor", as the height of the crushed peaks approaches zero.

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1.1.2.1 A thermal circuit is established so that heat flows from a source through a test rod, across the contact, through another test rod Through a thermal circuit cannot be insulated against into the sink. leakage of heat to that degree which is possible with electric circuits, good thermal insulation is applied to the rods, to have the isothermflow-line plot as nearly as possible a net of straight lines. The gradient is found by thermocouples placed in known positions, two of When steady-state conditions them as close to the gap as practicable. are reached (only Jacobs & Starr, /944, use a transient heat-flow method), the temperature readings are plotted against distances from a reference point, and result in a curved line, if the insulation is imperfect; otherwise the line is straight; the temperature drop across the gap presents itself as a discontinuity, if the two branches of the line are extrapolated to the interface.



Van Dusen ( /1247) points out that the magnitude of the discontinuity in terms of the abscissa (i.e. along the axis) gives directly the thermal resistance of the contact or specimen in terms of centimeters of the test rod material. Thus van Dusen expresses his results in brass, K. & Potter ( /947), and Brunot & B. ( /941) in steel, Weills & R. ( /948) in aluminum, and F. & Kepinski ( /942) in air. If the diagram is scaled, to find the temperature discontinuity at the interface, the concept of film coefficient h can be used (p. 138 /826).

Griffiths ( /900) describes nine designs of apparatus for measuring (in the N.P.L.) the thermal conductivity of some non-metallic materials. The majority of these designs are of the same divided-bar type as introduced by Northrup ( /1246) however refinements are applied, as guard-tubes, wire end heaters, etc. "Considerable care must be taken in the preparation of the plane faces of the test disks and rods to minimize the effect of air films between the specimen and rods."

Results for 15 materials are tabulated.

## 1.1.2.2

Some interesting thermocouple techniques have been used. Weills & R. used a multijunction differential thermocouple, which was a composite of ten differential copper-constantan elements in series, to measure Jacobs & Starr ( the temperature increase of the cooling water. /944) used a single differential thermocouple across the gap. All other experimenters used several thermocouples in a row, each side of the interface, some even in several planes, to check the uniformity of the The spacing along the rods was from 1/4" ( temperature field. /1198) to 1" ( (941); the distance of the nearest thermocouple to the /1247) to 3/8" ( (941); in most cases interface was from 1/16" ( the holes were drilled to the center-line of the test rods; in two cases /948) the hot junctions were midway between the  $\rho$  and /947 and ( the surface; in one case the drilling of the specimens was done in a (947); for the same purpose of precision special fixture or jig ( /948) used a travelling microscope to read the spacing of another ( the thermocouples; the diameter of the holes was from 0.024" to 0.060"; the largest wire size was No. 28 and the smallest: No. 40. In one case the two wires were led out along opposite diameters (buttwelded); In another single case a copper tube was fitted snugly into the hole (947) and the constantan wire pushed through it and silver soldered ( at the tip.

In one case ( /941) the thermocouples were soldered into place; in other cases the well was filled with oil ( /1247), copper dental cement ( /948), copper powder ( /947), and mercury ( /893). Generally the experimenters have assumed that the holes are drilled along an isothermal plane. Van Dusen ( /1247) cautiously

remarks that the depth of immersion (holes 1.5 cm deep, oil-filled, in 3 cm  $\emptyset$  rods) was sufficient to eliminate the effects of lead conduction, no appreciable change in the temperature indication occurring when the junction was moved one cm away from the axis. A homogeneity test of the thermocouple wires has not been mentioned, although a temperature gradient of nearly 500 °F in some cases existed along the wires (across the insulation).

In one case only (Weills & R., /948) the temperature gradient 1.1.3. was determined by the method of least squares, and the experimenter con-The insulation ranged sequently claims 1% precision for the gradient. from glass wool 1" thick plus Foam-glass 2" thick, over baked lavite, cotton waste, etc. to no insulation at all (K. & Tampico /1198). In the latter case a statement is made that when the current was 50 Amps. (the set-up represented a resistance-welding outfit) "the temperature was uniform and equal to the ambient temperature"; the plot for this condition is a straight horizontal line, i.e. there is no temperature gradient. Apparently the heat leaked out, however the temperature measuring set-up (thermocouples + potentiometer) was not sensitive enough to record it. At higher currents the temperature readings are rather inconsistent, being up to 27°F out of the line which is supposed to join the points. Although thermal conductance was not the main concern of these experimenters (K. & Tampico, (1198) it is a little surprising that they fail to notice the discontinuity in temperature, shown on their Figs. 8 and 9, and to interpret it as an evidence of thermal resistance. Their time to reach steady-state conditions is 1/2 hr to 1-1/2 hr, while other experimenters spent about 3 hours.

Another set-up where the thermal resistance of the interface is not the chief concern, is the "thermo-electric heat flux element" of Ziebland ( /917), consisting of two concentric metallic cylinders developing a thermo-electric voltage, which is a measure of the heat flow normal to their surfaces. The author found some discrepancy between the experimental and expected performance and attributed it to the existence of surface resistances between the layers due to roughness and imperfect contact. In a later model he was able to reduce this interface resistance so that the  $\pm$  6% deviations observed were of the same order as the experimental accuracy for the mean heat flow density.

Van Dusen ( /1247) and Jacobs & Starr ( /944) claim to have attained results reproducible to within 5%, the latter by complete repolishing (to optical flatness). Weills & R. ( /948) have determined their <u>standard errors</u> to be: temperature gradient within 1%; temperature drop within 2°F; thermal current within 2%; thermal conductivity less than 4%. They checked the apparatus by measuring the thermal conductivity of metals for which handbook data were available and found for Aluminum No. 1  $112 \frac{Btu}{hr.sq.ft.} \frac{oF}{ft}$ against 120 in Alcoa handbook, and for Al No. 2: 102 against 109.

Five only experimenters have published their results in form of curves: 1) Jacobs & Starr ( /944): two temperatures; one range of pressures; 2) Ellerbrock ( /1151): one range of temperature levels; 3) Brunot & B. ( /941): one range of pressures; Weills & R. ( /948): three ranges of pressure, one range of temperature levels, one range of roughness, one range of  $\frac{1}{\sqrt{\text{Roughness}}}$ ; K. & Potter ( /947): one range of pressures, one range of temperature levels. Thus

the influence of three variables has been investigated: 1) Roughness; 2) Pressure, and 3) Temperature level.

**1.1.3.1** Nobody has attempted to <u>correlate</u> results of other experimenters with their own, not even Weills & R. whose experimental work is most impressive.

K. & Potter and Brunot & B. mention rms roughness as not suitable, when comparison with surfaces not directly used in the experiment is desired.

Weills et R. give this significant conclusion: "If the parameters governing the thermal and mechanical behavior of a metal joint were completely known, the data presented would permit the prediction of its thermal resistance with a practically useful accuracy. Due to these unknowns and to the incompleteness of this study, no attempt was made to correlate all the observed variables by means of relationships which might be obtained by means of dimensional analysis". For the same reasons no correlation is attempted by the writer. 1.1.3.2 Roughness is the least measurable of the three variables mentioned, and only Weills & R. ( /948) have used it as abscissa. At 300 F and 10 psi they found that thermal conductance increases roughly tenfold when Roughness decreases hundredfold. At 300 F, when  $\frac{1}{\sqrt{R}}$  increases (roughness decreases) thermal conductance increases and the curves for higher pressures lie above those for lower pressures. /941) and F. & Kepinski ( /942) experimented also Brunot & B. ( with alignement of the scratches and placing them at an angle, however the results are not conclusive. Rusty surfaces are much less conducting than clean surfaces. The difference is more promounced when smoother surfaces were permitted to rust (Brunot & B.)

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Soft shims, like aluminum foil (Brunot & B.) or copper plating (Weills & R.) apparently flow under pressure and fill the voids thus substantially increasing the conductance of the joint. Alcock ( /923) mentions good practical results with copper plated cylinder liners. Brunot & B. found that with many thin Al foils the conductance may decrease again "due to the resistance between the layers of the foil". The writer suspects this to be the effect of the many layers of the oxide film invariably present on both sides of the Al foil.

When the voids between the rough surfaces are filled with some fluid other than air, the conductance of the joint increases markedly. /1247) found that when the surfaces were wrung Already van Dusen ( together with water or a glycerine solution, the effect of the contact could not be detected, being equivalent to less than 0.5mm of brass. He made use of this, to eliminate the contact resistance when inserting discs of other materials between the brass test rods, for the purpose of measuring their thermal conductivities. When he wanted to measure the k of liquids, he kept the rods separated by 3 very small mica separators and had the liquid staying between the rods by capillarity. When Brunot & B. ( (941) applied "smooth on" cement to the surfaces, the conductance was doubled and remained unchanging with pressure. (948) found that the thermal resistance is about Weills & R. ( one half as great for oil filled joints as for dry joints, at 10 psi., and that the effect of oil decreases at high pressures. They also found that at a given temperature, pressure, and roughness, the thermal resistance of both dry and oil-filled joints decreases in the order of steel, bronze, and aluminum, i.e. in the same sequence as the hardness values.

1.1.3.3 Pressure is measurable quite precisely, however in the case of contacts it too escapes exact determination, because (as mentioned on page 59) only a few points touch and there the pressure per unit microscopic area is very much higher than the pressure per unit of apparent For correlation of the results of one experimenter it would not area. matter whether total pressure or pressure per unit area is used. Otherwise, as Keller points out in the discussion of Weills & R. paper ( /948). the contact conductance is not related to the unit pressure but to the total force exerted on the contacting surfaces, because the number of a-spots is entirely independent of the macroscopic contact area. This force deforms the roughness elements in contact increasing the microscopic area of contact, and therefore the influence of pressure on contact conductance is interconnected with the influence of roughness on it. In fact, for some of the smoothest surfaces, hardly any influence of pressure has been detected (K. & Potter's 3 µ.in. specimens, /947; Brunot & B. 4 u.in. specimens, /941), probably because so many a-spots appear to be in contact simultaneously, that the local pressure on an a-spot is no more sufficient to deform it substantially. The most smooth of the surfaces experimented upon, the "optically flat" surfaces of Jacobs & Starr ( /944) seem to disprove this explanation if adsorption (which is increasing at lower temperatures) is left out of the picture. Again the smoothest of Weills & R. ( /948) surfaces of 10 p.in. roughness do not support K. & Potter's and Brunot & B. observations. Brunot & B. suggest that the pressure may make the rough spots indent the surface of the other block and thus allow more projections to come in contact. In addition to the substantially increased roughness value, the writer would try to find the reason in different

hardness and in a different type of roughness (thinner vs. flatter peaks) of the materials tested.

An interesting phenomenon has been observed by Weills & R .: "a hysteresis-like loop in the thermal conductance-pressure relation is obtained when the pressure is decreased following an increase." Their explanation is: "The metal-contact areas behave elastically following an initial plastic deformation." It appears as if a number of the junctions at the a-spots (metal surfaces brought close to each other, within the reach of molecular forces), which were formed later (and thus are less compressed than those formed earlier), have passed the zero stress and are now in tension produced by another number of the junctions made earlier and still remaining in the state of compression. Gradually, as the load is removed, one by one (McFarlane & Tabor /1220) the weakest junctions are broken, until the decreased total force exerted by the coming out of compression a-spots balances the total tensile stress of the non-broken a-spots.

The maximum pressures used were:

1.1.4.1

Jacobs & Starr	(	/947)	30 psi.
Van Dusen	(	/1247)	65 psi.
Brunot & B.	(	/941)	300 psi.
Cetinkale & F.	(	/893)	800 psi.
K. & Potter	(	/947)	3200 psi.
Weills & R.	(	/948)	8000 psi.
K. & Tampico	(	/1198)	40000 psi.

The maximum (dry contacts in air) resistance figures observed were: Van Dusen ( /1247) brass,  $2.6 k_g/cm^2$  17°C 5.0 cm. of brass rough ground

Brunot & B.	(	/941)	Silicon steel, 2 laminations 🔟	5 psi.	100°C	13.5 <u>deg C</u> watts/sq.in.	
91 H 11			Steel blocks 1000µin., shaped ⊥cuts, clean	2 psi.	100°C	4.2 <u>deg C</u> watts/sq.in.	
Fishenden & Kepinski	(	/942)	Steel, "minimum" sawcut	press .	?	0.00236 inches of air layer.	
K. & Potter	(	/947)	Steel, extreme roughness, 3320 'in. "rule by 90° milling o	95 psi d" utter	170°F to 197°F	0.00225 <u>hr ft<sup>2</sup> 9F</u> Btu	
Jacobs & Starr( /944) Copper, <u>in vacuum</u> , 8 psi-195°C <u>350 cm sec °C</u> replotted by Austin( /792 "optically flat" Cal							
The minimum (dry contacts in air) conductance figures observed were:							
Weills & R.	( )	/948) S 1	teel, ground, 00 µ in	2 psi.	300°F	120 <u>Btu</u> hr ft20F	
		a	round, 100 µ in	2 psi.	300°F	290 <u>Btu</u>	
		b g l	round 10 00 μin	0 psi.	300°F	hr ft2 °F 800 <u>Btu</u> hr ft2 °F	
Cetinkale & Fishenden	(	/893)	?	?	?	550 <u>Btu</u> hrft <sup>z</sup> of	
The minimum (dry contacts in air) resistance figures attained were:							
Northrup	(	/1246) "very	Cu, true surfaces"	1.6 kg on 3.8	cm Ø	31.2cm of Cu	
Van Dusen	(	/1247) "fine	brass ly ground"	4.4 kg	/cm2	0.85 cm brass	
Brunot & B.	(	/941)	Silicon steel, laminations $\bot$	200 pa	i 100 <b>°C</b>	9.7 $\frac{\text{deg. C}}{\text{watt/sq.in.}}$	
<b>н п 11</b>			steel blocks, 4 $_{i}$ in. lapped	300 ps	1 »	0.18 "	
F. & Kepinsk	i(	/942)	steel, m <sub>minimum</sub> sawcut	" press	•	.00081 inches of air layer	
K. & Potter	(	/947)	steel, 32 µ in. ruled	15 <b>7</b> 5 ps	i 670°F	.00003 <u>hr x ft<sup>2</sup> x °F</u> Btu	

The maximum (dry contacts in air) conductance figures attained were: /944) Cu <u>in vacuum</u> "optically flat" 2.3 kg/cm2 - 195°C 0.05 <u>watts</u> cm<sup>2</sup> °C Jacobs & Starr ( 1100°F 0.025 <u>Btu</u> ft hr °F Keller ( /945) strip coil, 10 psi. 100 per in. 500°F 16000 <u>Btu</u> hr ft<sup>2</sup>°F Weills & R. /948) steel, ground, 270 psi. (  $10 \mu in.$ aluminum, gound, 270 psi. 10 µ in. 500°F 16000 bronze, ground. 2800 psi. 100 µ in. 500°F 16000 Ħ Cetinkale & F. ( /893) ? 12500 ? ?

Some of the general conclusions of the experimenters are, speaking of conductance:

- Jacobs & Starr: "Only in the case of copper does the conductance vary linearly with contact pressure."
- Weills & R. ( /948): "The thermal conductance of a dry joint increases with pressure, linearly for steel and generally exponentially for aluminum and bronze, and decreases with a decrease in the roughness of the surfaces."

Speaking of resistance:

- K. & Potter ( /947): "Thermal resistance decreases with pressure in a manner which is essentially exponential. The rate of decrease is greater for rougher surfaces. For very smooth specimens the thermal resistance is practically independent of pressure."
- K. & Tampico ( /1198), concerning the electrical contact resistance of steel specimens: The change in contact resistance with pressure is most rapid in the range from 0-10000 psi. At pressures above 10 000 psi the change is relatively slow.

## 1.1.4.2

The temperature level at the interface ranged:

Jacobs & Starr	(	/944)	-195°C,		25°C			
Van Dusen	(	/1247)	15°C	•	39°C			
Cetinkale & F.	(	/893)		180°	F			
Ellerbrock	(	/1151)	10°F	-	200 <b>°</b> F			
Brunot & B.	(	/941)		10 <b>0°</b>	C			
Weills & R.	(	/948)	300°F,		.500°F			
Eichelberg	(	/1248)	250°C	-	360°C	(exhaust	valve and	seat)
K. & Potter	(	/947)	330°F	-	700°F			
K. & Tampico	(	/1198)	20°C	-	50 <b>0°C</b>			
Keller	(	/945)	~ 1	looof	,			

There is not much comment on it by the experimenters. K. & Tampico explain the decrease of (electrical) contact resistance by softening and yielding of the intimate contact points on the contact surfaces under the combined influence of temperature and pressure. In their case the local temperature at the a-spots may have been higher than the temperature measured, because heat was produced by passing electric current through the test pleces, and the actual current density, as contrasted to the apparent density, must have been much higher.

Weills & R. ( /948) mention that the average ratio of the conductance at 500°F to that at 300°F is 1.5. They explain that at low pressures the thermal conductance of the joint is proportional to the thermal conductivity of air, and inversely proportional to the thickness of the void space, and that the thermal conductivity of air increases by 20% with increase in t° from 300 to 500°F (p. 391 /790). At a given pressure the thickness of the void space, they continue, should be a function of the mcdulus of elasticity or hardness of the metal

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depending upon whether elastic or plastic deformation is considered. Upon increasing the t<sup>o</sup> from 300 to 500°F these quantities are reduced in a ratio of 1.4 for the elastic modulus (Ref. 5 of /948) and 1.8 for hardness (Ref. 6 of /948), which is in general agreement with the conductance measurement. At the higher pressures, they conclude, where the dominant heat flow is through the metallic contacts, the decrease in hardness should tend to increase the contact area and therefore to increase the joint conductance.

