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CONFERENCE ON

DIRECT ENERGY CONVERSION

NOVEMBER 4-5, 1963

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PREFACE

The Conference on Direct Energy Conversion, held November 4 and 5, 1963, at Argonne, was sponsored jointly by Associated Midwest Universities and Argonne National Laboratory. The U.S. Atomic Energy Commission provides financial support to both AMU and ANL, and thus helped sponsor the conference. All work reported by ANL authors was performed under the auspices of the AEC.

The members of the Program Committee were:

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Argonne National Laboratory:

B. I . Spinrad	Reactor Physics Division
R. C. Vogel	Chemical Engineering Division
A. J . Ulrich	Reactor Physics Division

Speakers at the conference were asked to provide summary accounts of their talks for these proceedings. The proceedings, in turn, provide an integrated record of the meeting and indicate in general the current status of direct energy conversion research in the organizations represented. It is emphasized that publication of these proceedings should not in any way prejudice further publication of the information in profession-oriented journals.

November 22, 1963

SESSION I

Monday, November 4, 1963

CHAIRMAN: FELIX T. ADLER
University of Illinois

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I-1. WHY STUDY DIRECT CONVERSION?

Bernard I. Spinrad
Argonne National Laboratory
Argonne, Illinois

The subject of this talk "Why Study Direct Conversion?" is a question of great generality; it has both a quick answer and a more detailed one. The quick answer is that our society is largely engaged in converting energy from one form to another for various uses. Thus we must understand energy conversion to understand our society.

For one thing, the study of energy conversion is fundamental to a number of scientific disciplines. For example, we study energy conversion on a cosmic scale in order to understand: (1) the behavior of solar flares and the solar wind; (2) the history of stars; (3) geomagnetic fields; (4) auroras, Van Allen belts, and lightning; (5) tides; (6) the origin of planetary chemicals (including the question of whether fission and fusion energy were liberated on a large scale after the basic planetary materials were laid down).

In the biological field equally important questions revolve around energy conversion such as: (1) nerve and muscle tissue behavior, (2) heat and light cycles of organisms, (3) reproductive cycles, differentiation and tumor formation, (4) the basic relations between energy, information and life.

Other scientific fields can give similar testimony to the importance of studying energy conversion as a fundamental process.

In addition, there are basic facts of our society which make it necessary to study energy processes very thoroughly. Our modern world is an energy society. The major distinction between modern society and those societies which went before it is our substitution of mechanical energy for human and animal energy, which substitution made the industrial revolution possible. Even the increased productivity of agriculture through the use of fertilizers and large scale farm equipment is a prime example of the workings of an energy society, for the energy put into the production of fertilizer and into the production and use of large farm equipment far exceeds the energy per unit output expended on agriculture in the primitive world. We use this extra energy to sustain more humans in nonagricultural pursuits. To take another case, it takes less energy for a man to dip a pail of water than to do it by employing a pump; but the pump liberates the man.

Although we tolerate this inefficiency because of the rewards it brings, it does not follow that we are really happy with the situation; although energy resources are now far more available to us than ever before,

the use of energy is still an item of appreciable cost. This cost translates into an expenditure of human toil, which we desire to minimize.

Now, in general, whenever a process can occur directly rather than through several intermediate steps, it is likely to be more efficient. This means that it is likely to be less costly in capital and in labor. Moreover, there is something esthetically satisfactory in performing tasks both efficiently and directly.

Another touchstone of our modern energy use is that we require its application to be carefully controlled. In welding, computing, and even steel-making, we supply energy of a specific type to a specific location at a specific time. The ability to convert energy sources directly into applications would be a major convenience; and human convenience is another goal of our energy society.

Finally, we have only recently realized as a matter of practical, rather than purely theoretical, significance that we can transduce energy in a variety of ways, some of which give the required form directly, and that these new methods of transduction can solve some of the most pressing modern technological problems, particularly in space exploration.

Thus, the interest in direct conversion stems from our energy needs, stimulating the search for more efficient use of energy resources, and from the realization that current processes only imperfectly match the generation of power to its ultimate uses. It also stems from the fact that new energy requirements, particularly those of space exploration, require new approaches.

Parenthetically, the term "direct conversion of energy" is usually taken to mean the conversion of heat to electricity without a mechanical intermediate, or the conversion of chemical energy to electricity without an intermediate thermal cycle. A much better term would be "new forms of energy conversion," and the question, "Why study new forms of energy conversion?" is the real subject of this paper.

Conserving Energy Resources

The increased efficiency which we hope to achieve from direct conversion could be of great importance in conserving the energy resources now available to us.

Our supplies of coal are very large. Even extrapolating the use of energy on the exponential curve which the world currently exhibits (yielding a doubling of consumption about every ten years) we have enough coal to meet our total energy demands for over 100 years. We have even larger supplies of solid fossil fuels which are of lower specific energy

value than coal - lignite and peat. However, these materials cannot be profitably mined unless their efficiency of use is increased markedly over the current value. Right now, on the average fossil fuels contribute only one quarter of their potential energy to the processes for which they are burned.