Somewhat in contrast to this is the statement of Kouwenhoven and Potter ( /947): "at constant pressure and in the absence of corrosion, thermal resistance is substantially constant as temperature level is increased."

They had trouble with corrosion at the interface and therefore substituted the inert gas argon for the atmospheric air.

Chemically active components (p. &7 of this review) are generally not present in solid-solid interfaces except as oxygen and moisture. Their action, corrosion, is discussed in pertinent handbooks (chapter 3,

/803, etc.). In connection with temperature level it should be stated that like other chemical reactions, corrosion increases with temperature exponentially (p. 297, /1254). As most liquid metal systems for heat transfer operate at elevated temperatures, inert gases are used for blanketing, to protect both the solid and the liquid metal ( /793). <u>1.1.4.3.</u> Finally some incomplete results should be mentioned. Ellerbrock ( /1151) checked the quality of a bond between an aluminum sleeve and aluminum fins on the outside and a steel cylinder on the inside. There were two interfaces in series. He mentions that the  $Al_{Al}$  fin bond was exceptionally good and that the experimental coefficients based on the temperature difference between the steel barrel and the cooling air fall about 18% on an average below the experimental coefficients based on the difference between the temperatures of the aluminum spacers and the cooling air showing that there is a drop in temperature in the bond between the steel and the aluminum. The temperature drop in the bond was 16°F max and was not uniform along the circumference.

Eichelberg ( /1248) has measured operating temperatures of Diesel engines and published reports already in 1923 and 1926. The exhaust valve and seat contact has been investigated only from the point of view of temperature distribution and thermal stresses. The piston-cylinder assembly will be considered with rubbing contacts.

Alcock ( /1250) mentions unpublished results obtained by Ricardo: Heat flow across the liner, down 13% of stroke: 67 000 Btu/(sq.ft.)(hr.); down 18% of stroke: 53 000 Btu/(sq.ft.)(hr.).
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#### RUBBING CONTACT OF SOLIDS\*

One of the earliest theories of rubbing contacts (which still stands - see /1225) is that of Amontons, published A.D. 1699 in "Histoire de l'Académie Royale des Sciences avec les Mémoires de Mathématique et de Physique."

In general, the theory has paid more attention to prevention 1.2.1. of heat generation in sliding contacts, than to the problem of conducting it away most efficiently. Attention to the actual mechanism has always been keen, however only the improved instrumentation of the 20% Century has permitted Bowden & Leb m ( /1225) to make a successful investigation on "The nature of sliding and the analysis of friction", the essence of which is: "The frictional force does not remain constant during sliding... the motion proceeds in jerks and large and violent fluctuations In the case of dissimilar metals the top surface occur in the friction. sticks to the bottom one and moves with it until, as a result of the gradually increasing pull, a sudden and very rapid slip occurs. The process is then repeated indefinitely. A simultaneous measurement of the surface temperature shows that this too is fluctuating and, at the instant of slip, there is a sudden temperature "flash". The exact behaviour depends upon the relative physical properties of the metals, particularly on the melting-point, and there is evidence that three distinct types of sliding may occur. The experiments suggest

\* Only a few publications on rubbing contacts are reviewed which the writer happened to come across without looking for them, because the subject is covered very fully in textbooks on "Friction and lubrication"

The most recent analysis seems to be that of Apkarian, of General Electric Co., in R52GL50 and R52GL52, dated March 1952, abstracted in Nuclear Sciences abstracts Nos. 2645 and 2646 of 1952. ( /1316, /1317).

that friction is due to a welding together of the metals at the local points of contact. These metallic junctions are large compared with the dimensions of a molecule and when they are broken the metal is distorted to a considerable depth.

Even if the surfaces are lubricated with mineral oils or other lubricants an intermittent clutching and breaking away of the surfaces occurs and the behaviour may be essentially the same. Certain longchain fatty acids may prevent stick-slip and allow continuous sliding to take place."

B. & Leben have found that a mean pressure of about 130 000 kg/cm<sup>2</sup> exists at the contact points, which is therefore well able to cause flow of metal, when a metal-metal junction is formed. Again, a shear stress of 50 000 kg/cm<sup>2</sup> was found, which is much higher than the ordinary shear strength of steel (6000  $kg/cm^2$  - roughly half the tensile Bowden & Tabor ( /1212) found that the real area of strength). contact of certain curved surfaces lies between 1/10 000 and 1/1 000 000 of a square cm. When a flat surface of 21 cm<sup>2</sup> area was used, which was "some million times as great as that for a curved surface, the actual value of the (electrical) conductance was almost the same." This confirms the remark of Keller (Weills & R. /948; page 112 of this Review) that the number of a-spots is entirely independent of the macroscopic contact area.

Thomas (/1251) has measured the temperatures at the a-spots: "several hundred degrees C are developed quite readily, although the mass of the sliding bodies remains quite cool. The hot spot area, as well as the temperature is varying throughout the duration of the hot spot. The hottest spots usually last about  $10^{-4}$  to  $10^{-3}$  sec. and their

area is of the order  $10^{-3}$  cm<sup>2</sup> under the specified experimental conditions... For most metals sliding on glass, surface temperatures of the order of 500°C - 1000°C are developed at sliding speeds of the order of 200 cm/sec and at a load of the order of 200g."

Rabinovich & Tabor ( /1224) have investigated the metal transfer (i.e. the wear) between sliding metals and have found that "for unlubricated surfaces the pick-up is about 40 times larger for similar than for dissimilar metals, although the coefficient of friction covers a relatively small range (~ 0.4 to  $\sim$  1). With well-lubricated surfaces the friction is reduced by a factor of not more than 20, whilst the pick-up may be diminished by a factor of 20 000 or more.... under these conditions the welded metallic junctions formed through the lubricant film play a very small part in determining the frictional resistance to motion. Consequently two lubricants possessing widely different abilities to protect the surfaces may give essentially the same coefficient of friction.... The results provide direct support for the view that the friction between metals is due largely to the formation and shearing of metallic junctions, and that the main function of a boundary lubricant is to reduce the amount of metallic interaction. The investigation also shows that the metallic transfer is immensely more sensitive to changes in surface conditions than is the coefficient of friction.

<u>1.2.2</u> One of the important discoveries about friction was that of Langmuir (Ref. 202 of /1253) that certain polar molecules (oleic acid, stearic acid, etc.) are much like a stick with a suction cap at one end (or like a lamprey) and that they have a very strong affinity for metals. "... the force with which an adsorbed film is attached to a surface may be just as large as though it were chemically combined with

or welded to, the surface". (p. 489, /1253). "Adsorbed molecules orient themselves with their polar end groups attached to the surface in a closely packed arrangement; the long hydrocarbon portion of the molecule extends from the surface in approximately perpendicular direction.... several layers of molecules may be oriented in this manner. When surface asperities pass each other, the pilelike structure that is formed will prevent metal-to-metal contact; but at the same time the surface asperities should offer little resistance to motion because of the flexibility of the long-chain molecules." (p. 490, /1253).

<u>1.2.3</u> The following classification of sliding surfaces can, consequently, be made (pp. 5, 7, /1253):

- 1) sliding of absolutely clean metal surfaces (outgassed in vacuum);
- 2) sliding with extreme-boundary lubrication ("normally" clean dry surfaces, or when lubricant fails) when the load is such that even the adsorbed molecules are torn off and welded bridges are made and broken at the high points of the sliding metal surfaces;
- 3) sliding with boundary lubrication when, at times, the "tail ends" of the adsorbed long-chain molecules brush those on the opposite metal surface;
- 4) sliding with fluid-film lubrication ("hydrodynamic" lubrication), when a wedge-shaped oil film, several hundred molecules thick at least, is forced, by the movement, between the surfaces and lifts the upper surface (against the load) so that it is floating on the lubricant.

The two experiments on heat transfer across lubricated solidsolid surfaces ( /1248, /1152) should fall within the class of fluid, film lubrication, because the clearance for boundary lubrication conditions should be about twice the length of a polar molecule, which is shown on page 6 /1253 as having a length of 0.1  $\mu$  in., while the minimum clearance in Fig. 6 of /1152 is  $\frac{0.01"}{2} = 5000 \ \mu$  in.

<u>1.2.4</u> Hersey (Ref. 25 in /1252) seems to have been the first to apply <u>dimensional analysis</u> to friction problems and to introduce the  $\frac{2N}{P}$  (or  $\left(\frac{N}{P}\right)^{as a}$  combined variable. Later a dimensionless Sommerf-eld number  $\left(\frac{r}{c}\right)^2 \left(\frac{\mu N!}{P}\right)^{a}$  appeared (p. 181 /1253) which "bears the same relationship to journal-bearing theory, as the Reynolds number does to fluid mechanics". Some consideration to heat transfer problems is given on p. 383 of /1253.

Dimensional analysis has been applied by Manganiello ( /1152) to his "inverted" engine. He suggests two alternative methods of correlation:

1) 
$$h = a_2 (T_p)^{r'} (V_s)^s (F)^t (W)^y$$
 -----(6)  
2)  $\frac{h D}{k} = a_3 \left(\frac{D V_s \rho}{\mu} \frac{C_p \mu}{k}\right)^n$  -----(7) or  $Nu = a_3 (Re \cdot P_r)^n$ 

secured to special rocking levers." The reasons why the results of Eichelberg and Manganiello & B. are not directly comparable are clear from this introduction by Manganiello & B. : "... in an investigation of piston temperature in an aircooled engine in which the variations of piston temperature with various operating conditions were independently determined (Ref. 2 of /1152). A satisfactory correlation of these test data could not be obtained because of the difficulty in evaluating the variation of the surface heat-transfer coefficient between the piston and the cylinder wall with the different engine operating conditions."

Eichelberg's results probably would be better comparable with Ref. 2 of /1152 (which is NACA Rep. No. 698). Manganiello & B. departed from an actual engine with fluctuating heat flow to an artificial device with a steady heat flow from the electrically heated stationary piston (without piston rings) across the oil film to the reciprocating sleeve.

Eichelberg publishes 14 graphs on heat transfer and a number of other graphs and tables.

He investigated the distortion of the temperature field, caused by the introduced thermocouple, by making a 25 times larger model (Fig. 13), so that the wires were 5/16" thick; the results are given in Fig. 14, p. 465.

Eichelberg also measured, in vacuum (for insulation against heat losses) the conductivity of cast iron at high temperatures and found a peculiar discontinuity at 433°C, however curves for cast steel and Duralumin were continuous.

Taylor ( /934) discusses experiments and theory of heat transmission in internal-combustion engines as listed in 16 references, including Eichelberg ( /1248) but <u>not</u> including Manganiello & Bogart ( /1152), and plots some results in seven diagrams. In his conclusion Taylor expresses the hope "that this discussion will help to show how a limited number of data, properly correlated, can be used to give useful information on heat flow and temperatures in - - internal comb. engine -- - will stimulate further experiment designed to yield basic data for the heat transfer processes in 2-stroke cylinders, and for critical points in 4-stroke cylinders not covered in this discussion."

Cameron ( /883) has conducted special experiments on heat transfer in journal bearings. He uses the "load criterion,  $1/\Delta$ , which is the non-dimentional parameter controlling bearing performance.  $1/\Delta$  is defined as  $\frac{\mu}{W/1} \left(\frac{\mathbf{r}}{\delta}\right)^2$  where  $\mu$  represents the oil viscosity,

V the shaft surface speed, W the total load, 1 the axial length of bearing, r the radius of shaft, and  $\delta$  the radial clearance (bearing radius minus shaft radius)". Compare with Sommerf-eld number, page 126.

His results are plotted in five diagrams and "give a general picture of the factors which determine the final equilibrium temperature of the bearing, and shows which variables require more detailed investigation."

Without reference to particular experiments and without connection with heat transfer, a few interesting paragraphs will be mentioned.

Theories of <u>dry</u> friction are discussed on pp. 459 and 500 of /1253.

Self-repairing properties of boundary lubricants are described on p. 495 of /1253.

Solid lubricants, for extremely high pressures, like tungsten disulfide, molybdenum disulfide and silver sulfate, are mentioned on page 12 - 62 of /803.

1.2.6 The Run-in process is discussed on pp. 455-457 of /1253. "When two moving surfaces make contact along the crests of the surface roughness waves, the softer of the two surfaces may either improve in smoothness or be damaged by the operation." Shaw and M. use a very characteristic expression: "Just what occurs to the surfaces in the run-in process appears to be quite a mystery"..... "It appears that run-in involves the combined improvement of surface finish and surface structure. Though taper-section studies have shown that the improvement in surface finish is minute, little is known concerning actual metallurgical changes taking place at the surfaces and their consequences. If newly machined surfaces are loaded too heavily at first, they may be seriously damaged. The nature of the damage depends upon the combination of metals that is When a harder metal is caused to slide over a soften one, the used. damage is predominantly in the form of flowing out and tearing of the softer metal. If however, a softer slides over a harder one, considerable amounts of the softer metal remain behind on the stationary surface. The harder metal may also be damaged by the soft slider's plucking out particles of the hard specimen. The damage will be greatest when like metals or a combination of metals of high initial solid solubility are rubbed together."

The influence of adsorbed films on the wear of sliding contacts has been strikingly illustrated by Uhlig (p. 324 /1192): "The rate of wear of carbon brushes in generators or motors has been proved to depend, for example, on substances such as water physically adsorbed on carbon. If the partial pressure of water in the atmosphere is lowered, as at high altitudes in the case of aircraft generators, the decrease in amount of adsorbed film substance leads to brush wear at an intolerable rate (21, 22). In the extreme, adsorbed water vapor reduces the rate at which graphite wears by a factor of 1000 or more (22)."

- /803 "The less common metals" p. 4-67 in Kent's Mech. Eng. Handbook, Design and Prod. volume 12 ed. 1950.
- /883 "H Tr in Journal Bearings" by: Cameron, A. Preprints II 1951. ASME & IME
- /934 "H Tr in internal combustion engines."
  by: Taylor C F. Preprints V 1951.
- 948 "Thermal resistance of joints formed between stationary metal surfaces."

by: Weills N. D. and Ryder, E. A.

in Trans. ASME 1949 <sup>71</sup>/pp. 259-267.

/1152 "Piston H Tr coeff. across and oil film in a smoothwalled piston reciprocating-sleeve apparatus."

by: Manganiello, E. J., Bogart, D.

in NACA E-110 = ARR No. E5K08 of Dec. 1945.

/1212 "The area of contact between stationary and between moving surfaces." By: Bowden, F.P. and Tabor, D. in PRS A Vol. 169/391-413 1939.

/1224 "Metallic transfer between sliding metals: an autoradiographic study." by: Rabinowicz, E. & Tabor, D. in Proc. Roy. Soc. A, V. 208/455-475 1951.

/1225 "The nature of sliding and the analysis of friction."
by: Bowden, F.P. & Leben, L.
in Proc. Roy. Soc. A <sup>V. 169</sup>/371-391 1939.

- /1248 "Some new investigations on old combustion-engine
   problems." by: Eichelberg, G.
   in "Engineering" Vol. 148 pp. 463, 547, 603, 682.
- /1251 "Surface temperature due to friction between sliding solids." by: Thomas P. M. in Proc. 7th Intern. Congr. Applied Mechanics, 1948, London.
- /1252 "Theory of lubrication"

by: Hersey, M. D., book: Wiley, 1936.

- /1253 "Analysis and lubrication of bearings."
  by: Shaw, M. C. and Macks, E. F.
  book, McGraw-Hill, 1949.
- /1316 "Analysis of journal bearing theory and test results."
  by: Apkarian, H. Gen. El. Co. 1. 3. 1952. 29p.
  in R 52 G L 50.
- /1317 "Sleeve bearing test equipment".
   by: Apkarian, H. l. 3. 52. l4p. Gen. Elect. Co.
   NSA 2646 in R 52 G L 52.

### 21. Heat Transfer across a stationary solid-liquid metal interface.

<u>2.</u>

Although the theory of convective heat transfer has been extended to molten metals (Hyman & Bonilla, /1058, etc.) nothing has been found by the writer which would parallel the theories of Karush ( /1057) or of Cetinkale & F. ( /893) for heat transfer across the interface.

2.1.1 For <u>non-wetting conditions</u> the following remarks would apply: Any difference in the heat transfer between solids in contact and across a solid-fluid interface, could be only quantitative and not qualitative because the same general mechanism would apply; any theory however should appreciably differ from that derived for solid contacts.

The surface of the liquid metal cannot be rough (except on a molecular scale), as the surface tension always stretches it to a smooth curvature. This cannot be said concerning the alien film on top of the liquid surface. Its thickness and structure can differ from place to place depending upon local circumstances.

<u>2.1.2</u> The surface of the solid metal would generally have some degree of <u>roughness</u>, whether a pipe or a boiler.

Additional general information on roughness has been found in Shaw & Macks (p. 444 /1253):

Table II-I Relationship between RMS surface roughness and predominant

10,

peak-to-valley dist	ance (Ref. 346 of	/1253
(Sine wave form	$2 \sqrt{2} = 2$	2.8)
Finish	Ratio	
Fine grind	4.5	
Hyprolap	6.5	
Sandpaper	7	
Superfinish	7	

Loose abrasive lap

the "predominant peak-to-valley distance" being about half the maximum peak-to-valley distance found anywhere on the surface.

As mentioned on page 81 of this Review, the tip radius should be small enough to reach to the bottom of the valleys. Way (Ref. 374 of /1253) has measured the roughness of a polished surface having a peak-valley distance of 75 µ in by means of three different tracer points:

Tracer point radius	Reading h max	Discrepancy
500 $\mu$ in. (standard)	30 µ in.	60%
100 "	52 <b>"</b>	
50 <b>"</b>	60 <b>"</b>	20%
calculated	75 <b>"</b>	

Changes in roughness of the solid element of the contact could not be expected from the influence of pressure but only from corrosion, abrasion, or clogging of the voids.

Hyman & B. (p. 61, /1058) pictures an unwetting liquid as touching a rough surface of a solid in isolated peaks (the surface tension of the liquid preventing it from filling the valleys) and the volume of separation filled with vapor of the liquid (and any blanketing gas).

For the solid-solid contact, the fluid thickness was assumed constant (page 74), however now the fluid (between the solid and liquid metal) thickness not only would change with pressure, as the liquid would penetrate deeper into the valleys of the rough surface, but the fundamental layer of fluid, interrupted only by 4 to 10 (or more) "columns" in the form of a-spots, would have disappeared, because the liquid metal would not need to crush the asperities in order to compress the fluid (gas) in the valleys. Now the number of a-spots should be large, compared to 4 or 10, and the conductance of such an interface should, generally, be better than for solids; in other words, the constriction resistance (or resistance to bottlenecking) should be smaller.

Meyer (or any other) hardness would now be unimportant, as even at the highest pressures, acting on the liquid metal, hardly any difference in compressive stress between the valleys and the roughness peaks would be noticeable. Thus the constriction number (page 74) would have to be determined in a different way.

2.1.3 <u>Corrosion</u> with liquid metals is a serious problem and will be considered when reviewing the literature on the particular metals. It may be remarked here that it was a major problem with commercial mercury boilers (Hackett /970; Smith & Thompson, /112) and reduced the steam-producing capacity to 40% of the normal. A chemical compound formed which nearly clogged the tubes.

2.1.4 <u>Solubility</u> of solid metals in liquid metals is again a problem (solid solubility, or metal transfer across the interface, was mentioned for completeness on page 93) and will be discussed when the suitability of different liquid metals for heat transfer will come up. <u>2.1.5</u> The overall conductance across the solid-liquid metal interface appears included in the "film coefficient h". While for hot gas, according to Austin (pp. 83-85, /792) the relatively stationary film at a plate has a resistance 300 times that of the metal (and thus the wall material has very little influence on the rate of heat transfer), Trocki ( /793) observes that for liquid metals the

wall resistance gains in importance. His tabulation shows a decrease of the temperature drop across the film from 99% (of the overall temperature difference) for gas to 59% for water and to 22.4% for liquid sodium. <u>2.1.6</u> The problem of a solid-liquid metal interface resistance to heat transfer disappears entirely (the resistance due to the relatively stationary film of liquid remaining, however) if the liquid metal perfectly wets the solid metal surface, as then all alien surface films and all voids are eliminated and cold welding results (see pp. 59 and 88) along the entire interface. Therefore <u>wetting</u> will now be discussed in some detail.

On page 85 it was already quoted from Udin ( /1194) that the surface atoms are at an energy state intermediate between that of the interior atoms and vaporized atoms. This excess energy in the surface supplies the driving force for any process which leads to a decrease in surface area. Udin (p. 131, /1194) classifies wetting: 1) No wetting of the solid by the liquid.

 $\begin{cases} SV < IS; \\ 2 \end{cases}$  Imperfect wetting.  $\begin{cases} SV > IS > IS \\ SV - IS \\ SV \end{cases}$ 

ðs∨

Fig. 11 "Complete surface equilibrium for the case of imperfect wetting."

A droplet of liquid which partly wets a solid substrate will take a shape which minimizes the surface energy of the system.

$$\begin{cases} \sqrt{SV} + \sqrt{LS} \cos \emptyset + \sqrt{LV} \cos \theta = 0 \\ \sqrt{LS} \sin \emptyset - \sqrt{LV} \sin \theta = 0 \end{cases}$$

Eq. 13.

Vsv O VLs

Fig. 12. "Partial surface equilibrium for the case of imperfect wetting."

In this case the  $\perp$  component of the liquid: gas vector is balanced by elastic forces in the solid phase.

 $\langle g_{SV} - \chi_{LS} + \chi_{LV} \cos \theta = 0$  Eq. 14.

- 3) For perfect wetting  $\Theta$  becomes 180° and one may write only that  $\langle \rangle_{SV} \ge \langle \rangle_{LS} + \langle \rangle_{LV}$  Eq. 15. or  $\langle \rangle_{LS} < \langle \rangle_{SV} - \langle \rangle_{LV}$
- 4) The liquid phase not only wets the solid completely, but also penetrates and films over the grain boundaries. This case occurs when X<sub>LS</sub> < 1/2 X<sub>B</sub>. It is possible for this category to overlap
  2) and 3). An outstanding example is the system liquid bismuth: solid copper, responsible for the extreme hot-shortness of lead-free copper containing a small fraction of one per cent bismuth.

The above descriptions apply, of course, to absolutely clean components, in vacuum. In practice some adsorbed films and/or oxide lqyers will intervene. Even previously cleaned and outgassed in vacuum metal surfaces will not be wetted by liquid metals, if they are taken out of the vacuum for any short time. Uhlig (p. 324, /1192) describes an experiment with steel and mercury. Freshly broken steel surfaces are not wetted by mercury. "Gases from the air adsorb so rapidly on the fractured edges that mercury atoms are held outside the field of force of the iron surface. However if a similar U is broken below the surface of mercury, the fractured ends are now rigorously clean and mercury adsorbs on or wets the iron surface. ... all metal surfaces are covered by adsorbed layers of gases and sometimes oxides as well, which effectively alter surface properties of the metal. If a metal surface should be clean, the appreciable surface forces account for immediate bonding with any convenient nearest neighbors. ... cold welding results, and the bond so formed is equal to bonding anywhere else in the metal lattice."

An example of what happened when alien layers were eliminated is furnished by Hackett (p. 649, (970) "The mercury-filled tube became a suitable and reliable absorber of heat at unbelievably high rates." "The steel was found to be perfectly wetted with the dilute Hg-Na-Ti amalgam to such a degree, that intimate and positive contact occurred between the steel and the Hg. The spheroidal properties of the Hg were entirely gone, and the liquid spread over the tube surface to form a tenacious layer almost impossible to wipe away. Sodium was believed to be the wetting agent, causing a breakdown and removal of oxides on the surface of the steel and in the Hg, thereby allowing actual intimate contact of the Hg and the steel. The sodium was also thought to reverse the meniscus of the Hg, thereby causing it to spread uniformly over the tube surface to produce the effect of wetting."

1

Bailey & Watkins ( /1260) have experimentally investigated the flow of liquid metals on solid metal surfaces and its relation to soldering, brazing, and hot-dip coatings, in other words - wetting of solid metals by liquid metals. [The volume was in the process of binding - not available.]

Wetting is discussed in the numerous experiments with mercury (e.g. /922, /929, /930, /935, /936, /957, /959, /964, /965, /966, /968, /971, /975, /987, etc.).

Two experiments are known to be conducted especially for the investigation of wetting: by Stromquist ( /830) which has not been received from Chalk River Library , and by Moyer & Riemen ( (1106) on wetting by sodium. The latter observed a transition from an unwet (angle of contact  $> 90^{\circ}$ ) to a wet (angle of contact very small) condition taking place between 350 to 450°C. It was presumed by them that in the wet condition the H Tr would be materially increased, due perhaps to the reduction of the metallic oxides by liquid sodium. During one of the first runs they observed, at about 375°C, a sudden change in temperature distribution, indicating a large increase in the heat transfer coefficient. The H Tr coefficient of the film was approx. equal to that of 1/4" of stainless steel (before the change took place.) Several attempts were made to reproduce these data but without success. Among the difficulties the experimenters mention lack of characterisation of the surface of the stainless steel blade: "It is well known that the thickness and composition of oxide layers on stainless steel change markedly with heat treatment, polishing or abrasion, type of machining, It is probably true that in no two and treatment by solutions. experiments were the stainless steel surfaces identical. Even with the same sample the cleaning treatment between runs undoubtedly affected the surface conditions."

The writer combines the statements of the experimenters on the reducing activity of sodium with the statement by Uhlig ( /1192), quoted on page 88, that stainless steels are covered with

a monolayer of oxygen, and offers this attempt of explanation: During the non-wetting, the separating film was this monolayer of oxygen. As it is bonded to the metal lattice, it appears to act like a very thin glove on the "fist" of the stainless steel, hardly affecting the (A multimolecular layer could be pictured as a cushion). H Tr at all. At the appropriate temperature the sodium pulled stronger on the oxygen layer and detached it, forming  $Na_20$  (or  $Na_20_2$ ). The change in H Tr was, however, too small to be measured. Their experiments were conducted exactly in conditions necessary for good cleaning of surfaces from any alien films: high vacuum and elevated temperature. They would never be able to observe something like the effects of mercury on the iron boiler (Smith & Thompson, /1112) because the high pressure in the boiler was favorable to forming of alien films. Their isolated experience during the first runs may be due to slow outgasing of the system; when it was complete, then, possibly, the dirt films were gone, and only the monolayer of oxygen remained on the stainless steel. Its disappearance however remained unnoticed.

For the mercury boilers "wetting agents" have been used: 2.1.71) A sodium concentration 100 ppm by weight of mercury (Hackett, /970); 2) 0.002% metal magnesium (Smith & Thompson, p. 641, /1112); a low % of Titanium, which is a function of the temperature, with a spread of 0.0001% for 850°F up to 0.001% for 1000°F saturation mercury temperature (Smith & Thompson, p. 641 /1112). The Titanium completely stopped the solubility of steel. The magnesium is essential to maintain the Titanium active; Titanium assists in the wetting of steel by Hg. To concentrate the information on the solidliquid interface, some experiments will be mentioned which actually belong into section 2.2.

Werner, in 1948 ( /1262) [Not received from Chalk River Library] seems to have investigated the individual film heat transfer coefficients.

Bonilla, in 1948/49 (p. 16 of /1111) gives the following interpretation of a film coefficient: "If turbulence exists in the main bulk of the fluid, the effective thermal conductivity is much increased. However, a thin layer of fluid adjacent to the solid does not have freedom of motion for turbulence and is equivalent to a stationary or stagnant layer of thickness L. From heat-transfer experiments, typical values of L could be computed for different conditions and tabulated or correlated so that they could be estimated for the same or other conditions when required. Instead of this, however, the ratio K/L is customarily employed, given the symbol h, and designated "film coefficient of heat transfer".

Any resistance at an interface is missing from the above definition.

Lyon, in 1949 (p.48, /962) mentions that "because of impurities in the system, it is quite possible that a scale may have formed on the tube surfaces", and on page 56 : "Additional studies in this field are needed: \_\_\_\_\_\_ 3) To determine the effect on heat transfer, if any, of non-wetting by liquid metals of heat exchanger walls." <u>2.1.8</u> In his <u>experiments</u> with lead-bismuth eutectic, Seban, in 1950, ( /961) observed fouling of the heat exchanger. Discrepancies with theoretical predictions were expressed as an additional resistance R which, when included in the thermal circuit, would produce the deficiency. "If the additional resistance is considered to reside in the interface region between the fluid and the exchanger surface, it

can be partly rationalized by noting that a magnitude of  $R = 30 \times 10^{-5}$  could be produced by a layer of air or nitrogen 0.0001 inches thick. Although the roughness of the exchange surfaces is unknown quantitatively, it was probably great enough so that such gas as would be retained in the asperities of the surface due to the non-wetting characteristics of the fluid would have an effective conduction thickness of about the magnitude cited. Qualitatively, such an effect can be noted in Table II, where the additional resistance for the stainless steel tube is less than that for the steel tube, and the stainless steel tube is known to have a smoother surface than the steel tube."

Hyman & Bonilla, in 1950, refer to Seban, on page 25 ( /1058) and on pp. 44-46 describe their own experiments on wetting: "Calculation showed that the temperature drop through a silicone film of 0.8 thousandths of an inch at the various rates of power input would account for the deviations from the previous measurements. Therefore it appears that these results are explainable by fouling of the surface with a thin tenacious film of silicone fluid." "This amalgamated surface gave coefficients that were indistinguishable from those obtained with the same iron surface in i/ts original "wetted" condition."

"Thus, no effect of "wetting" was detected, and it seems safe to assume with a clean surface wettability has no effect in natural convection heat transfer" (p. 46, /1058) "Therefore, in the case of a rough surface, a decrease in liquid surface tension (increased "wettability"?) would decrease the vapor filled volume of separation and improve heat transfer" (p. 61, /1058) "The debate about the effect of surface wetting on heat transfer may vanish when the terms are more clearly defined." (p. 61, /1058). Johnson et al., in 1952 ( /834) mention that their test section was not "wetted" ("tinned") and that their results fall 25% -35% below the Martinelli-Lyon prediction. By changing the blanketing gas from He to N they were able to observe the effect of gas conductivity on the thermal resistance of the separation volume. They found the h-curves for N 10-15% lower than those for He because the conductivity of N is lower than that of He. Calculating the thickness of the layer [results not stated] they found, however, that this thickness was not sufficient to explain the results.

2.2

Heat transfer across a solid-liquid interface when the liquid is in forced convection.

All the remarks of the preceding section apply, and the following in addition:

1) The relatively stationary layer of liquid (laminar layer, boundary layer) adhering to the solid surface experiences a much larger disturbance by the flowing liquid than in natural convection, and its thickness decreases with increase in Reynolds number (for water: p. 11, Nikuradse,

/514), however its thickness could never be reduced to zero as Miller ( /1255) apparently wishes to prove: "The myth is that the presence of the laminar film was established.... The fact is that the velocity measurements.... actually indicated that there was no laminar film" (p. 94, "Exploding a heat transfer Myth, NEPA-804, /1255)

Nice photographs of the laminar and turbulent boundary layer, in air, taken with the aid of a Zehnder Mach interferometer, are reproduced by Eckert & Soehngen ( /903).

For non-wetting conditions it is hardly conceivable that the peaks of the rough stationary surface would not hold a layer of liquid metal anchored in the valleys, and for wetting conditions even a geometrically smooth surface would hold at least a monomolecular layer of the liquid metal absolutely stationary because of the cold welding at the interface (p. 324, /1192).

Thus, no actual change in the conditions at the interface would be expected against those of the precedent section.

2) The surface roughness of the solid metal would acquire the significance of the sand-roughness in pipe-flow experiments of Nikuradse, and instead of a rm s value a peak-to-valley distance would be needed for the relative roughness  $\frac{k}{r}$  (p. 10, /514).

Nobody of the experimenters seems to have measured the roughness 'of the rather smooth pipes and tubes.

Experiments on this section were reviewed already in the preceding section.

H Tr from a solid metal to metallic vapor, at rest.

No pertinent literature found as yet.

### Ditto, vapor flowing.

2.3

The only references found are Bonilla ( /1256) and Bromley ( /1257). These seem to indicate that experiments on extracting heat from nuclear reactors by means of boiling metals may have been conducted. Whether superheating was applied is not known. Investigations of physical properties of sodium, for example, have been carried to rather high temperatures. Inatomi ( /1108) has tabulated the enthalpy and entropy of sodium vapor up to 2600°K. Ginnings et al. /1109) have experimentally determined the specific heat of sodium (989) has determined the viscosity of up to 900°C. Panchenkov ( different molten metals; for sodium up to 628.2°K. Thompson ( /1104) has tabulated efficiencies of liquid-vapor power cycles up to 3000 psi and 1155.2°K.

Condensing of liquid metals has been studied by Bonilla et al. ( /1256), on mercury at heat fluxes up to 300 000  $\frac{Btu}{ft^2hr}$  (This booklet, of 8 pages, has not been, by omission, requested). Wetting would again come up and reference is made to pp. 135 - 142.

Commercial use of mercury boilers was mentioned in connection with wetting (Hackett /970; Smith & Th. /1112) and is described also on pp. 4-06, 4-07, 8-95 to 8-98 of Kent ( /804). Superheated Hg vapor is mentioned at the top of the Table I p. 4-07. It appears, however, that the commercial boilers have no large interface between the liquid Hg and its vapor; instead Hg seems to enter the "Mercury fog bank" p. 8-97 ( /804) as a spray of small droplets and this

process of evaporating Hg would come partly under 2.2, partly under 3. and partly under 2.5.142.5.2. Apparently some superheating of the mercury vapor would be necessary so that the entering fog could be heated and evaporated.

(Trans. ASME of 1942 were not available any more, for checking).

## 2.4 Heat Transfer across the interface between two liquid metals, at rest.

A Nuclear Reactor could be imagined of two metals, one, in a molten state, as the heat generating nuclear fuel, and the other boiling for metallic steam production. (Whether such a combination would work, is doubtful. Probably it would not lend itself to control.)

No literature found as yet.