Since fossil fuels have their energy stored as chemical free energy, which is thermodynamically as noble as mechanical or electrical energy, the required transduction can be performed in principle at high efficiency. A fuel cell is one way. Therefore, the problem of developing large scale, economic and efficient hydrocarbon-burning fuel cells is a very important one for the energy resources of the world. A factor of four improvement in efficiency would not so much stretch the supply of coal itself, but would make it economic to tap the world's very large supplies of low-grade fossil fuels. Because fossil fuels are preferred for transport, the development of automobile-size fuel cells would also be a most significant matter.

Our next energy resource is nuclear energy, the energy available from fusion of light elements or fission of heavy ones.

In the case of fusion energy, we have a fuel, deuterium, which is for all practical purposes limitless. The earth's supply of deuterium dissolved in the oceans is very large and the energy cost of extracting it is small. Thus we predict no depletion of deuterium availability for millions and perhaps billions of years. A generalized faith in progress permits one to guess that fusion will be an asymptotic energy source, so that if we can solve our energy problems for the next millennium or so we need have no fear that future millennia will be starved for energy.

But the fact is that we do not now know how to extract energy efficiently from fusion. Of the forms of nuclear energy conceptually available to us, the fission of heavy elements is currently the only practical way. In this case, we have a situation similar to that of coal, but with an extra dimension. The quantity of energy available to us from the burning of U^{235} is limited. For example, it has been estimated that the United States' energy needs could be satisfied for only a generation by the burning of all the U^{235} domestically available at low cost. The United States is a large enough geographical sample of the world so that it is reasonably probable that our uranium supply situation is typical and the United States is also a typical consumer in an advanced technology.

Fortunately, however, natural uranium contains two isotopes, with U^{238} being approximately 140 times as abundant as U^{235} . Breeder reactors permit the U^{238} to be essentially completely transformed into fissionable material and burned, and therefore the successful attainment of breeding would multiply our efficiency of use of uranium minerals by a factor of more than 100. This would mean that the very large supplies of very low

grade uranium which exist in the world could be profitably mined. These supplies are so extensive that fission through the breeding cycle could also perhaps supply the asymptotic world energy needs. It is breeding, rather than efficiency, which makes nuclear energy so attractive in the long run.

In fact, although increased efficiency of power generation may have some part in stretching the availability of fissionable materials, direct conversion's greater promise for a nuclear age resides in another possibility. Cheaper and simpler processes for heat-to-work conversion could ameliorate the attrition of components which causes the plants themselves to wear out.

One other form of energy available to us in very large quantities is solar energy; it is available to the world at about 1 kw per square meter. In a very advanced society an individual human being might consume about 10 kw of power, so solar energy falling on 10 square meters of the earth's surface is in principle, enough to sustain one human being at an advanced technology. Thus, if we knew how to utilize solar energy at 100% efficiency we could support properly a world population of 15×10^{12} people. Even a small fractional efficiency would be enough to support adequately what we consider an asymptotic world.

However, the fraction which is available to us is much smaller than generally realized. Approximately $\frac{3}{4}$ of the solar energy falls upon the oceans and more than half of the remainder falls upon essentially uninhabited portions of the world. We thus lose a factor of about ten to start with. Then, our most widespread use of solar energy is in agriculture, which transduces energy at less than 3% efficiency. The conversion of food energy to other uses is probably less than 10% efficient. Finally, in our modern energy society a very great amount of extra energy is added to the growth of crops. I would guess that our total efficiency for use of solar energy is less than one part in a thousand. That figure would mean that solar energy could sustain perhaps 15 billion people, a world population which will probably be realized within our lifetimes.

Therefore, it is of the highest importance to find out whether a modern industrial society can make more efficient total use of solar energy; if we can do it, then solar power also becomes a possible asymptotic energy source.

Efficiencies of Current Transduction Processes and New Ones

I have expanded on the ways in which increases in efficiency of energy conversion can add to our practical energy reserves. I should now like to turn to a generalized discussion of energy conversion, to illustrate better the inefficiencies of current practice, and to formulate more directly some of the gaps in our abilities.

Table I, Forms of Energy, simply lists the major types of energy which are available to us, and the generalized forms of energy which are desirable end products. Some energy sources of major significance have been omitted as being intrinsic intermediate steps; e.g., geothermal energy is an intermediate step in which nuclear energy from natural terrestrial radioactivity is transduced to heat; atmospheric energy is available as an intermediate step in which solar energy and the earth's gravitational potential are transduced into kinetic energy. On the other hand, I have sidestepped the question of whether solar energy should be considered as arising from gravitational potential or nuclear energy by listing it as a prime source.