#### Ditto, the liquid metals flowing relatively to each other.

The above-mentioned combination could also be imagined as a comparatively light liquid cooling metal floating on top of the molten nuclear fuel and flowing along the interface to carry the heat away.

Hamilton (/1218) analyses natural convection within fluids in which heat is being generated. The nature of the fluids was not mentioned in the reference to this booklet.

### 2.5

### Heat Transfer between a liquid metal and a metal vapor.

<u>2.5.1</u> Moyer & R. ( /1106) had liquid sodium, in high vacuum, with a heater at the bottom of the vessel and cooling coils at the top; nothing is known about the temperatures of the vessel at these locations. The evaporation was such that contact was lost between the stainless steel blade and the sodium surface. Apparently condensation at the cooled surface was not returning enough sodium to keep the level steady.

Some heat would be transferred to a metal vapor in fractional distillation of a metallic "mixture" (e.g. distillation of Hg from some amalgam). If oxygen would be present, the interface would be oxidecovered. (Experiment of Lavoisier).

# 2.5.2 Heat transfer between liquid metal and metal vapor in flow.

Liquid metal could be imagined in a container for heating up by blowing in metallic steam.

Commercial mercury boilers (Hackett /970; Smith and Th. /1112; Kent /804) appear to evaporate the Hg from small droplets (fog) and thus some information on the process might be obtainable from experiments on droplets of other liquids: Brown ( /854), Sjenitzer ( /858), Richardson ( /860), Snyder ( /872), and Bloom ( /1258). (These publications not read as yet).

The boiler is probably kept as free from air and other gases as possible, however some gas (including oxygen) may be present and may adsorb on the droplet surface, interfering somewhat with the heat transfer from the superheated Hg vapor to the Hg droplets.

Some very small drops of liquid metal, covered with a very thin shell of oxide, were found in the heat exchanger of Seban (p. 4, /961), causing some fouling.

2.6

Heat Transfer across an interface between two streams of vapor.

Only an imaginary wall-less heat exchanger between two metallic vapor streams could come under this section (the interface would be rather blurred). No literature found as yet.

### CONCLUSIONS

#### Part I.

If <u>perfect</u> contact is assumed between two metals, there is no resistance to heat flow between them, and the usual mathematical theory of heat conduction applies (p. 69).

In practice, however, the surfaces are imperfect, and the following additional considerations apply:

- Surfaces are rough; in other words: contact is made at a small number of so-called a-spots only; these yield to pressure, permitting more a-spots to be formed; (p. 59);
- Surfaces are covered with alien films of chemical compounds and/or adsorbed fluids (p. 84);
- Interface voids, due to roughness, are filled with some fluid, sometimes short-circuiting the heat flow across the a-spots.
   (p. 111).
- 4) Alien films on the solid surfaces prevent the liquid metals from "wetting" ("tinning") them (p. 135).
- 5) Eventually convection and radiation supplements the conduction across the interface voids (pp. 93-96).

The two theories, of Karush and of Cetinkale & Fishenden (table on page 77), have a limited application and are incomplete. The practical application of the first is only hinted (p. 71). For the application of the second, data are necessary which can be obtained by special instruments only: 1) a "Talysurf" profilometer (p. 75); 2) a testing machine for obtaining the <u>Meyer</u> (not any other type) hardness of the surfaces (p. 74). The results of the discussed experiments are not directly comparable because experimental conditions and circumstances differed. Even disregarding the less important variables, the non-uniformity in describing the mechanical condition of surfaces is the most serious obstable to correlation of results. Not a single investigator has attempted correlation (p. 110).

Rubbing contact of metals presents the additional effect of shearing the a-spots (p. 123), with consequent high local temperatures (p. 124). Adsorption phenomena are important (p. 125) if lubrication of the surfaces has to be assured at all loads. The run-in process is still "quite a mystery" (p. 129).

Liquid metals generally do not wet the solid metal surfaces. This problem seems to be solved by the theoreticians (p. 135), however the investigators are rather confused (pp. 138, 140-142), and report contradictory results. Difficulties are seen with reference to stainless steels, because the conditions on their surfaces depend upon previous heat treatment, working (machining, grinding, polishing, etc.), and treatment by solutions (cleaning, etc.).

Wetting seems to be securable by the application of a combination of several known means: high vacuum, high temperature, selective adsorption phenomena, and wetting agents ("flux") (pp. 138-139). The uncertainty of the results is reflected in the following statement by Lyon et Poppendieck, in Liquid Metals Handbook, 2nd ed., June 1952 (p. 207 /1330): "Until more information is obtained on the contact resistance between nonreducing liquid metals such as mercury and lead ...... the predicted h should be divided approximately by 2 for a conservative estimate of the heat-transfer surface required

in a forced-convection heat exchanger". Thus, not only are the troubles at the interface drowned in the film coefficient, but even a factor of safety is introduced.

Little is available concerning the interface between metallic vapors and solid or liquid metallic surfaces. For mercury the experience with mercury -steam power plants provides some clues. On the vaporization of sodium a theoretical discussion is available (Feldman, in NAA-SR-123 /1417), however it refers to the chemical problems only without even mentioning the interface. A theoretical analysis by Bromley (p. 145) includes a vapor film (metallic, or of any other vapor) of thickness a, however the results are again expressed by way of the film coefficient h.

Thus, whether solid, liquid, or vaporized metals are involved, there is sufficient uncertainty about their interface to warrant further investigation.

In particular the following problems remain:

1) An adequate and universally acceptable system of describing surface condition in mechanical terms, either as "roughness" (and its dependence on pressure, temperature, time, etc.), or involving "a-spots" (and their shape factor, number, etc.);

2) The same for alien films, protective films (as on stainless steel), and adsorbed fluids;

3) The same with reference to wetting by liquid metals, below and above boiling point;

4) The same for metallic vapors, and their superheating;

5) All above-mentioned definitions and relationships tied-in into a complete theory of "Heat transfer between two metals in contact."

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### ADDENDUM

to the thesis

(submitted August 1954)

# THE MECHANISM OF HEAT TRANSFER

## ACROSS METALLIC INTERFACES

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Note: The formal "residence" requirements provided the full-time-employed author with some more time which was partly applied to further study of some aspects touched upon in the thesis.

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### Historical statement of previous investigation.

The mechanism of heat conduction has been investigated by so many that Hume-Rothery(1931) uses 136 pages to review the electronic part of the heat conduction in metals. Therefore only such aspects of the older theories can be considered which have some relationship with modern theories.

The interest displayed in crystalline substances can be explained, for the practical investigator, by the purification of a substance by repeated crystallization, and for the theoretician by the great regularity of structure.

The preference given to investigation of specific heat vs. thermal conductivity is due to the comparative ease and simplicity of calorimetric methods as compared with the difficulties of obtaining a steady and uniform flux of heat(even with guard rings,etc.). It is only natural that theoreticians were more concerned to explain the readily available data on specific heats, and less concerned about thermal conductivity.

To find a reason for recalling Fourier's(1822) description of the mechanism of heat conduction, this sketch begins with the mechanical theory of heat, and then passes on to the theories of specific heat, of thermal conductivity, of special aspects of metals, and lastly - to some aspects of the theories which are based on guanta and on wave mechanics.

The earliest supporter of the mechanical theory of heat seems to have been Lucretius/p.27,vol.II,Niven(1890)/,and more recently Lord Bacon/p.478,vol.I,Glazebrook(1922)/ who lived

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from 1561 - 1626. According to Meyer(1899)p.11, "we may look on Daniel Bernoulli as the first author of the fundamental notion of the kinetic theory ...but...the author of a scientific system ...founded on this notion is Clausius, and with him Maxwell has done most to promote and develop the theory". Bernoulli's Hydrodynamica brought this idea in 1738; Rumford bored a dummy cannon/p.118,Brown(1954)/ in 1798, and Davy rubbed two chunks of ice in 1799.

Next came Fourier's (1822) explanation of what heat is. On p. 37, after a criticism of the caloric theory, he continues: "L'état libre de la chaleur est celui de la lumière;...La chaleur agit de la même manière dans le vide, dans les fluides élastiques, et dans les masses liquides eu solides, elle ne s'y propage que par voie d'irradiation ... \* This sounds very much like present-day theories /p.6,Jakob(1949):"In solids intermolecular radiation may play a part"/.Neither Maxwell's historical sketch /pp.27,364-5,421,vol.II,Niven(1890)/,nor Encyclopaedia Britannica/p.322,vol.ll,l4.ed./, nor Glazebrook's Dictionary/p.478, vol.I/ mention it , however. Fourier mentioned (p.30) that heat radiation is absorbed already within a few layers of molecules, and these act on more distant points. He also talked a lot about heat transmission and radiation from molecule to molecule (e.g.pp.4,8,19,26,28,30,31,39-42,589) and did not mind "qu'on fasse consister la chaleur dans la seule transmission du mouve-heat transfer across interfaces.

Julius Mayer was the first to employ, in 1842, the phrase "mechanical equivalent of heat"/p.479, vol.I, Glasebrook(1922)/. Joule, between 1843 and 1878, made numerous accurate determinations of it. Lord Kelvin wrote "On the Dynamical Theory of Heat" in 1851, and Clausius - in 1857. Maxwell's paper was read to the British Association in 1859.

The caleric theory was supported by many even after the mechanical equivalent of heat had been established experimentally. For example, Maxwell, in a review of Tait's book "Thermodynamics" (published 1868), criticized Tait's support for the caloric theory/p.661, vol.II, Niven(1890)/. Apparently the city-dwelling scientists had never heard of the experimental proof given ages ago by the ancient camper who produced heat by expending muscular work: He succeeded to kindle his camp-fire by collecting the smouldering chips cut by a hardwood drill from a softwood log.

Discussing heat radiation Planck(1900), p.69.mentioned radiating oscillators "somehow connected with the atoms". A lively discussion by physicists of the black-body radiation finally pushed him to postulate that "das Energieelement  $\mathcal{E}$ proportional der Schwingungszahl  $\mathcal{V}$  sein muss, also:  $\mathcal{E} = h\mathcal{V}^{\bullet}$ , i.e. that energy is radiated discontinuously in packages whose energy content is high for high frequencies and low for low frequencies. Drude(1904)p.683, suggested that vibrations of electrons could produce the higher frequencies of the spectrum, and calculated that in the case of  $CaF_2$  the infrared radiation could be due to vibrations of a

mass corresponding to a molecular weight of 60. He concluded that this mass could be made up of the Ca-40 atom together with one F-19 atom, however he found no explanation how the other F-19 atom would participate. Einstein(1907)p.188.used Planck's formula for the frequency of a radiating oscillator. He tabulated the natural frequencies of vibration of a number of atoms and molecules, expressed as the corresponding wavelengths ranging from 12 microns for C to 61 microns for KC1. He assumed that the atoms in a substance would be vibrating independently, all with the same frequency. Sutherland (1910) calculated the natural frequencies of molecular vibrations from the elastic constants of solids, and found them approx. eight times lower than the lowest observed frequencies. Answering a question by Sutherland, Einstein (1911) p. 170, stated that the infrared frequencies would arise from reciprocal vibrations of ions, however the elastic waves in bodies involve whole sheets of molecules, and that the corresponding frequencies therefore should be lower. At first objecting to Sutherland's method of calculation as being too crude, Einstein used again Planck's formula and , for silver, found good agreement with Sutherland(p.174). When Nernst and Lindemann, by a "cut and try" method, altered Einstein's final formula adding to the single natural frequency one-half of this frequency, and achieved a remarkable fit with experimental values of specific heat, Einstein (1911a)p.679, considered the change of energy of a vibrating atom during one half of a period, and found that it was of the same order of magnitude as the energy itself. From this result he

concluded(p.685) that an atom emits a whole spectrum of frequencies, the width of which is of the same order of magnitude as the frequency  $\nu$  itself. He agreed that  $(\nu + \frac{1}{2}\nu)/2$  could then be considered as the "natural" frequency of vibrations.

Debye(1912)p.790, concluded that the theorem of equipartition of energy between the degrees of freedom is not correct. He agreed with Einstein that several frequencies are reasonable because of the large dependence of every atom upon its neighbours, entailing anharmonic motion. Its Fourier analysis would provide a large number of harmonic frequencies. Debye started with Sutherland's expression (which he attributed to Einstein, probably because it appeared in Einstein's paper without specific reference to its author) based on the elastic constants of a solid body, and added further refinements of the theory of elasticity. Calculations on this basis would lead to an infinite number of frequencies; if, however, the atomistic structure of the body is considered, the possible normal modes cannot exceed 3N, where N is the number of atoms in the body. Therefore Debye introduced a corresponding highest frequency alongside with a density of frequencies (spectral lines) proportional to the square of the frequency, in the infinitesimal interval of frequencies. His theory resulted in a good agreement with experimental data on specific heats.

Born and Karman(1912) started with an atomic string, for which exact solutions can be found. The plus and minus signs before the radical led to a higher and a lower natural frequen-

cy ,which became known as the optical branch and the acoustical branch. These authors then proceeded to generalizations for the three dimensions, and the modern edition of this theory is presented in a book by Born and Huang(1954).

Later Debye(1914)p.50, admitted that the atoms of solids cannot be considered as oscillating independently. Instead their combined motion should be represented in the form of superimposed elastic waves of all frequencies possible in the given body. He also applied the method of Born and Karman to take care of the atomistic structure of the body.

More recent theories of specific heat are those of Thirring(1914), Born(1914,1923), Blackman(1935,1941), Kellerman (1941), Leighton(1948), Born and Huang(1954), and others. The contemporary writers seem to prefer Debye's theory, however everybody mentions that not one of the theories fits all the experimental data, because approximations are necessary due to the fact that "the calculation of f(v) for any real crystal is at present an unsolved problem"/p.3, Mott and Jones (1936)/. There is a section on specific heat in a recent survey of the physics of the solid state by Seitz(1954).

Seemingly much less has been written explicitly concerning the thermal conductivity of non-metals. Jakob(1949)p.101, quotes from Debye's book an expression for thermal conductivity derived again from considerations of atomic and melecular vibrations, and revealing a striking similarity with the corresponding expression for gases derived from the kinetic theory.

Two more theories are those of Peierls(1929) and of Papapetru(1934), the latter much the simplest of all.

Meissner's(1935) explanation of thermal conductivity is not a complete theory, but only a reasoning based on some properties of electric circuits.

Everybody writing about the thermal conductivity of metals went back nearly a hundred years to quote Wiedemann and Franz(1853) who found that the ratio of thermal and electrical conductivities is a constant.

This constancy was disturbed, however, by observations that the thermal conductivity hardly changed at all with temperature while the electric conductivity exhibited a definite temperature coefficient. To rectify this situation, Lorenz(1872) introduced the absolute temperature into the Wiedemann-Franz ratio, which then became known as the Lorenz number.

Later measurements caused even the Lorenz number to become in-constant, particularly so when measurements were made at temperatures approaching the absolute zero. There some metals lost nearly all of their electrical resistance (supra-conductivity) while keeping the thermal resistance. Eucken(91,1925) therefore adopted the policy of writing the thermal conductivity as the sum of two terms, one metallic,  $k_m$ , and the other non-metallic,  $k_i$ , so that

 $k = k_m + k_i$ .

Riecke(1898)p.355, assumed that the electrical conduction in metals is similar to the conduction in electrolytes, i.e. free positive and negative particles move between the molecules.

Drude(1900)p.577, had the particular success in deriving the Wiedemann-Franz-Lorenz ratio from a hypothesis that in metals there are free electrons which obey the kinetic theory developed for gases. Many other theories have been advanced, however none of them were found entirely satisfactory. One of the troubles was the very small contribution of the electrons to the specific heat of metals, inconsistent with the equipartition law. This was discussed theoretically and checked experimentally by Richter(1912) and Richarz(1912). At the Solway Congress , in 1927, the situation was described as "very confusing".

Relief came from the quantum theory. Pauli had already announced his exclusion principle, forbidding electrons to enter any place where already two electrons with opposite spin were present (or where one electron of the same spin had its quarters), so far in atoms only. It appeared to Fermi(1926) that Pauli's principle could be applied also to gases. Similar ideas were advanced by Dirac. Thus a new kind of statistical distribution of velocities appeared, Fermi-Dirac statistics, which had Maxwell's statistics as its limit at high temperatures. Sommerfeld(1928) had the idea to apply this new statistics to the electron gas in metals, and could remove the trouble with the specific heat of electrons.

Among others, Peierls(1930) formulated a theory of elec-

trical and thermal conductivities of metals. Bloch's(1928) theory won such an approval that Hume-Rothery(1931) included in his book a summarized translation of it. Further work by Nordheim(1931),Sommerfeld(1934),Borelius(1935),Makinson(1938),Hume-Rothery(1944) should be mentioned. Wilson's(1953) book seems to bring the most complete treatment of the theories of metals.

### The atomic string.

The three-dimensional solid presents too unwieldy a situation for initial analysis. Therefore a number of scientists started from the one-dimensional solid, a string. For our purposes only those models are suitable which are composed of lumped masses on a weightless string, duplicating atomic structure in crystals.

Rayleigh(1894)p.172, discusses the discontinuous string mostly from the point of view of music, however on p.232 he also considers travelling waves along it. His paper of 1887, on bodies with periodic structure may contain additional discussion.