TABLE I. Forms of Energy

SOURCES	
<u>Type</u>	<u>Embodiment of Source</u>
Chemical free energy	Fossil fuels
Nuclear binding energy	Radioactive material, uranium, deuterium
Gravitational potential	Head of water in dam, tides
Electromagnetic radiation	Solar radiation
APPLICATIONS	
<u>Type</u>	<u>Use as End Product</u>
Kinetic (mechanical)	Motion: Transport, mechanical action
Electrical currents	Almost none, but we know how to transport this type and transduce it efficiently to almost all other forms of application.
Electromagnetic radiation	Heat, light, communication, photosynthesis
Chemical free energy	Metals, chemicals

The ultimate application of energy seems to be limited to three types: kinetic, electromagnetic, and chemical. I have also listed electrical current energy as an application, since it is conveniently and efficiently transported and transduced to the other forms. If we have electrical currents, most of our problems are solved.

Table II, Transduction Processes, illustrates the steps we currently take in processing energy to its use. The first, direct contact chemistry, is generally inefficient in energy use because excess heat is generally added (and usually wasted) in order to improve reaction kinetics. Also because, as in the case of iron ore reduction, excess reagent is generally put through the process and discarded. The process is certainly direct conversion: one version of chemical potential to another. Nevertheless, the more sophisticated industrial chemistry tends toward improvement of efficiency by electrochemical processes. Perhaps the inefficiencies of present processes are intrinsic.

TABLE II Transduction Processes

Source	Intermediate(s)	Product	Examples	Comments
Chemical potential	None	Chemical potential	Reduction of steel	Current practices are wasteful but need not be
Chemical Nuclear	Thermal	{ Mechanical Waste heat }	Transportation	Waste heat governed by second law of thermodynamics
Chemical Nuclear Solar			Central station power	
Chemical Nuclear Solar	None	Thermal	Comfort heat Industrial process heat	Efficiency of use of free energy governed by product temperature level
Chemical Nuclear Solar	Thermal	Electrical Mechanical Waste heat	Water purification	So far, quite inefficient
Gravitational	Mechanical	Electrical	Hydro power	Requires favorable geography
Solar	None	{ Chemical Waste heat }	Photosynthesis	Vital, but inefficient

The second process is illustrated by a car engine or by a nuclear or conventional ship, and the third by a nuclear or conventional electric power station. Solar energy is included among the sources for central station power because of the possibility of solar reflectors being used in space-power systems. For both transport and central station power, the efficiency of energy conversion is limited in the heat-to-work step, both by the second law of thermodynamics and by the great irreversibility which we build into our equipment. The second of these factors is the more significant, for with cycles running at 627°C source temperature and 27°C sink temperature, a Carnot cycle would yield a 67% efficiency, whereas we commonly get only 40% efficiency or less.

To the extent that such applications are fueled from chemical sources, we have three ways of increasing conversion efficiency: by going to fuel cells (ultimate efficiency close to 100%); by finding other processes which use a heat-to-work step but have few intrinsic thermodynamic irreversibilities; or by retaining current conversion practices and utilizing higher temperatures (ultimate efficiency, $0.6 \times 0.9 = 0.54$). High temperatures together with transduction by thermodynamically reversible processes might yield ultimately efficiencies of about 0.85, which would continue to compete with chemical direct conversion.

If the energy source is solar or nuclear, conversion to heat would permit only the use of high temperatures and reversible processes as ways of increasing efficiencies.

Turning now to the fourth process, the conversion of prime energy sources into heat is a basically inefficient energy use. Fortunately, comfort heat requirements for humanity are not great; good insulation practices permit the chemical energy of the body to supply it, whether by protective clothing or high quality building; and it represents a very small fuel consumption in the 10 kw per person I have assumed. Industrial process heat is another matter. It would be asymptotically a significant, though not major, energy use. If the need is for high temperature, then the energy is not degraded much, and waste can be gainfully used, for example to generate electricity. If the need is for lower temperature, then an efficient society would obtain it in conjunction with heat-to-work equipment. The asymptotic supply of process heat is conceptually obtained primarily as a byproduct.

The fifth process is one which is receiving increased attention, both conceptually and practically, at present. The problem of procuring fresh water for our needs grows even more acute as our population multiplies and our civilization advances into desert areas (which include the oceans). To procure it, we must add chemical free energy to the water. Three processes are proposed: electrodialysis or related processes, freezing, or distillation. The first of these is conceptually the most efficient, but appears to be best suited to brackish water. The second relies upon the availability of mechanical energy for refrigeration and is particularly efficient in reducing impurity concentrations in the initial stages, but it is difficult to derive a pure product from it and mechanical equipment is difficult to scale up to very large sizes at high efficiency. The third is most appropriate for large throughputs and purification of sea-water but the chemical nature of sea-water is such that relatively low temperatures are required in the conversion of heat to chemical potential, and thus low thermodynamic efficiency is associated with it.

If I am forced to guess, I would extrapolate that electrochemical processes would be appropriate for cleanup of brackish waters in arid plateau areas, permitting multiplication of rainfall by widespread

recirculation of the water. Near the sea, three-stage processes look attractive: a first cut by freezing, followed by distillation, followed by electrodialysis. The freezing is employed to reduce the concentration of those chemicals which form scale; distillation can then be performed at higher temperatures, increasing process efficiency; and electrodialysis may be attractive for final cleanup. Of course, an enthalpy free-energy balance is required among these steps.

Other estimators have recently concentrated on distillation alone. Then water purification is a form of industrial process heat. I have commented on this matter previously. If water purification is not to be a burden on efficient use of energy, it must be done either in a context of much larger use of free energy, or in an efficient fashion as I have just outlined.

The sixth energy process on my outline is that involved in generating hydroelectric power. It is extremely efficient. It is, however, derived from a tiny fraction of our solar power, and its application is limited by geography. It goes without saying that, where available, it should be tapped.

The last, (solar energy) is a vast energy resource, highly inefficient in its transduction. It is capable of supplying our energy needs indefinitely if we turn the entire world, ocean included, into a garden. Unfortunately we do not yet know how to do this without expending even greater energy. Of course, it must be listed in any case, because efficient or not, it is the only transduction process we know of which can support life.

The foregoing processes have been described in detail to illustrate the squandering of our resources in many of our industrial techniques. I have already pointed out where we might hope to do better. Table III lists some of the processes which are conceived for that purpose.

The first is that of the fuel cell. Through its use we hope to bypass the thermal steps in the conversion of chemical to electrical energy. These are the steps which are responsible for the greatest irreversibilities. The problem is not to substitute irreversibilities in the fuel cell, which may be of two types: heat losses in the electrolyte; or requirements for too evanescent or too bulky equipment, putting an energy drain from manufacturing industries into the energy-conversion cycle. The way we determine this is by cost. When electricity from fuel cells is cheaper than that from turbogenerators, we may be reasonably certain that we have improved the total conversion efficiency of our economy.

Passing on from fuel cells, we next proceed to ways in which we can utilize high temperature heat efficiently. Chemical fuels, solar radiation and nuclear fission can all be used to heat working fluids to such high

temperatures that very efficient thermomechanical cycles can be postulated. We have almost despaired of energizing rotating machinery at high temperatures without excessive deterioration of the machinery (which is as already explained, an irreversibility). But we can make efficient and rugged nozzles, which are devices for converting the thermal potential of the fluid into mechanical energy of the fluid itself. If we can now make the fluid a conductor, we can in turn transduce this fluid energy into electrical current energy. This, then, is the basis for the second scheme - "MHD" for "magnetohydrodynamic" energy conversion. The main problems seem to be to prevent excessive irreversibility from friction in the fluid.

TABLE III. New Transduction Processes

Source	Intermediate	Product	Popular title
Chemical	None	Electrical	Fuel cells
Chemical Nuclear Solar	} -Thermal- { Mechanical Waste heat	} -Electrical	- MHD
Chemical Nuclear Solar			
Chemical Nuclear Solar			
Chemical Nuclear Solar	} — Thermal — {	{ Electrical Waste heat	} - Thermionic Thermoelectric
Chemical Nuclear Solar			
Chemical Nuclear Solar			
Nuclear	Microscopic particles	{ Chemical Waste heat	- Chemonuclear reactor
Nuclear	Microscopic particles	{ Electrical Waste heat	- Plasma reactors
Solar	None	Electrical	Solar cells
Solar	None	Mechanical	Solar sails

The next item concerns a pair of techniques for bypassing the mechanical step in the thermal-to-electrical cycle. Thermionic conversion uses very high temperature heat to achieve electron emission from a surface. The electrons work against a potential and finally are deposited on a cooler surface. The potential difference, which is the difference in work functions of the hot and cold surfaces, is under ideal conditions (and in the right units) the difference in temperature between the hot cathode and cold anode. Energy losses are by radiation, deviations of the work-function from ideal behavior, and heat conduction. One aim of the mainstream of thermionic research is to reduce these energy losses to a trivial value. The other aim, and the more pressing, is to construct durable equipment, for thermionic conversion equipment has so far been too short-lived for any but transient applications.

Thermoelectricity is an old process, using the potential differences in semiconductors exposed to a temperature gradient to generate electrical currents. In such materials, one always has thermal losses due to both conduction of heat and internal I^2R losses. Consequently, the efficiency of thermoelectrics is low, and although it is being improved by modern research, it will probably never be high.

The next item is the chemonuclear reactor, a device which aims at converting the microscopic charged particle motions of fragments from nuclear fission into chemical free energy. Again, heat is the undesirable by-product. The charged particles from fission lose their energy by ionizing the material they penetrate. They create tens of thousands of ion pairs with tens of electron volts energy per pair. The search is for a technique of getting these ion pairs to initiate endothermic chemical chain reactions such that the reaction products contain all of the free energy available. It is too early to tell now whether this goal is possible or impossible, but it seems unlikely that a very efficient process can be found.