Born and Karman (1912)p.297,discuss a linear diatomic chain, and their model is repeatedly discussed ,with slight variations, by other writers: Schaeffer and Matossi(1930)p.288, Wilson (1953)p.138, Born and Huang(1954)p.55, and others.

The form of the differential equations, and therefore the form of the solutions, is the same whether mechanical or electrical oscillatory systems are considered.

Meissner(1935) compares SiO<sub>2</sub> molecules with electrical oscillators assembled into a network.

By analogy, masses then are substituted by inductances, L, springs by capacitances, C, displacements by charges, q, velocity by current, i, or j, if we wish to reserve i for -1, and acceleration by  $dj/dt = \frac{4}{3}$  (where the '' denote doule differentiation with respect to time).

A reversed substitution can convert the solution back

into the mechanical form.

Consider ') one row of identical lossless coupled resonators each consisting of an inductance L and a capacitance C, in series, and being connected to ground, on each side, by a capacitance C'. Thus the n-th mesh contains,going clockwise,ground, C', C, L, C',ground. The coupling capacitances C' are shared by the adjacent meshes ,and are the substitute for coupling springs. Subscripts of the type n-l, n, and n+l are used to denote the preceding, the one considered, and the following resonator. The differential equation is expressing Kirchhoff's second law, that the algebraic sum of voltages and voltage drops in a closed circuit adds up to zero:

 $q_n/c + Lq_n + (q_n - q_{n+1})/c + (q_n - q_{n-1})/c = 0$ 

For other meshes the subscripts only will change, as mentioned above. For an infinitely long row the number of equations will be infinite.

By inspection, we expect a particular solution of the type

After substitution and cancellation of e there remains a set of algebraic equations of the type

$$A_n/C - Lw^2 A_n + (A_n - A_{n+1})/C' + (A_n - A_{n-1})/C' = 0$$

')These considerations are based on an example given by Prof.P.R.Wallace in the "Applied Mathematics" course.

Assuming  $\mathbf{A}_n$  of the form  $\mathbf{A}_n = \mathbf{e}$  we have for the other meshes :

$$\mathbf{A}_{n+1} = \mathbf{e} \qquad = \mathbf{e} \quad \mathbf{e}$$
$$\mathbf{A}_{n-1} = \mathbf{e} \qquad = \mathbf{e} \quad \mathbf{e}$$

nθ

When these expressions are substituted and e is cancelled, the typical equation becomes

$$-Lw^{2} + 1/C + 2/C' - (e^{2} + e^{2})/C' = 0$$

$$2\cosh \theta \text{ can be substituted for } e^{2} - \theta \text{ , and then :}$$

$$\cosh \theta = 1 + \frac{1}{2}C'(1/C - Lw^{2})$$

If  $Lw^2$  is smaller than 1/C, or  $w^2$  is smaller than 1/LC, the rhs is positive,  $\Theta$  is real, and the amplitudes along the row decrease exponentially; such a frequency cannot be propagated through this system.

When  $Lw^2$  is larger than 1/C, the rhs becomes smaller than one, and it can represent a cosh if the argument is complex. Substituting i0' for 0 and replacing cosh i0' by  $\cos 0'$ , we get

$$\cos \Theta' = \frac{1}{2}C'(Im^2 - 1/C)$$

In this case  $\Theta$  is purely imaginary, the amplitudes are in  $\Theta'$ not diminished, and  $A_n = e$  expresses only rotation in the complex plane. For  $Im^2 = 1/C$  the rhs is one,  $\Theta$  is zero and  $A_n = 1$ , without dependence upon n or C'. Thus, in this type of electrical filter, the natural frequency passes unchanged, and the phase of higher ones changes depending upon the coupling.

#### The Fermi-Dirac statistics.

The Maxwellian distribution of velocities is not suitable for very light gases at low temperatures, particularly for the free-electron-gas in metals, for which all terrestrial temperatures (except those of "atomic"bomb explosions) are low enough to cause this degeneracy.

Quantization considerations lead to a different type of statistics.

If some electrons are supposed to be enclosed in a box of the type used in the kinetic theory of gases, and only one coordinate, say x , is considered, the motion of an electron can be represented in a phase space /Fig.81,p.532,Slater and Frank(1933)/ with x as the abscissa and momentum as the ordinate. In this space the motion of the electron between the walls is represented as a line parallel to the x-axis at a positive height which corresponds to the constant positive momentum of the electron. This line extends from zero to A , which are the boundaries of the box along the x-axis. When the ordinate at A is reached, in ordinary space the electron is stopped by the wall and reversed. In the phase space this collision with the wall is shown as a line parallel to the momentum axis and extending from the given positive momentum through zero momentum to the negative momentum of the same magnitude. This line is perpendicular to the x-axis because the coordinate x does not change during the reversal of momentum. The motion from wall A to wall zero is again a line of constant(negative) momentum and the collision with the wall zero is represented by an upward line along

the ordinate axis reaching the horizontal line of the positive momentum. The area enclosed by the described horizontal and vertical lines represents the total change in energy of the electron, and this can be only an integer multiple of the quantum, h . Considering other electrons, only one more can have the same quantum number n (with opposite spin, however, to comply with the Pauli exclusion principle); the rest of them, in pairs, may have n+1, n+2, or n-1, etc., differing from n by integers. The areas of the corresponding rectangles would then differ from each other successively by h .

The same considerations apply to the y, and z coordinates, so that the three-dimensional case is represented in the six-dimensional phase space by a box /Fig.49,p.260,Hume-Rothery (1931)/ whose projection on the  $x, p_x$  plane is the rectangle described, and whose volume is h<sup>3</sup>. Thus, the two lowest-state electrons may occupy the box at the origin, providing an electron density of 2/h<sup>3</sup> per unit volume, the next pair may stay in a "concentric"box enclosing the first, and having a volume of  $2h^3 - h^3 = h^3$ ; the next box would have a volume of  $3h^3 - 2h^3 = h^3$ , etc. In the projection on the x,p plane these boxes would show up as higher and higher rectangles increasing in area by steps h at a time. This would signify that whenever an electron (in pairs) is added in the ordinary space, it must have a next larger momentum in the phase space, so that even at the absolute zero of temperature only one pair may have zero energy, and all other pairs must have higher energies.

If the extension of the box along the x-axis is reduced

to a value A/2, the ordinate in the phase space must be doubled, so that the area of the rectangle would not change. In other words, crowding of electrons together in three-dimensional space necessarily increases their kinetic energy and therefore requires work /p.533,Slater and Frank(1933)/. This becomes evident when two atoms try to interpenetrate, i.e. to crowd electrons into a smaller space.

The maximum kinetic energy of an assembly of electrons in the lowest energy state (i.e.when all lowest energy levels are completely filled) can be determined by integration, over the momenta, of the electron density in phase space, which is  $2/h^3$ , or of charge density  $-2e/h^3$ , where -e is the charge of the electron. This integrand is a constant, and comes before the integral sign, so that the integral of the momenta,  $\int dp_x dp_y dp_z$ , only is required. In a momentum space, with  $p_x$ ,  $p_y$ ,  $p_z$ , as the variables, a surface of constant kinetic energy is a sphere /p.534, ibid./ 2, 2, 2

$$\mathbf{E}_{k} = \frac{\mathbf{p}_{x}^{2} + \mathbf{p}_{y}^{2} + \mathbf{p}_{z}^{2}}{2\mathbf{m}}$$

the radius of which is , for the maximal energy,  $p = (2mR_{max})^{\prime}$ , where m is the mass of an electron. The required integral is the volume of this sphere

$$4\pi p^3/3 = 4\pi (2mE_{max})^{3/2}$$
, and the

charge density is

$$q = (-2e/h^3)(4\pi/3)(2mE_{max})^{3/2}$$

From this

$$E_{max} = (1/2m)(-3h^{3}\gamma/8\pi e)^{2/3}$$

When energy is imparted to this assembly of electrons, only those electrons will be raised to the first empty level above E<sub>max</sub> , or higher, for which their own energy plus the added quanta provide the energy associated with the empty level. As the guanta of heat radiation are associated with comparatively low frequencies, and therefore are not very energetic, the chances are that only the electrons in the upper levels will be affected by heat, and the remainder of them will stay in the lower states indefinitely. This is evident from a plot of the number of electrons per unit energy range against the energy level /Fig.6-2,p.194,Harnwell and Livingood(1933)/. The curve starts from the origin, rises parabolically to Emax , which is 8.91 x  $10^{-12}$  ergs for tungsten, and then drops to zero. When the temperature was raised by 300, only the electrons from approx. 8.5 x  $10^{-12}$  erg to  $E_{max}$  participated, and reached a maximum level of approx. 9.3 x  $10^{-12}$  erg, while the rest of them did not leave their levels at all. For 3000 the electrons down to 7 x 10<sup>-12</sup> ergs participated, and some of them were raised to a level of  $11.5 \times 10^{-12}$  ergs.

This explains why the electrons in a metal contribute so little to the specific heat, and upset the equipartition law.

When energies become so great (at astronomic temperatures) that all electrons move out of their original solitary cells and participate in the uptake of energy, then Maxwell's distribution law is approached.

Since the expressions revealing the degeneracy of a gas have the mass of the particle in the denominator /p.265. Hume-

-Rothery(1931)/, the degeneracy is less pronounced for heavy particles. Hume<sup>1</sup>Rothery, p.265, states that "an electron gas will at 36,000 C be degraded to approximately the same extent as helium at 5 K if it contained the same number of particles per unit volume", i.e. the departure from Maxwell's statistics will hardly become noticeable at all for helium gas, while electron gas will not obey it even at the surface temperature of stars. The effect of this is exhibited in Fig.50, p.264, Hume-Rothery (1931), where the existence of zero-point energy for degenerate gases makes the energy-temperature curve to depart from the straight line through the origin and to become nearly horizontal, i.e. any temperature changes in this region affect the energy of the particles but very little.

The spacing of the energy levels can be found when the Schrödinger equation is solved with the boundary conditions that the wave function  $\psi(x)$  must vanish at the boundaries x=0 and x=A. Mott and Jones(1936)p.51,show that for the n-th level

 $E_n = \frac{\pi^2 n^2 \tilde{n}^2}{\Lambda^2 2m}, \text{ where } \tilde{n} \text{ is } h/2\pi$ 

For the distance A of the order of atomic dimensions the spacing is of the order of electron-volts, however when A = 1 cm, the energy of the ground state is only  $3 \ge 10^{-15} \text{ e.v.}$ (p.51, ibid.) and thus corresponds to an electron practically at rest.

#### Atomic vibrations.

The frequency of vibrations depends both upon the magnitude of the vibrating mass and upon the stiffness of the spring:

The electrical forces between the atoms are such, that a displacement in any direction sets up a restoring force directed toward the equilibrium position. This leads usually to such a regular lattice structure that the relative position of the atoms in a crystal can be given to one part in 100,000 /p.22, Arkel (1949)/. The atomic restoring force, however, does not seem to be proportional to the displacement, because the other end of the "spring" is not fixed but is pulled away by the neighbour if the spring tension is reduced. This may be one cause of the anharmonicity of the atomic vibrations.

Since the electrical forces between the particles are changing with certain powers of distance, there is available a variety of "spring constants", however it alone would not suffice to explain the extreme variety of frequencies. It is the countless number of possible combinations of electrons, protons, neutrons, complete atoms, and molecules, that provide the range of vibrating masses. A small part of the mass is due to the conversion of energy into additional mass when a particle is accelerated to a high velocity, because

$$m = m_0 / (1 - v/c)^{1/2}$$

For ordinary velocities this effect is negligible, however for  $\mathbf{v} = 0.99999c$  the mass of an electron increases 194 times : It may be mentioned in passing that Newton may have foreseen the possibility of the dependence of mass upon velocity/p.137, Stranathan(1942)/ when he stated his second law originally in the form

$$\mathbf{F} = d(m\mathbf{v})/d\mathbf{t} = \mathbf{v} d\mathbf{m}/d\mathbf{t} + \mathbf{ma}$$

Calculations of the natural frequencies have been performed, although they are extremely complex/p.157, Herzberg(1945)/ because of anharmonicity, damping, coupling, etc.

In the theory of simple harmonic motion all angular displacements are assumed small, so that any sines may be safely approximated by tangents and by the angles themselves. Large displacements lead to non-linear differential equations/p.4, Andronov and Chaikin(1949)/.

According to Herzberg(1945)p.2ol, the amplitudes of the quantized oscillations, though usually small, are by no means infinitesimal and therefore for accurate calculations cubic, quartic, and higher terms in the potential energy must be considered.

When change of state occurs, there must occur large amplitudes, because then some of the "aprings" are "broken", leaving only softer ones intact.

Besides the mechanical anharmonicity due to large amplitudes, there is also an electrical anharmonicity due to polarization. The dipole moment varies with the variation of distance between the nuclei in the molecule/Fig.74, p.241, Herzberg(1945)/.

When two electric systems of the same natural frequency are coupled, the combined system shows the largest response some distance away from the resonant frequency, on both sides of it; a band-pass filter results.

With (coupled) atomic systems there would be some difference in the equations of motion depending upon the type of coupling, whether by means of springs alone(ionic lattice) or whether there would be also a common mass (sharing of electrons).

Herzberg(1945)p.161-167,tabulates some spring constants of molecules, and mentions an experimental method for the determination of the normal frequencies of vibration, (p.157). Actual scale models are made of steel balls connected by heavy springs, and are excited mechanically by coupling with an eccentric. The largest amplitudes of the components are noted while the exciting frequency is varied, and thus a picture of the molecular vibrations is obtained. Herzberg does not mention, however, a fact which deserves attention : Maximum amplitude does not occur at resonance but deviates from it considerably if the damping is not negligible. Coupling also affects the position of maximal response. To overcome difficulties due to non-weightless springs, geometrical similarity can be replaced by energy similarity(p.158, ibid.).

A somewhat tangible proof that heat and atomic vibrations are due to each other can be obtained from Fig.8 of a paper by Bragg(1931).There it is shown that as the temperature is raised the measured distributions of charge(representing the chlorine and sodium ions) obtain lower and flatter peaks and wider bases indicating increased amplitudes of vibration. At a height of approx. 7.5 electrons/Å, the width of the chlorine peak is 0.6 Å 0,75 Å, and 1.0 Å respectively for absolute temperatures of 86 290 , and 900 K.

#### The wavelengths emitted by vibrating atoms.

The shortest wavelengths arise when the constituent parts of the atom vibrate.

Gamma-rays, with a wavelength of a small fraction of an  $\tilde{A}$ , arise from transitions of nucleons /p.182, Lapp and Andrews (1948)/.

X-rays, ranging from 0.01 - 100 Å, (p.15, ibid.), are caused by electron transitions in the electron shells deep within the atom (p.71, ibid.), where the restoring forces are very large. A peculiar case of radiation is the explosion of an atomic bomb. the X-rays in this case originate not only from the usual electron transitions, but also from the extreme excitation by high temperature. The Wien's displacement law predicts that the 10,000,000 C hot fire ball would emit <u>heat</u> radiation with maximum energy in the 2.9 Å region of X-rays ! /p.20, Lapp and Andrews (1948)/. Of course, the usual gamma and other radiations would come in addition.

Ultraviolet light ( 1 to 4,000 Å ) and visible light ( 4,000 to 7,600 Å ) is the result of transitions involving only the outermost electrons (p.65, ibid.).

Some of the infrared radiation, ranging from 0.76 micron to 400  $\mu$ , or 7,600 Å to 4,000,000 Å, may come from the outermost electrons (p.65, ibid.), however most of the infrared or heat waves are emitted when the complete atoms vibrate and rotate(p.17, ibid.) and when molecules vibrate and rotate. For example, the vibrations of the atoms within the water molecule produce wavelengths of 2.325, 2.66, and 6.26 microns /p.241, Fig.103, Schaeffer and Matossi(1930)/.

Hydrogen atoms also emit a radio wave of 21 cm /p.327, Spitzer(1955)/ permitting the investigation of interstellar

clouds by radio-telescopes.

At the temperatures prevailing in furnaces, the infrared radiation of any significance falls between 0.8  $\mu$  and 15  $\mu$  /p.21, Wohlenberg (1940)/. Incidentally, this range is incorrectly stated by Hershberger(1954)p.126, as 7  $\mu$  (due to an error while converting 7,000 Å into 7  $\mu$  instead of 0.7  $\mu$ ) to 20  $\mu$ , and the same conversion error occurs when he converts 1.25 cm into 125,000  $\mu$  instead of 12,500  $\mu$ .

Wohlenberg(p.27) states that the rotation of molecules shows up as wavelengths of about 50 p, and the energy involved is small because the quanta are of comparatively low frequency. Oscillations of molecules, with rotations superimposed, produce higher frequencies, being due to more powerful quanta. Wohlenberg tabulates three bands of radiation (or absorption) for  $CO_2$  as 2.4 to 3.0 µ, 4.0 to 4.8 µ, and 12.5 to 16.5 µ, and for water vapor as 1.7 to 2.0 µ 2.2 to 3.0 µ, 4.8 to 8.5 µ, and 12.0 to 30.0 µ.

Hershberger(1954)p.127, mentions, absorption spectrum of ammonia gas in the wavelength region from 70 to 100  $\mu$ , and that the 1.25 cm radar waves were absorbed by water vapor(because of a rotational transition in the water molecule) to such an extent that the range of the equipment "fell woefully short of that anticipated". He states the (3.3) line of ammonia (rotational) as 23,870.11+0.02 Mc/sec (which corresponds to 12,550  $\mu$ ) irrespective of the source of ammonia, and suggests it as a frequency standard. The absorbed energy can be demonstrated as heat(p.133,ibid.), and also as sound, if the ammonia is contained in a rubber balloon, and modulated microwaves are used.

The observed microwave absorption arises from transitions between pairs of energy levels corresponding to the inversion of the ammonia molecule/p.127, Hershberger(1954)/.

Molecules can combine into larger groups with a lower frequency of absorption/p.270,Brode(1955)/ and emission.

Brode(p.265,ibid.) uses a new unit : the millikayser,mK, which is equivalent to  $cm^{-1}x10^{-3}$ , or one thousand waves per cm.

In this comnection it is important to remember that the <u>frequency</u> of vibrations (which depends upon k/m) is the more fundamental and more constant magnitude, and cannot be altered once the wavetrain has left the source /p.3, Lapp and Andrews (1948)/.The wavelength, and with it the wave number, depends both upon the relative velocity (Doppler effect) and upon the properties of the medium. These produce changes in the observed velocity of propagation, and influence the wavelength over the relationship:wavelength x frequency = velocity of propagation.

Sutherland/p.82(1935)/ mentions that internal vibration of radicals, against other parts of molecules, helps to identify them; e.g. the NO<sub>3</sub> group emits approximately the same wavelength of 14 microns in all the nitrates. When the groups vibrate against each other , lower frequencies result. For example, in the NaCl lattice all the Na-ions can vibrate in phase against all the Clions, emitting a wavelength of approx. 50 microns.

When monochromatic light falls on crystals, there arise also Raman frequencies, being combination frequencies of the infrared natural frequencies of the molecules with the exciting frequency /p.153,Schaeffer and Matossi(1930)/.

The influence of coupling on the frequency.

Let two undamped vibrating systems ,  $k_1$  ,  $m_1$  ,  $k_2$  ,  $m_2$  , be coupled by a spring  $k_3$  stretched between the masses, while the other ends of  $k_1$  and  $k_2$  are attached to two supports.

The equations of motion are

$$m_1 \mathbf{x}_1 + (k_1 + k_3) \mathbf{x}_1 - k_3 \mathbf{x}_2 = 0$$
  
$$m_2 \mathbf{x}_2 + (k_2 + k_3) \mathbf{x}_2 - k_3 \mathbf{x}_1 = 0$$

Assuming solutions of the type

$$x_1 = C_1 e^{iwt}$$
,  $x_2 = C_2 e^{iwt}$ 

we obtain after substitution and cancellation of  $e^{iwt}$ 

$$-\mathbf{w}^{2}C_{1} + C_{1}(\mathbf{k}_{1} + \mathbf{k}_{3})/\mathbf{m}_{1} + \mathbf{k}_{3}C_{2}/\mathbf{m}_{1} = 0$$
  
$$-\mathbf{w}^{2}C_{2} + C_{2}(\mathbf{k}_{2} + \mathbf{k}_{3})/\mathbf{m}_{2} - \mathbf{k}_{3}C_{1}/\mathbf{m}_{2} = 0$$

There are three unknowns,  $C_1$ ,  $C_2$ , and w , however we can solve the equations for w in terms of the ratio of  $C_1$  and  $C_2$ . From the first,

$$C_1/C_2 = \frac{k_3/m_1}{(k_1+k_3)/m_1 - w^2}$$

and from the second

$$c_{1}/c_{2} = \frac{(k_{2}+k_{3})/m_{2} - w^{2}}{-k_{3}/m_{2}}$$

Equating them we obtain a biquadratic equation in w . For simplification assume the two systems to be identical: $k_1 = k_2 = k$ ;  $m_1 = m_2 = m$ . Then  $w^2 = (k+k_3)/m + k_3/m$ .

Thus two possible frequencies of vibration are

$$w_1^2 = (k+2k_3)/m$$
 and  $w_2^2 = k/m$ 

the second of which is independent of the spring constant  $k_3$ 

For  $k_3 = 0$ , both systems have their natural frequency. When  $k_3 \neq 0$ , the second solution shows that the systems still can keep their natural frequency of vibration, if they vibrate in step and never stretch the coupling spring. If  $w_2$  is substituted into the equation for the amplitude ratio, there results a ratio of +1, i.e. the amplitudes are always equal and of the same sign, as anticipated.

If  $w_1$  is substituted, the amplitude ratio becomes -1 ; this means that the masses now oscillate in opposition, and with a shorter period, because double the coupling spring constant is added to the spring constant of the system.

For illustration put m=l , k=l , and let  $k_3$  vary from zero to 7.5 ; then the following table results:

k <sub>3</sub>	2k3	1+2k3	$w_1 = (1+2k_3)^{1/2}$
0	0	1	1
0.22	0.44	1.44	1.2
0.48	0.96	1.96	1.4
0.78	1.56	2.56	1.6
4.0	8.0	9.0	3.0
	15	16	4.0

Since  $w_2 = 1$ , it is seen that when  $k_3$  reaches half the stiffness of k, the frequency is already 40% higher, and becomes very large with very strong coupling.

Since in crystalline solids the forces between the component particles could be of the same order of magnitude as the coupling forces, a large influence of the coupling on the natural frequency of vibration can be expected.

This corresponds to Bragg's(1931) picture of a solid as a threedimensional spring mattress.

Coupling in a quartz crystal is discussed by Meissner(1935) p.291, with a much different conclusion. He derives the degree of coupling from the slowness (approx. 0.2 mm per sec.) of heat propagation, and not from the forces between the particles. On this basis he finds that the coupling coefficient is much smaller than one percent, which does not seem to be reasonable. He believes that heat is propagated only by energy transfer from one of the atomic oscillators to the next, however he fails to mention that energy would also swing back to the preceding oscillator unless the coupling is severed after the following oscillator attained peak amplitude. This "check-valve" type of coupling was the main achievement of the extinguishing-spark-gap-radio-transmitters ("Löschfunkenstrecke-Sender") of the old days.

According to Herzberg(1945)p.374,additional coupling between the rotation and the vibration of molecules is produced by the Coriolis acceleration.

In electrical circuits there exists a simple picture of the effect of coupling, if the coupling is inductive: The two inductances then form a transformer, and the constants of the second circuit are transformed-in, according to the (ratio)<sup>2</sup> of the windings, into the first circuit.

The influence of damping on the frequency of vibration.

In problem 4,Slater and Frank(1933)p.37,the above-mentioned question is asked.

For simple harmonic motion, the expression for the displacement at time t is

 $x = Ae^{slt} + Be^{s2t}$ , where A and B are arbitrary constants, and s, and s<sub>2</sub> are

$$s_{1,2} = -C/2m \pm i (k/m - (C/2m)^2)^{1/2}$$
;  
Here C is the damping coefficient, m is the vibrating mass, and k is the spring constant.

The vibrations change into aperiodic motion when

$$k/m = (C_c/2m)^2$$
 ,where  $C_c$  is the

critical damping coefficient. For simplification let us introduce a dimensionless ratio  $\mathbf{z} = C/C_c$ , so that for aperiodic motion  $\mathbf{z}=1$ . Then the condition for aperiodic motion becomes

$$k/m = (C/2zm)^2$$
, and  $C/2m = z(k/m)^{1/2} = zw_n$ 

where  $w_{n/2\pi}$  is the natural frequency of vibration.

The solutions of the auxiliary equation then become

$$s_{1,2} = -zw_n \pm i(w_n^2 - z^2w_n^2)^{1/2} , on$$
  

$$s_{1,2} = w_n(-z \pm i(1-z^2)^{1/2}) .$$

The general solution, with the decay term before the bracket, then becomes

$$\mathbf{x} = e^{-\mathbf{z}\mathbf{W}_{n}\mathbf{t}} \left[ \mathbf{A}_{e} e^{i(1-\mathbf{z}^{2})^{1/2}} \mathbf{W}_{n}\mathbf{t} - i(1-\mathbf{z}^{2})^{1/2} \mathbf{W}_{n}\mathbf{t} \right].$$

It is now obvious that  $w_{damped} = w_n(1-z^2)^{1/2}$ 

The percent decrease of the frequency with increasing damping can be seen from the following table:

Z	$(1-z^2)^{1/2}$	% decrease of w	
0.1	0.995	0.5	
0.2	0.98	2	
0.3	0.954	4.6	
0.4	0.917	8.3	
0.5	0.866	13.4	
0.6	0.80	20	
0.7	0.714	28.6	
0.8	0.60	40	
0,866	0.50	50	
0.9	0.436	56.8	
0.95	0.312	<b>6</b> 8.8	
1.0	0	100	

Thus, for small damping the period is only a few percent longer, however for z = 0.86 it is already doubled !

Since energy is withdrawn from atomic oscillators, and the rate of its withdrawal is not constant, their oscillations are damped, and the frequency is changing.

Therefore Einstein's(1907)p.188, assumption that the atoms in a homogeneous body would vibrate independently, all with the same frequency, was a very crude approximation.

#### Maximal amplitude does not occur at resonance

(except when there is no damping).

In problem 11,p.38,Slater and Frank(1933) the question is asked for which forcing frequency,smaller than the natural frequency,peak amplitude occurs. Apparently this is meant to correct the misconcept that peak amplitude occurs at  $w = w_n$  forced The expression for the amplitude, when the denominator of

the magnification factor reaches a minimum, i.e. when

$$(1 - (w_{f}/w_{n})^{2})^{2} + (2zw_{f}/w_{n})^{2}$$

reaches a minimum. Differentiating with respect to the ratio of the frequencies, and equating to zero, we obtain

$$w_{f}/w_{n} = (1-2z^{2})^{1/2}$$

as the condition for peak amplitude of forced vibrations.

Similarly we can obtain

$$w_{f}/w_{n} = (1-2z^{2})^{-1/2}$$

as the condition for peak maximal acceleration to occur. ( Both peaks may be of importance for the design of machine elements undergoing forced vibrations, particularly vibration measuring instruments, where z is approximately 0.6 .)

When values of the two peaks are computed, the following table results:
Z	$(1-2z^2)^{1/2}$	$(1-2z^2)^{-1/2}$
	· · · · · ·	· ,
0.1	0.98995	1.01
0.2	0.959	1.043
0.3	0.906	1.104
0.4	0.825	1.212
0.5	0.707	1.414
0.6	0.529	1.89
0.7	0.141	7.09
0.707	0	840

1

When examining any plot of the magnification factor against the frequency ratio, it will be noticed that the curve which would connect the peaks of the plotted curves, would be the plot of  $(1-2z^2)^{1/2}$  against the frequency ratio.

As the value of z approaches 0.707, the forcing frequency for peak amplitude departs more and more from resonance; thus, for z = 0.6 peak amplitude occurs when the forcing frequency is approx. one half of the natural frequency, and for z = 0.707zero-frequency (steady) force will produce peak amplitude.

If  $(1-2z^2)^{-1/2}$  is plotted, the curve is approximately symmetrical, about  $w_f/w_n = 1$ , to the previously mentioned curve, however it leads to an infinite value of the frequency ratio for the limiting value of z = 0.707. In other words, for large damping, peak maximum acceleration occurs at forcing frequencies much above resonance, already at  $w_f = 7 w_n$  when z = 0.7

It is interesting to observe that the quantity which has

its peak precisely, and always, at resonance  $(w_f = w_n)$  is the maximal velocity of the mass, and with it the kinetic energy. This becomes evident when the expression for velocity is brought to a form where  $mw_f - k/w_f$  appears in the denominator. Then the condition for peak maximum velocity becomes  $mw_f = k/w_f$ , or  $w_f^2 = k/m = w_n^2$ .

When the response of a vibrating system is plotted, "resonance curves" result, and the two peaks mentioned above appear on both sides of the resonance, where the maximum velocity has its peak.

For a system of m = 2, C = 4, k = 57.2, z = 0.25and  $w_n = 5.35$ , the following table was prepared, where X is the amplitude and X<sub>o</sub> is the deflection caused by zero-frequency force:

	t t	1	1	1		1 1		1 1
<b>₩</b> f/₩n	X/Xo	kΧ	₩f	Cwf	Cw <sub>f</sub> X	<b>v</b> f <sup>2</sup>	2 <b>X</b>	2w <sub>f</sub> <sup>2</sup> X
0	1	57.2	0	0	0	0	0	0
0.2	1.04	59 <b>.</b> 5	1.07	4.28	4.35	1.145	2.08	2.38
0.4	1.16	66.6	2.14	8.56	9.96	4.58	2.32	10.6
0.6	1.39	79.5	3.21	12.84	17.8	10.3	2.78	28.7
0.8	1.84	105	4.28	17.12	31.4	18.32	3.68	67.4
0.94	2.03	116	5.02	20.08	41.8	25.20	4.06	104
1.0	2.0	114.4	5.35	21.30	42.6	28.62	4.0	114.4
1.2	1.4	80	6.42	25,68	36	41.22	2.8	115.2
1.4	0.84	48	7.48	29.92	25.1	55.95	1.68	94
1.6	0.58	33	8.56	34.24	19.8	73.27	1.16	85.7
1.8	0.42	24	9.63	38.52	16.1	92.74	0.84	78
2.0	0.33	19	10.70	42.80	14.1	115	0.66	75.6

This example shows that peak maximal acceleration occurs at  $w_f = 5.72$  , resonance at w = 5.35 , and peak amplitude at  $w_f = 5.02$  .

#### Does heat need ether for propagation ?

Heat from the sun traverses space nearly devoid of matter. Logic required some carrier for the electromagnetic waves, and Maxwell's electromagnetic theory explained electromagnetic waves, e.g. light, as transversal vibbations of an intangible fluid which however behaves much like a solid of extreme modulus of elasticity, because the waves are propagated with the highest velocity known.

It is well known that heat radiation is of the same nature."One is never sure as to whether he is dealing with short radio waves or long heat waves" says Hershberger (1954)p.126.

The usual explanation of how waves pick up energy is: The source sets adjacent particles into vibrating motion, and this is propagated, across the elastic constraints, to further particles. Experiments so far have not demonstrated the existence of ether, and the physicists seem to have lost interest in it. Ether is temporarily shelved by a compromise: Light travels as a hail of photons riding on a guiding wave/p.304, W.Wilson(1955)/which has the velocity of light, and heat photons differ only in energy.

The theory of relativity has gradually placed more and more emphasis on the time-space continuum. Although for Lorentz there still existed a stationary ether/p.28.Robertson(1954)/, "Einstein simply ignored the ether "/p.301,W.Wilson(1955)/. The postulates, of light having the highest possible velocity, and scales contracting, were in fact devised to explain the failure of the experiments. The author still hopes that ether will survive.

#### Why is heat conduction so slow ?

Heat radiation is propagated through space nearly instantaneously, with the velocity of light. When, however, it strikes a non-transparent obstacle, considerable time elapses before the heat becomes noticeable on the far side of the obstacle. Also sound waves, said to be participating in the flow of heat/p.790, Debye(1912)/, travel quite fast in air and still faster in solids.

The question arises, why is heat slowed down ?

Concerning sound waves it can be stated that they mainly cause vibrations of the whole body, or of substantial parts of it, and when they reach a boundary of the body, some of their energy is transmitted to the surrounding medium. Nevertheless these sound waves excite also some modes of vibrations associated with individual atoms and molecules, and this fraction of sound energy is distributed throughout the body, being lost for the excitation of the surroundings, except that ultimately it reaches them in the form of heat.

Meissner(1935)p.291, has a very definite picture for the slowness of heat conduction in quartz. From the observed velocity of heat flow in quartz crystal(approx.0.2 mm/sec), and the known distances between the atoms in  $SiO_2$ , he reaches the following conclusions:

1) Along the 0.2 mm there are 11,000,000 atomic oscillators , in which the two oxygen atoms vibrate against the silicon atom.

2) If the one second is split between them, each has got  $0.9 \ge 10^{-7}$  seconds for action along this row.

3) When this time is expressed in periods, there result approx. one million of oscillations for this action.

4) The action itself is:The preceding oscillator is assumed to have reached the amplitude corresponding to the temperature involved; the coupling with the next oscillator is less than 1% (derived by Meissner from above-mentioned observations); this oscillator starts with amplitude "zero" and gradually reaches full amplitude; a third oscillator is excited , in turn , by the second, etc.

This picture does not seem to be reasonable.

What Meissner calls "Kopplungskoeffizient" is, according to Hutte I (1942)p.231, the ratio of the coupling spring constant to the sum of it with the system spring constant, e.g.  $k_3/(k_3 + k_1)$ . For this to be less than 1/100, the coupling spring must be approx. one hundred times weaker than the system spring. Would not then the SiO<sub>2</sub> molecules tend to fall apart ?

Again, Meissner explains the 100- to 1000-fold higher thermal resistance ') of amorphous solids as being due to still weaker coupling between the irregularly piled-up oscillators. True, the irregular structure of the amorphous solids involves larger distances between the molecules, much as in liquids, however then the amorphous solids would simply "evaporate".

') Meissner expresses it in thermal ohms, and also refers to french practice of using "Ohm-thermique".

An expression by Arkel(1949)p.139, seems to imply the opposite, that the molecules of  $SiO_2$  are very strongly held to-gether: The series will therefore show a maximum in the heat of vaporization, and we know that this maximum occurs at  $SiO_2$ .