The fifth technique listed depends upon the fact that there is no sensible upper limit to the temperature at which a nuclear reactor can go critical. The sole limit is our ability to confine the critical mass in its critical volume. If we can perfect our techniques of confining plasmas magnetically, we could make a magnetically contained fissioning plasma reactor. The addition of fission energy would cause the fuel to circulate in a manner analogous to, say, a natural-circulation boiler. The nature of a high temperature plasma is such that internal friction is of no consequence, and the energy of the circulating plasma could be converted magnetohydrodynamically into electricity. There would be some, but only a very little, waste heat in the ideal process.

The last two techniques are ways of transducing solar energy in unusual ways. A solar cell is, of course, a special type of thermoelectric device which responds preferentially to very high temperature differences, corresponding to upper temperatures whose radiation is mostly in the visible. It is subject both to the normal problems of thermoelectrics and to problems of collection efficiency.

A solar sail is simply a lightweight optical reflector which would permit a voyager in space to navigate without fuel - provided he is patient enough to learn to live with extremely small accelerations. Given light enough reflective materials (not known at present), this is a potentially practical technique for exploring the inner solar system.

Space Applications

Until now, I have talked primarily of the mundane uses of energy in our society. However the last two items I have mentioned illustrate an incentive for the study of direct conversion which stems from the emerging human interest in the exploration of space.

To move a heavy object - an exploratory scientific vehicle - from the surface of the earth to a different part of the solar system and return takes an extraordinarily large amount of energy. If we have to supply chemical fuel not only for the launch, but for later stage propulsion and auxiliary power for the mission, we must have a very large launcher and expend very large amounts of energy. If we can replace chemically fueled systems with nuclear or solar power systems, we can make a lighter launch vehicle or have a larger exploration ship. Since launch weight is responsible for the largest energy (and capital) expenditure of the mission, this substitution would be economic even for very expensive nuclear and solar systems.

But they must be reliable (for it would be imprudent to expend all this energy on a high-risk mission) and the entire power system, and not merely its energy source, must be light.

With this introduction, I shall now dichotomize the space applications of direct conversion. The first is the conversion of nuclear energy to heat to useful thrust in a nuclear rocket. The efficiency that counts in this context is the efficiency of conversion of propellant mass flow into thrust. A nuclear reactor, heating hydrogen, is about twice as efficient as the best conceivable chemical rocket system. What remains to be proved, of course, is the reliability of this system.

Although this is the major nuclear space activity at present, the greater stimulus to study more general conversion processes stems from our need for electrical power in space. This power can be used either to energize electrical propulsion systems, or to provide long-lived power supplies for extraterrestrial scientific, housekeeping, and communications operations. The electrical propulsion systems currently look more promising than their competitors, solar sails, which I have previously mentioned; and except for some very low power communications applications, extraction of electrical power from heat produced by nuclear reactors or solar reflectors appears more feasible than the use of solar cells, which I have also previously mentioned, for the latter seem to be simply too heavy for advanced requirements.

The problem of changing heat into electricity, in space, is dominated by three conditions which are often in conflict. The first is light weight. The second is high reliability. The third is that the only heat sink available is thermal radiation to space. Now, since the amount of heat which can be radiated from a surface is proportional to the fourth power of absolute temperature, the light weight requirement forces the sink temperature of conversion processes to values around 1000°K. Otherwise, the radiator alone would be too heavy. The source temperature must, of course, be considerably higher. Thus, space power systems must be high-temperature systems.

Now unfortunately, our experience with rotating machinery has taught us that high temperature does not permit high reliability. Therefore, we are faced with the choices of providing spare parts and repair capability, adding weight and forcing the optional sink temperature down; or developing techniques of transduction which are independent of rotating machinery. At the same time, having been forced for other reasons to consider quite high temperatures, we are not unusually dismayed by the temperature levels appropriate for efficient thermionic transduction or for the production of ionized gases of metal vapors required for MHD.

Conclusion

Economic efficiency in our use of energy resources for our normal terrestrial pursuits, and the stringent requirements of power supplies in space are the incentives for studying new forms of energy conversion. Since our energy resources are still high, the space applications are the more pressing now. In the long run, and without understating the enormous effect of discoveries in space on both our attitudes and our techniques, one of the best things about this pressing incentive is the certainty that it will ultimately result in the more efficient and orderly utilization of energy in the world. This, in turn, will definitely be required if we are to attain a world in which each member of our species can devote his life to creative work of a uniquely human character.

I 2. PROPERTIES OF GASES AT HIGH TEMPERATURES

A. B. Cambel
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Presented by R. C. Warder, Jr.

Extensive computer calculations of the thermodynamic properties of dissociated and ionized gases have been made in the Gas Dynamics Laboratory at Northwestern University. Assuming a mixture of perfect gases consisting of atoms, molecules (neutral and singly ionized), negative atomic ions, electrons and up to four positive atomic ions, investigators calculated the equilibrium composition, internal partition functions and thermodynamic properties of argon, nitrogen and oxygen plasma by the methods of statistical mechanics for six pressures (0.01, 0.1, 0.5, 1.0, 2.0 and 5.0 atmospheres) at 100°K increments for temperatures up to 35,000°K. The information obtained includes internal partition functions for all heavy species, chemical composition, mass density, entropy, internal energy, enthalpy, Gibb's and Helmholtz' free energies, specific heats at constant pressure and volume, the effective gamma and equilibrium sound speed.

The internal partition functions for nitrogen molecular species were calculated by an approximate technique proposed by Mayer and Mayer using the most recent spectroscopic data available. For oxygen molecular species, the method of Stupochenko et al. was employed to determine the intermolecular potential curves; the internal partition function was computed by direct summation over the energy states so determined. The electronic partition functions for atoms and atomic ions were computed using published data for observed electronic energy levels plus estimated energies for electronic states which are predicted but not observed spectroscopically. These electronic partition function series were terminated by application of the Debye cutoff criterion and a corresponding lowering of the ionization potential was included.

Mach-Zehnder Interferometer

An eight-inch Mach-Zehnder Interferometer, designed and constructed in the Gas Dynamics Laboratory, is the basic instrument to be used in this study. As is well known, the interferometer is used to measure the optical path length (index of refraction times the physical length) of a gas through which the light of the interferometer passes. The fringe pattern formed by the interference of two coherent beams of light is distorted due to a change in the optical path length of one of the beams of light. By measuring this shift of the fringes and knowing the path length, the change in the refractive index can be found at every point in the flow field.

The interferometer can thus be used to measure electron densities and, with increased accuracy, electron density profiles in arc-heated plasmas. This measuring technique is possible without recourse to the assumptions of thermal equilibrium or gas neutrality which are sometimes questionable assumptions. The atom and ion densities can be obtained by subtracting out the electronic contribution to the refractive index. In this case neutrality must be assumed to obtain the ion density and then the atom concentration can also be determined.

With the present accuracy of measurement of fringe shift and the small size plasma, a 25% error in temperature can be expected at 10,000°K. However, a modified optical comparator is being redesigned using a photomultiplier to increase the accuracy of the fringe shift measurement. The fringe pattern is a sinusoidal variation in light intensity and the accuracy is determined by how accurately the center of the fringe can be located. By observing the interferogram negative with a photomultiplier, basically a photographic densitometer, an accuracy of ± 0.03 fringe width has been achieved. By careful photographic control of the film density it will be possible to measure fringe shifts to this or perhaps even to a higher degree, reducing the error in temperature measurements and also reducing the lower limit of measurable electron densities.

The current study being conducted with the interferometer is of the laminar argon plasma stream produced by a Thermal Dynamics F-40 Plasma Torch. With the interferometer a plot of the temperature and concentration profiles is being obtained. This study will be used to check the accuracy obtainable with the interferometer plasmas studied and to determine how accurately fringe shifts can be measured with the modified optical comparator.

Future studies will be based on the fact that the interferometer gives a visual photograph of the flow pattern of the plasma jet and is well suited for determining the transition from laminar to turbulent flow. In certain operating regimes the transition has been observed at various lengths along the plasma jet axis on the interferograms. For many studies with the laminar jet, this transition regime could invalidate the results obtained using the assumption of a laminar jet. The various effects causing the transition, such as power input to the arc and flow rates of test gas, will be studied.

A final objective will be to formulate in a comprehensive manner the usefulness, accuracy, limitations, potentialities and application considerations of optical interferometry in plasma diagnostics with and without applied magnetic fields. In conclusion the usefulness of optical interferometry in plasma diagnostics will be compared with the various other diagnostic tools.

Magnetoaerodynamic Drag Studies

Preliminary studies of magnetoaerodynamic drag have been conducted in the hyperthermal plasma arc tunnel of the Gas Dynamics Laboratory and drag measurements made on a model consisting of a hemispherical nose and cylindrical afterbody. The model, 3.6 cm in diameter and 8.3 cm long, consists of an internally cooled copper shell containing a solenoidal electromagnet that will produce steady state magnetic fields as great as 1900 gauss at the stagnation point of the model. The model and internal electromagnet assembly are mounted on a sting which allows the model to be moved to various positions in the plasma flow field. The sting contains the cooling water tubes for the model and electromagnet as well as the power leads for the electromagnet which may be energized at will.

In the measurements made to date, an argon plasma was used and the free stream pressure was varied from about 4 to 7 mm Hg. Plasma flow velocities of up to 9,500 feet/sec were used although with larger power inputs to the arc jet and lower gas flow rates, higher values may be obtained. The maximum stagnation temperature prior to plasma expansion through the supersonic nozzle used to obtain the high speed flows is between 16,000 and 20,000°K depending on the power input to the arc jet. The average plasma free stream temperature is, of course, much lower.