Very loose coupling means very sharp peaks of resonance, depending also upon the amount of damping. The atomic oscillators experience no viscous damping because the particles move in ether (or in empty space, if ether does not exist), and no ether wind has been detected so far, i.e. ether does not exhibit any viscosity. There is no Coulomb damping, because the particles do not slide on each other. There is no solid damping, because this is due to "internal friction", which does not exist, because there is not any physical contact between the molecules in a solid besides the interpenetration of their fields of electrostatic force. For example, any "solid damping" effect in a flat spring is due only to some spreading of energy. Instead of being stretched only in the desired direction (for the upkeep of the wanted vibrations) the bonds between the particles become stretched also in all other directions. If motion spreads sideways, energy spreads as well. Thus practically all molecules of a vibrating spring will be kept in some motion, and will spread some energy also to supports and other surroundings. Since viscosity is an electrostatic effect, and friction as well, a generalized statement can be made that all damping effects are finally the diffusion of energy, along the molecular oscillators, in unwanted directions.

At this opportunity the mechanism of "absorption" could be discussed. There are several phenomena to which the well-

known attenuation law of the type  $I_x = I_0 e^{-px}$  can be applied. Some kind of energy flow suffers exponential decrease of intensity. Where goes the missing part? From the foregoing discussion of damping it will be obvious that the absorption is again simply a phenomenon of energy escape in unwanted directions. If the energy flow is not directly vibrational energy carrying heat, any other kind of energy (the absorbed part of it) is first exciting atomic vibrations which then distribute the energy throughout the body, and to surroundings, as heat. For example, when X-rays eject electrons from the shells of the atoms, imparting to them some kinetic energy, this is passed on to other particles in the neighbourhood and appears as heat. A lethal dose of X-radiation raises the body temperature by about 0.001 C /p.91, Lapp and Andrews(1948)/. Another example is the shortwave diathermy, where this absorption is the purpose of the application.

For heat energy absorption, when it comes from another body, the picture is not much different: The incident flow of energy may be in the form of heat radiation (electromagnetic waves) or in the form of kinetic energy of molecules or atoms. In the latter case laws of impact apply, supplemented by the rule that all transactions must occur in multiples of quanta. Radiation can to a certain extent pass freely through the body ') in question (much like visible light does) except through metals.

 Sutherland(1935)p.5, for example lists the most suitable prism materials for infrared:Quarts up to 3.5 µ, Fluorspar:3 - 9 µ,
 Rock-salt:8 - 16 µ, Sylvine:15 - 20 µ, Potassium bromide:19-28 µ.

Transparency is explained by Shockley(1954)p.45:"In general it is a property of wave motion that waves can proceed unattenuated in periodic structures. This is true of acoustical waves in a gas, of mechanical waves in a solid, or of electromagnetic waves moving through electrical filters or periodic metallic structures in space. In all of these cases if the structure is perfectly periodic, the wave will proceed indefinitely without attenuation (The structures must be lossless to be analogs of the wave equation for electrons)."

Mott and Jones(1936) picture the behaviour of an ideal metal in Fig.45,p.110, where long waves are stopped in a thin surface layer, and for short light waves the metal is partially transparent. They quote from Wood, that the alkali metals become transparent in the ultraviolet. On p.116 they mention that 500  $\AA$  is the order of the distance to which light penetrates metals.

Since heat radiation is short electromagnetic waves, the same reasoning applies as in the case of radio-frequencies. Were it assumed that the electric field would penetrate into the metal, then an electric current would follow which would carry electric charge to the surface, and thus provide termination for the electric lines of force, and preclude further penetration of the electric field into the metal. Should the magnetic field penetrate into the metal, it would induce voltage and cause heavy current along the surface of the metal, producing a magnetic field which would cancel the originally penetrating magnetic field. For nonideal metals these effects are not too strict, and the fields gradually drop to zero within a small depth of the metal, the elec-

tric field sooner than the magnetic field.

Concerning that part of the radiation which cannot pass the body due to its transparency, i.e. the stopped part, we would observe two distinct effects: 1) Its quanta would find atoms, molecules (and electrons) which have empty levels to be transferred into. The energy of these transitions would, to some extent, be transmitted over the bonds to the particles inside the body, producing a flow of heat. When the amplitudes are small, little energy is drawn from the waves, however when resonance occurs, (in the quantum picture: when the quanta are just slightly more powerful than is necessary for the transition), amplitudes are much augmented.and then the absorption of energy becomes significant. 2) Every oscillator is capable of absorption, and every resonator is capable of emission. Energy may swing back and forth as between two identical tuning forks. What was not taken up by the adjacent resonators for further transmission to the inside of the body is reradiated by the oscillators at the metal surface, and this part of energy appears as the reflected ray.

Returning to the resonance peaks, there is then only one phenomenon affecting them, because damping was just explained as the escape of energy through the coupling between the particles. If all the effect is only an escape of roughly 1% of the energy, then the resonance peaks are very sharp and high. Such a setup is much like a wavemeter loosely coupled with a transmitter. It is the sharpness of tuning, which makes it possible to measure the wavelength, preventing the response of the meter whenever the

transmitter is slightly off the tuning.

Meissner mentions the internal frequency of the SiO<sub>2</sub> molecule as 3 x  $10^{13}$  per/sec ,which corresponds to 10 microns. He does not specify the "few" other frequencies, except that they are within a band of  $10^{12} - 10^{13}$  per/sec , corresponding to 33  $\mu$  - 3.3  $\mu$ . His molecular resonators could sharply respond only to a "few" frequencies, if they were emitted by the source, and would reject all other frequencies, much like a pushbutton receiver, i.e. the ability of quartz crystal to pick up heat would, to a certain extent, depend upon the temperature of the source. Experience, however, shows that every substance, including quartz, picks up heat at any temperature (provided there is a temperature difference), i.e. responds to all frequencies of heat motion. Therefore the resonance curves must be very flat, and the coupling must be tight.

Although Meissner ,p.290, quotes Bragg's(1931) expression that the elastic waves have to fight their way through a fog of secondary waves, he apparently does not approve Bragg's picture. This latter, however, seems to be more reasonable, because: 1) It does not mquire such an unbelievably weak coupling between the atomic oscillators; 2) it permits the propagation of many normal modes, and not only of a few resonant frequencies; 3) it corresponds to the experience.

It also provides a better explanation of the slowness of heat flow. When the coupling between adjacent oscillators is tight, the energy spreads quickly along the row(however leads to slowness) with the velocity of the elastic waves. At this point the atomic string could help.us. Should a long string be disturbed in the

middle, this disturbance, when receding, would split in two.travel to both ends, and die out on the way if the damping were excessive. With small damping, the disturbances would become reflected at the ends and meet again in the center, travel again to the ends, etc. until the energy would be dissipated. Were the excitation persisting and producing a number of wavelengths, one of them might fit in with the length of the string to produce standing waves and other wavelengths might produce an unceasing race of waves forth and back. Smaller amplitudes could be expected far from the excitation place, because energy would be dissipated on the way. With a small number of differing wavelengths the energy level at a certain location could fluctuate considerably, however with a very large number of interfering waves the pattern of energy flow should become (statistically) steady: at the source the level would be highest, and would gradually fall.to reach lowest level at the far end, only sufficient to supply the outflow through the support. Thus, although the actual waves would run back and forth with their large velocity of propagation the flow of energy would be caused by the difference of the composite amplitudes along the string, and thus would be slow. In the threedimensional solid, pictured by Bragg as a spring mattress, there are millions of atomic strings in all directions, and strongly interconnected at multiple points. Several or all of the normal mode vibrations, with combinations, of the atoms and molecules would occur simultaneously, or in succession. Higher harmonic frequencies should occur also, as well as combination frequencies due to the anharmonicity of vibrations. In anisotropic bodies the elastic properties would differ along the three axes, adding some more variety. The solid body would transmit both longitudinal waves

and transversal waves, because it strongly resists deformation in every direction. Thus the resultant spectrum of frequencies is expected to suggest a picture of a jungle forest with all types of vegetation. The multiple reflections from the boundaries of the solid, and the multiple interference should cause such a criss-crossed picture of waves that Bragg's (1931) expression about a fog of waves seems to be completely fitting.

For metals some unexpected changes in the picture may occur in the future, because the superconductivity still is not explained /Burton,Smith and Wilhelm (1940),Wilson (1953)- Seitz (1954)p.90, even remarks:"for nearly 50 years this topic has remained an outstanding mystery"- and the thermal resistivity passes through a minimum, and rises rapidly at the lowest temperatures (also for quartz) /Burton,Smith and Wilhelm (1940) p.260, however for the present time the picture of the free electron gas as the main agent for heat conduction in metals seems to be accepted. The conduction along the ionic lattice seems to be much less important.

The Fermi-Dirac statistics explains why those free electrons which may participate in the transfer of heat, have high velocities, corresponding to energies of the order of 10 electronvolts. To fit in with the picture of the fog of waves, they could be represented by their de-Broglie waves, however the particle picture is simpler. The slowness of the energy transportation by the free electron gas is, in fact, obvious, because the picture is the same as with any other gas in the kinetic theory of gases. There seems to occur some drift of charge as well : a more

energetic crowd of "hotter"electrons pushes the less energetic bystanders before itself. This causes a thermoelectric potential difference to appear in a metal in which a temperature gradient exists /Thomson emf ,p.20,Foote,Fairchild and Harrison(1921)/. This drift velocity of the electrons is small compared with the high individual velocities.

## Some factors affecting the measurement of temperature.

In practical systems the equilibrium is considered as reached when the measuring instruments do not show any difference in temperature between the (formerly) hot end and cold end of the body, or between bodies in contact. That this, due to the decreasing driving force, theoretically requires infinite time, was pointed out already by Fourier(1822)p.32.

With temperature measuring devices, the equilibrium is more properly a steady-state heat flow condition: The mercury does not rise further when the thermometer loses as much heat to the surroundings as it receives from the hot body. As there is always resistance to heat flow, there is a temperature drop along the thermal resistances from the hot body to the mercury, or to to the hot junction of a thermocouple. This entails a temperature indication which is not identical with the temperature of the hot body.

Thermometers and thermocouples are always in some measure covered with alien films. These do not constitute any appreciable source of error for immersed devices, because the temperature drop across the film is not measurable, the cross-sectional area for heat flow being comparatively large. However in cases when these devices just touch another surface, and the space of separation is gas-filled (in addition to the films), the constriction resistance at the small area of contact with the hot body may introduce considerable error, particularly if the other side of the bulb is exposed. Wrapping of the bulb

with tinfoil, and insulating the assembly, should ameliorate the situation.

Another point of importance is the disturbance created by the measuring instrument. A drastic example is the case when a certain voltmeter consumed nearly all the power generated, thus causing an extreme internal voltage drop, and a very low reading, which could be interpreted as a failure of the generator. When the heat capacity and the heat dissipation of the thermometer becomes appreciable in comparison with the heat capacity of the hot body, the temperature reading may be too low.

A large source of error (a warning against which does not appear in print often enough) lies in the method of correction for the cold-junction temperature, necessary when it is not the same which was maintained during calibration.

It is realized by everybody using thermocouples, that calibration curves are not straight lines, however the method of plotting them in short straight lengths makes one less mindful about this property of them. Printed tables also tend to obscure this fact.

Recently the author was puzzled why the L&N thermocouple material in use at McGill University was found by Rogers(1953) p.131, "to read about  $12^{\circ}_{\mathbf{F}}$  below the standard values for copperconstantan ...over the whole temperature range used...". He made a special check of the material ,from the same spool, and found close agreement with L & N tables.

The question came up again when steam temperature by a copper-constantan thermocouple, with cold-junction-temperaturecorrection according to instructions on.p.54 of "Pyrometric Practice"/Foote,Fairchild and Harrison (1921)/,was found 13°F higher than shown by a mercury-in-glass thermometer in an oilfilled brass well. The instructions are: "The true temperature of the hot junction is obtained by adding to the observed temperature the value K(actual c.j.temperature minus c.j.temperature at calibration), where K ... for rough work may be assumed 1.0 for base-metal couples...". For example, the thermometer read 263 F, the reference junction slidewire on the potentiometer was set on 0 F, the actual cold junction temperature was 64 F, and the millivolt reading was 4.95 mV, which, by tables, corresponds to 212 F. When (64 F - 0 F) = 64 F were added to 212 F, there resulted a temperature of 276 F , or 13 F higher than shown by the thermometer.

Later another reference to this factor K was found on p.246, ibid. stating that K is "equal to the mean slope of the calibration curve over an interval about  $50^{\circ}$ C, in the neighbourhood of the cold junction temperature, divided by the slope at the observed temperature...". When this formula is applied, K for the example given is found as K = (0.022 mV/F)/(0.027 mV/F)=0.815. Then only (64 - 0)0.815 = 52 F have to be added to 212 F resulting in 264 F which is reasonably close to the thermometer reading.

When a method ( The author is grateful to Dr.T.Lin for this reminder) given by Hodgman(1953) was used, even closer agree-

1 The milduce

ment was obtained: The temperature of the cold junction was converted into millivolts, added to the millivolt reading, and then the temperature above 0 F read from the tables. The 64 F above zero correspond to 1.37 mV above zero, and together with the 4.95

it gives 6.32 mV above zero, corresponding to 263 F. This latter method seems to be the safest.

Whether Mr.Rogers's observation was due to some electrical trouble in the automatic potentiometer(which was the original guess by the author) or whether it has something to do with the cold-junction temperature corrections (the reading was, however, low and not high) cannot be determined without reference to the actual calibration data which were not available. (The author's interest in this case is due to the earmarking of the same potentiometer for his future experimental work.)

### Contact angles.

The degree of wetting is usually stated by reference to contact angles(p.135, Review). Much more than elsewhere, the condition of the surfaces and the peculiar properties of the liquid and of the solid require careful attention.

Besides the solid and the liquid, there is also some gas adsorbed on the surfaces. Spreading of the liquid depends very much upon the removal of the adsorbed gas. A liquid which disselves the adsorbed gas spreads on the solid, while otherwise the gas would prevent wetting. If one experimenter is not aware of the adsorbed gas, and another removes the gas previously, their measurements will differ substantially./p.89, Fisher (1950)/.

There is another unnoticeable alien film on all surfaces exposed to the atmosphere: an adsorbed film of water(p.129a, Review) Spreading of some liquids may be prevented by this film while in other cases the water may have to be displaced first, or consumed, causing a delay/p.95, Fisher(1950)/.

If the liquid molecules consist of groups which attach themselves to the surface in a selective way(polar molecules, p.124,Review) the contact angle measurement will depend upon the orientation of the molecules at the surface. Fisher, p.85, ibid., mentions a case with soaps of long-chain fatty acids, where the angle was found either  $0^{\circ}$  or greater than  $90^{\circ}$ 

If the liquid is inhomogeneous mechanically(for example, a flocculated suspension), Fisher (p.89, ibid.) warns that "any contact angle measured for such a material is entirely fictitious".

In addition, the evaporating molecules of the liquid "can be pictured as leaving the bulk of the liquid and depositing in advance of the main body of the liquid" The liquid therefore does not form a sharp demarkation line but is , in spreading, "associating with its own molecular species deposited in adjacent areas of the solid".(p.89, ibid.).

The actual demarkation line of the liquid and of the solid has, of course, the usual uncertainty of shape (p.56, Review), and it must not be overlooked that the best microscope still does not resolve these details of the shape of the menistum, nor does permit the measurement of the angle at its vertex. Fisher (p.88, ibid.) states that "the line is always drawn at a region considerably removed from the actual junction of liquid and solid."

He mentions also (p.89) several causes of non-equilibrium conditions, making the measurement of the contact angle dependent very much upon the duration of the experiment. Very viscous liquids spread much slower than less viscous, and will be at a disadvantage if the experimenter is impatient. Also the evaporation of the liquid drop may impede spreading, if the replenishment is slow.

## Soldering.

Although it is a very old art, Bailey and Watkins(1952) p.57, are compelled to remark:"The causes of difference in 'solderability' are not known, for the basic factors controlling flow are not well understood."

Flux is observed to remove the thin oxide films growing fresh after mechanical cleaning, and also the adsorbed gas film, both from the solid metal surface and from the liquid metal surface, so that the attraction forces between the metal molecules can come into play /Bailey and Watkins(1952)p.64/. Fluxes also reduce the surface tension of the solders /p.75, ibid./. "Acid" flux does it much better than the "non-corrosive" fluxes, possibly also due to some electrolytic action. Even cast iron can be softsoldered when acid flux is used.

Previous "tinning" of the tubes of liquid-metal systems using lead alloys could be advantageous, and the "acid"flux should be effective also in this case.

Pure tin /p.64,ibid. / spreads much less well than some of the tin-lead alloys, which was also the experience of the author.

The attraction forces between the solid metal and the liquid solder depend also upon a good fit /Smith-Johannsen(1952) p.55/ of the active groups,molecules and atoms,so that not only a few molecules come within molecular distances from each other, but a whole array of them meets another array, and the attraction forces cover a region larger than microscopic.

No doubt, one cause of the seizing of bearings is this "good fit" effect, particularly if, instead of dissimilar metals for the shaft and for the bearing, the same metal is used for both. Copper sliders on copper (electric) contacts show the same seizure effect.

A critical temperature has been observed/Bailey and Watkins (1952)p.61/ above which the fluxes become so active ,that the rate of spreading of the solder suddenly increases greatly. The best spreading characteristics (approximately 370% of those for pure tin) have been found at approx. 50% tin in the solder, and at a soldering temperature  $60^{\circ}C$  above the liquidus temperature of the solder /p.58,ibid./.

# Derivation of the 3-dimensional heat flow equation by vector methods.

The Fourier (1822)p.54, one-fimensional heat flow equation F = -K dv/dz, or in our notation  $D_x = -k \partial T/\partial x$ , is based upon the experimental fact that the heat flux density  $D_x$  (computed for a unit area normal to the x-axis) is proportional to the temperature gradient along the x-axis, the minus sign expressing the decrease of temperature with increasing x. Similar expressions can be formed along the y and z axes. For an isotropic body k can be assumed to be constant. Considering  $D_x$ ,  $D_y$ , and  $D_z$  as components of a vector <u>D</u>, and denoting the unit vectors along the axes as <u>i</u>, <u>j</u>, and <u>K</u>, we have

Since the vector  $\underline{D}$  is expressed as a gradient of a scalar function  $\underline{T}$ , it has no curl ( curl  $\underline{D} = 0$  ), and therefore  $\underline{T}$  is a potential function with the usual advantages.

If heat is generated at a time rate g per unit volume, its amount per volume dv is g dv, and for a volume v the amount would be found as a volume integral of gdv. The amount of heat necessary to raise the temperature in a volume dv from zero to T would be cdv cT (where c is the density and e is the specific heat). Again a volume integral would give the amount of heat for volume v. This heat content might change with a time rate which could be found by differentiation, with respect to time, of the last-mentioned integral (assuming c and also  $\varphi$  to be constant):

$$\frac{\partial}{\partial t} \int_{\mathcal{V}} c \rho T dv = \int_{\mathcal{V}} c \rho (\partial T / \partial t) dv .$$

Let the volume  $\nabla$  be enclosed by a surface  $\mathbf{s}$ . If more heat would be generated than the heat capacity of the volume  $\nabla$ would require, some of it would flow out across the surface  $\mathbf{s}$ . The outflow across an element  $d\underline{\mathbf{s}}$  of it, per unit time, would be  $\underline{\mathbf{D}}.d\underline{\mathbf{s}}$ , and the total outflow would be expressed by the surface integral of  $\underline{\mathbf{D}}.d\underline{\mathbf{s}}$ . The heat balance then would have the form

$$\int_{\mathcal{V}} g dv - \int_{\mathcal{V}} c \rho (\partial T / \partial t) dv = \int_{S} \underline{D} ds$$

By Gauss's theorem /p.188,Slater and Frank(1933)/ a surface integral can be converted into a volume integral over the volume bounded by the same surface:

$$\oint_{\mathcal{S}} \underline{D} \cdot d\underline{\mathbf{s}} = \int_{\mathcal{U}} (\operatorname{div} \underline{D}) d\mathbf{v}$$

After substitution we have

$$\int_{\boldsymbol{\nu}} g d\boldsymbol{v} - \int_{\boldsymbol{\nu}} c \rho (\delta T / \delta t) d\boldsymbol{v} = \int_{\boldsymbol{\nu}} (di\boldsymbol{v} \underline{D}) d\boldsymbol{v}$$

The size of the volume  $\mathbf{v}$  can be chosen arbitrarily small. Therefore, instead of equating integrals we may equate the integrands:

$$g - c\rho \partial T / \partial t = div \underline{D}$$
, and using (1)  
 $g - c\rho \partial T / \partial t = div \underline{/} - k (grad T) / .$ 

Without heat generation g=0, and  $qr \partial T/\partial t = k\nabla^2 T$  or  $\nabla^2 T = (qc/k)(\partial T/\partial t)$ , which for steady state reduces /p.117, Fourier/ to Laplace's equation  $\nabla^2 T = 0$ .

## Electrical analogies.

Electrical phenomena were discovered later than mechanical, and the first writers on electrotechnics adapted the known mechanical terms: There is an electromotive force, overcoming a resistance to flow, while producing an electric current, etc. Not long ago writers on mechanics began to borrow from electrotechnics: Ohmis law is used /p.108,Guide(1949)/ to explain heat-flow resistance; <u>Kirchhoff's law</u> is used /p.12-09,Kent,Power(1950)/ to explain computation of thermal resistances in series and in parallel. A thermal ohm as a unit of thermal resistance is defined /p.14-216, Pender, Del Mar (1949), p.1-166, Eshbach(1952)/ in degrees centigrade per watt rate of heat flow. Thermal volume resistivity is then the thermal resistance of a cube with one centimeter on side, expressed in thermal ohms. Thermal surface resistance is computed from the thermal surface resistivity, expressed in degrees centigrade of temperature drop caused by heat flowing at the rate of one watt from each square centimeter of surface. Of course.a temperature difference of 1 C is maintained between the opposite faces of the above-mentioned cube for a determination of its thermal conductivity.

Unfortunately some authors are not consistent in the application of the electrical analogies. For example, electrical resistance is obtained as (rho x L)/A ,and thermal resistance is expressed in the same form by Jakob(1949)p.8,American Standards Association(1943)p.13,and others, using 1/k in place of rho. However at the same time expressions of the type L/k are called thermal resistances/p.3-13,Kent,Power(1950)/,and even 1/k is called thermal resistance (p.12-04,ibid.).

The use of thermal resistance as a reciprocal of thermal conductivity (p.18-28,ibid.) might be just a misprint, as probably is /p.115,Guide(1949)/ also a formulation that "thermal resistance ...is expressed in Fahrenheit degrees per (Btu)(hour)(square foot)" while it should have been (°F)(hr)(ft<sup>2</sup>) per Btu.

In connection with the varying definitions of thermal resistance, the analogy with electrical current is not always obtained. While a true analogy to amperes as coulombs per second would require calories per second, or Btu's per second, i.e. q = Q/t / p.3-12, Kent.Power(1950).p.105,Guide(1949),p.13,A.S.A.(1943)/,some authors /p.292, Guide(1949)/ call q/A = Q/tA the rate of heat flow, which actually is a heat current density, and some even alter the meaning of Q as a quantity into Q expressing a rate of heat flow /p.5, Eckert(1950) / and q expressing the specific rate of heat flow (or the heat current density). The latter apparently wish to keep the appearance of perfect analogy, and nevertheless to obtain the conductivity in units found in the tabulations of practical data. Even in one and the same book /Guide(1949)/ on p.14 q means Q/tand C = 1/R means kA/L /also p.13,A.S.A.(1943)/.heat transferred per unit time and one degree across the whole body involved, however on p.167 the same symbol C is used for a quantity expressed in Btu per (hour)(sq.foot)(<sup>o</sup>F), and thus is actually the conductance of a path of unit area. The same applies to the use of the symbol R on p.14 and on p.167.

In electrotechnics the crosssectional area of the conducting body is usually small compared with its length, and remains well within the limits of easy visualization. Only when it comes to flat bodies, like electrodes in electroplating, or plates of batteries, unit area is considered, however then the term current <u>density</u> is used. In heat transfer work the crosssectional area varies enormously, and is large in comparison with the thickness ("length") of the body. It is reasonable, therefore, to refer to unit area, however again it should be done so by using the term: heat current <u>density</u>.

For the sake of clarity, the author suggests the notation used on p.13 of the Guide(1949):

C ; the conductance of the whole body.

C<sub>2</sub> : the conductance of a path of unit area.

R : the thermal resistance of the whole body.

r = 1/k : thermal resistivity /p.8, ibid./.

Although no symbol is given there for the thermal resistance of a path of unit ara@, (American Standards Association ,p.13, uses RA), the author, by analogy, suggests for it the symbol  $R_a$ .

Then the true analogy to Ohm's law is conserved, while the symbols used in tables of practical data need only be supplemented by the subscript **a**.

A tabulation of the analogies follows.

Heat. Electricity. Total quantity of heat transferred, joules or Btu, Q Charge, coulombs Q Thermal current, or heat 🗈 transferred per unit time, q = Q/t, joules/sec or Btu/hr .... Current, coul/sec a Ι Thermal current density or amperes D = q/A = Q/tAjoules/(sec)(cm<sup>2</sup>) or  $Btu/(hr)(ft^2)$  .... D Current density I/A Thermal conductivity joules/(sec)(cm<sup>2</sup>)(<sup>o</sup>C/cm) or Btu/(hr)(ft<sup>2</sup>)(°F/ft) ··· k Conductivity gamma. Thermal conductance C = kA/Ljoules/(sec)(<sub>0</sub>C) or Btu/(hr)(°F) ..... C Conductance G Th.conductance of a path of unit area, Ca = C/A == =k/L; or  $C = C_R A$ ; joules/(sec)(cm<sup>2</sup>)(°C) or  $Btu/(hr)(ft^2)(^{o}F)$  .... Ca ? Thermal resistivity, r = 1/k (thermal ohms)(cm) = $=(^{O}C/cm)(sec)(cm^{2})/joules$ or (°F/ft)(hr)(ft<sup>2</sup>)/Btu ··· r Resistivity rho (ohms)(m)

Thermal resistance, R=1/C El. resistance, R = 1/G  
R = rL/A = L/(EA) R = (rho)L/A = L/(gamma)A  
thermal ohms = °C/watts = ohms  
= (°C)(sec)/joules or  
(°F)(hr)/Btu ..... R R  
Thermal resistance of a  
path of unit area, 
$$R_a = 1/C_a$$
  
 $R_a = RA = rL = L/k$ ;  
(thermal ohms)(cm<sup>2</sup>) =  
 $= (°C)(cm2)/watts$  or  
(°C)(sec)(cm<sup>2</sup>)/joules  
or (°F)(hr)(ft<sup>2</sup>)/Btu .... R<sub>a</sub> ?  
Thermal motive force, .... dT Electromotive force R  
( dT to mean temperature  
difference) °C or °F volts  
Ohm's law.  
 $q = dT/R = dT/(rL/A) = AdT/(rL)$  I =  $R/R$   
 $q/A = D = dT/R_a = dT/(rL) = dT/(RA)$  I/A =  $R$  /RA

$$R = dT/q = dTt/Q = 1/C = 1/C_{a}A = rL/A = L/kA \qquad R = E/I$$

$$R_a = RA = AdT/q = tAdT/Q = 1/C_a = L/k = rL \qquad RA = EA/I$$

$$C = q/dT = Q/tdT = C_a A = 1/R = kA/L \qquad G = I/R$$

$$C_{a} = C/A = q/A dT = Q/t A dT = 1/R_{a} = 1/R_{a} = k/L \qquad G/A = I/AE$$

....

#### Some conclusions .

Heat is the combined effect of :

- a) the kinetic energy of electrons, atoms, and molecules;
- b) the vibrational energy of electrons, atoms, molecules, and assemblies of molecules;

c) the energy of short electromagnetic waves ( 0.76 to 400  $\mu$  ) originating from quantized transitions of electrons, atoms, and molecules.

When macroscopic systems are considered, the smallness of the quantized steps makes the impression that energy changes are continuous.

Atomic and molecular vibrations are anharmonic due to mechanical and electrical causes, and a Fourier analysis would show many harmonic frequencies. The number of possible normal modes increases with the number of atoms in the molecules, and this causes many more combination frequencies. In consequence, already a spectrum of a single molecule is quite complicated.

Even waves of the order of 1 cm in length have manifested themselves as heat, and indirectly the "absorbed" part of all electromagnetic radiation appears as heat.

Heat is acquired by a substance :

- a) when particles of the heat source collide with the particles of the substance, if they are free to move about;
- b) by resonance of such vibrators, in which the particles are interlocked in a structure, with waves arriving via other parts of the structure, or arriving from space, and even when the exciting frequencies are submultiples or multiples of  $w_n$ .

Heat is propagated :

- a) if the energy level at a certain point in the substance is different from the level at an adjoining point. The level could be imagined as computable by a Fourier synthesis of all elastic waves passing the point in question, and of all particles passing the point as their respective de Broglie waves.
- b) by means of impact of particles, by means of transport of excited oscillators (convection,drift), by means of communication of energy across the bonds between particles, and by means of electromagnetic waves linking the emitting and absorbing bodies which are outside the reach of the molecular forces acting a short distance beyond their surfaces.

Heat is given up, or emitted, by the same mechanism as it is acquired, and both processes occur simultaneously, striving toward equilibrium.

Within amorphous non-metallic solids vibrational energy is the main form of heat conduction.

In crystalline solids the regularity of the lattice reduces the distances between the atoms (tightens the coupling between the atomic oscillators), and reduces the resistance for the travelling thermoelastic waves, as every periodic structure does.

In solids the resistance to deformation is present in all directions, and therefore there occur both longitudinal and transversal and polarized vibrations.

The atomic string provides insight into the race of thermoelastic waves through a crystal. A disturbance would run along an infinite atomic string with the velocity of the elastic waves,

because there would not be any interference. A filtering effect, however would show up.

Any real body, even the finest wire, is composed of millions of atomic strings in all directions, interconnected in a regular or partly irregular lattice. Due to this interconnection, every elastic wave would disturb the others, affecting their amplitudes and phases. In some cases it would lead to destructive interference, while in other cases constructive interference may occur, as well as standing waves. Therefore even an infinite extension of a solid would not provide the circumstances for heat propagation with the velocity of the elastic waves, however it would eliminate the multiple reflections from the boundaries of the body. These however, do not seem to affect the statistical picture markedly, because the size of the body does not seem to affect the steadiness of it while the region of higher temperature is advancing.

At liquefaction the amplitudes of atomic vibrations reach such magnitudes, that the atoms escape from the holding power of the neighbouring nucleus, and become free to move about, "holding hands" as it were. Therefore transversal waves could hardly **prist**, however longitudinal (compressional) waves still carry the energy, aided now by direct impacts and by transportation effects. This explains the drop in thermal conductivity at liquefaction.

When still more kinetic energy is imparted to the molecules (vaporization), they are able to break the last "springs", and then only internal vibrations of their components occur, as well as inversions, rotation, and more complicated forms of individual motion. Exchange of heat energy now occurs by impact and radiation.

Transportation effects become important.

Radiation spreads across the space between the molecules with the velocity of light, and is absorbed (and emitted) at resonant frequencies of molecular structures; it is distributed to other molecules by collisions.

Metals also are crystalline solids, and therefore lattice vibrations play an important part. As with other solids, the lattice structure acts as a filter, letting some frequencies pass, and attenuating others. It also provides the means for spreading the vibrational energy sideways. The coupling with adjacent atoms, and the "damping" caused by this coupling, affect the response of adjacent atomic vibrators. The coupling acts both ways, i.e. energy is also returned, if the energy level of the resonator begins to exceed that of the transmitter. When the picture of "internal friction" in solids is replaced by a picture of interacting electrostatic force fields, then the internal "damping" effects can be explained as (lateral) diffusion of the energy flow along the coupled atomic oscillators. The diffusional type of energy flow is also indicated by the identical form of heat conduction and of diffusion differential equations.

Metals show very small transparency for electromagnetic waves (heat radiation), because the secondary effects of the impinging waves cancel these within ideal metals.

An exclusive mechanism for heat conduction in metals is the electron gas effect, overshadowing by far the other effects. Most authors picture the valence electrons as free to move bet-

ween the positive ions, however some find the effective number of electrons as a fractional number. Some picture them as assembled inba lattice of electrons free to move with respect to the ionic lattice.

Assuming that they act individually, and obey the laws of the kinetic theory of gases as corrected by the Fermi-Dirac statistics, we need only to mention some of the differences with other gases.

The equipartition law does not hold for them, because most of them are confined to inactivity while waiting for sufficiently powerful quanta which could raise them to empty levels of energy high above. Even at highest industrial temperatures only a small number of them participates in the heat motion actively, i.e. with energy uptake and delivery. This explains their small contribution to the specific heat of the metal.

The active ones possess comparatively high energies, i.e. high velocities. Their diameter by the classical theory was much smaller than that of a proton, however due to Heisenbergs principle of uncertainty the wave mechanics ascribes to them a diameter of the order of 200 diameters of a proton (and this was the reason why they were no more admitted as bricks for building a nucleus: they were bigger than the whole nucleus). Even with a comparatively large diameter they still find much free space in between the nuclei forming the lattice, and their mean free paths are considered to be of the order of several hundred atomic diameters. When, however, the lattice vibrates with larger amplitudes, or is irregular due to defects, or due to impurities, their col-

lisions with the ions become more frequent and the free path is reduced. Nevertheless they are long-distance carriers of energy, and contribute most to the high thermal conductivity of metals. Their action as carriers of heat energy differs somewhat from their action as carriers of the electric current, because at very low temperatures some metals lose the last trace of electrical resistance (which is still described as an outstanding mystery !) however keep some thermal resistance , which emen shows a minimum just<sup>at</sup> about one degree absolute, and rises again when absolute zero is approached.

With reference to the means for reducing surface roughness, polishing could be mentioned as reducing the constriction resistance, however it changes the crystalline structure of the metal surface to an amorphous one (Beilby layer), thus increasing somewhat the thermal resistivity in this region. Whether the combined effect is positive could be ascertained by actual computation.

The thermal conductivity of an amorphous mass can be improved if part of its volume can be replaced by crystalline matter. E.g. filling of an electrical insulating compound with quartz sand/p.291,Meissner(1935)/ increases the thermal conductance of the assembly from 2 to 5 times.

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