To date, two different models have been studied, a copper model and another model of identical size and shape but coated with a ceramic insulating material. Drag measurements with the two models for similar test conditions showed that the conducting body (copper) experienced a greater drag upon application of the magnetic field than did the non-conducting body (ceramic coated).

These results are in qualitative agreement with the theoretical predictions of Reitz and Foldey and show the importance of including the effects of electrical conduction currents along the model surface in any realistic analytical treatment of magnetoaerodynamic drag.

The bow shock stand-off distance with and without an applied magnetic field was photographically recorded for a group of representative test conditions. The increase in the stand-off distance upon the application of the magnetic field was correlated with the magnetic interaction parameter and found to be in qualitative agreement with the theoretical curves from the analytical investigations of Lykoudis and Bush. The experimental data substantiated Lykoudis' work which shows the bow shock stand-off distance to be dependent not only upon the magnetic interaction parameter but also upon ϵ , the density ratio.

Although the final data of the preliminary magnetoaerodynamic drag experiments are presently being processed and, hence, no detailed

graphical or tabular compilation is as yet available, the following preliminary conclusions based on the studies may be made:

- 1) The plasma flow is chemically reacting. (Neither equilibrium nor frozen.)
- 2) The shock structure around the model varies somewhat as the free-stream plasma conditions are changed.
- 3) In the comparative experiments, i.e., when the drag "with internal electromagnet on" was compared to the drag "with internal electromagnet off" an increase in the drag of 4 to 10% was observed for various combinations of plasma flow conditions and applied magnetic field strength.
- 4) When the data obtained with the conducting copper model were compared with the insulated ceramic covered model, it was noted that the conducting body seemed to result in a slightly higher drag force.

It is evident that the continuous flow magnetoaerodynamic drag measurements yield significant data; hence, further systematic study is indicated.

I-3. THERMONUCLEAR RESEARCH IN WESTERN EUROPE

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The laboratories visited were Alfven's laboratory at the Royal Institute of Technology in Stockholm, Sweden; the University of Uppsala, Uppsala, Sweden; the Danish Atomic Energy Laboratory at Risø, Denmark; the Italian laboratory at Frascati, Italy; the Max-Planck Institute in Munich, Germany, and the new plasma physics laboratories at Garching outside Munich; the French laboratory at Fontenay-Aux-Roses; and the British laboratories at Culham and at Harwell.

The Royal Institute of Technology, Stockholm, Sweden

A study of the coaxial plasma gun is being carried on by Adam Dattner who, with Wilcox of the U. S. A., has built a coaxial structure not for a study of the projected plasma, but rather for a study of the motion along the coaxial structure. A central wire, insulated and mounted within the central coaxial electrode, carries a high current making a B_θ . The much weaker discharge current between the central coaxial electrode and an outer cylinder forms the plasma which moves along the tube. A wide range of gas pressure is used, 100 microns to 100 mm. The greatest speed calculated as E/B_θ is not experimentally exceeded either by the current sheet or by light signals. Sometimes at high pressures the current sheet speed falls far below E/B_θ . At very high currents there sometimes is a second mode with a low E sustained across the coaxial structure. Data are accumulating on the behavior of this gun. Spectroscopy is one of the diagnostic tools which is being used. We had extensive discussions on the stability of current sheets in guns of various lengths and on the interpretation of the present collection of data.

Another experiment of Dattner's has to do with the scattering (absorption, reflection, and transmission) of radio-frequency electromagnetic waves of 20-cm wave length in a wave guide crossed by a mercury vapor discharge of 2-cm diameter. It was in this apparatus that the variation of plasma density along the mercury discharge was observed by Dattner.

Because of current concern about the effect of the solar plasma wind on the earth's magnetic field, small scale experiments are being made by Lindberg and Block on plasma projected against the dipole field of a terrella.

Some time ago Alfven pointed out interesting possibilities for a high-pressure-gas-insulated pinch discharge. Smars has studied such

discharges and demonstrated spectroscopic purity of the discharge. Beautiful Kerr cell shutter photographs show sharp images developing $m = 1$ and $m = 2$ growing perturbations, which finally develop into a scramble of the image. The pinch is fast and the instability is bad in 1 microsecond. The pinch is started in the center by mechanically drawing an arc down the center first.

The apparatus used by Lehnert for confining a rotating plasma was undergoing some tests, but Lehnert was not there. A high power 2.5-megawatt coil for pulsing had been installed. Without a clamp (free wheeling) the plasma rotates for 250 microseconds.

A search for electric fields parallel to a magnetic field was being made by Bloch using a 2-to-1 mirror with pulsed end coils to raise the mirror ratio to 30 to 1. The plasma was formed in a PIG discharge. The question of the existence of electric fields parallel to magnetic fields comes up in the interaction of the solar plasma wind with the earth's field.

In a new research laboratory in the nearby Electrical Engineering Department, Professor Agdur is developing his research using the interaction of radiation and plasmas. Several microwave experiments have been set up.

The University of Uppsala, Uppsala, Sweden

At the University of Uppsala the toroidal discharge did not seem to be used much, but a variety of technical developments using very high voltage and power were in progress. R. Nilsson and Lars Hogberg explained some of them.

A one-million-volt switch and capacitor combination was being developed; one version was in use and a new model 200 cm long and 100 cm in diameter was being assembled. The purpose was to accelerate plasmas inward by a fast pinch. The charged capacity plates are in a high-pressure tank at two atmospheres with spark gaps to connect them in series. The new tank is designed for twenty atmospheres.

At Uppsala there was a theta pinch used for a source of light by two or three spectroscopists for spectroscopic research, not for plasma research.

A laser-heated metal point was found to emit 10^5 to 10^6 amperes/cm².

Danish Atomic Energy Laboratory, Risø

Observations on the torque given to the plasma in a theta pinch were under way. A torsion pendulum hanging on the vertical axis of the pinch

rotates in the expected direction but with a torque of only about 1% of what was expected, according to T. H. Jensen's trial model of the process of the discharge lifting off of the wall. This model assumes half gyrocircumference trajectories with impact on the wall losing all of the particle momentum.

In another experiment two short and fat Marshall guns project plasma to make collisions. High electrostatic fields are being sought as a result of counter streaming plasmas.

There is concern about the hesitancy or lack of interest that local industry seems to have for picking up new technical possibilities resulting from research. This apparent lack of full appreciation of research by business and industry was pointed out not only when I was in Sweden, but especially in Denmark and also to some degree in Germany and in England. Good scientists must find good jobs in industry to bring about industrial appreciation, but attractive jobs cannot be created unless there is initially some appreciation within the industry.

Frascati Laboratory, Italy

Dr. Bunnelli was concerned with certain planning for the future laboratory program. There may be expansion in directions other than plasma physics partly because Italian industry is not swiftly putting new technical developments to work.

J. E. Allen and Bunnelli were involved in the theta pinch of 18 cm diameter having a length of 100 cm. It was intended for magnetohydrodynamic shock studies, but at present breakdown studies are in progress. The current causing B_z passes through a six-sector turn with six voltage gaps. This tends to provide a smooth circumferential electric field instead of the transverse electric field which normally exists at time zero in a one-turn theta pinch coil due to the combination of $\partial A / \partial t$ and there were, in addition, electrostatic screens used to smooth out B_θ for breakdown studies.

Optical diagnostics with lasers and framing cameras were available and showed excellent details of density gradients and instabilities.

Dr. Linhart and Dr. Masonier pursue the idea that if we can only have confinement for the order of 200 transits of the confining volume, then we should strive to achieve densities of 10^{20} particles/cc and very short times of 10^{-6} seconds.

A pinching aluminum or copper foil 7 cm long and initially 7 cm in diameter can be collapsed to a rod 2 mm in diameter with 3×10^6 amperes at 40 kv. The experiments seek to find how to assemble the foil into the finest possible line at the center.

Another experiment uses a curtain of LiAlH_4 pinching from 20 cm diameter. The powder is sifted electrostatically into the gap through collimators to form the cylindrical curtain. An aluminum electrode spark partially vaporizes the particles and the ensuing discharge drives the curtain inward. One wants a pinch collapse to such a fine line that if deuterium ice were used, reactions would occur. Linhart thinks it might barely be possible ultimately to get the energy to make the reaction go.

At a remote site Linhart compresses magnetic fields by high explosives. He reaches 3×10^6 gauss and he thinks he needs 10^7 gauss to be interesting. A 20-meter diameter cavity in the ground would be used to contain a 100-ton high explosive experiment.

Max-Planck Institute, Germany

Professor Biermann explained the development of plasma physics research in the Munich area. Some continues at the new Max-Planck Institute in Munich; for example, the M. S. field configuration for avoiding toroidal drifts is under theoretical and experimental study. Schmidt is there for the theoretical work and Wolf was involved in the experiments. The technology of making the properly shaped toroidal walls of glass is difficult, but the shop help is very impressive. Some of this work has been described in the literature. It appeared that the burden of finding a desirable field shape was largely left to experiments on equilibrium instead of pursuing the problem vigorously by calculation. Some fields tried compressing the plasma into a flat shape but prevented the toroidal drift. The question of whether the equilibria so created are expected to be stable has not yet been given an answer.

Institut für Plasma Physik, Germany

This institute was formed by a corporation set up by Dr. Heisenberg and Dr. Biermann among others. Its funds come from three sources, the federal government and the Länder being two of them. This institute is now one of the most impressive in Europe. There are four large new buildings, each containing a professor's project - Professor Funfer, Dr. Wienecke, Dr. Von Gierke, Professor Schluter. The latter has a theoretical building. A much larger engineering building is being erected nearby and Lüst has just been appointed to start a space science institute. These developments are very impressive outwardly and there is much excellent work, clever and convincing, being carried out in many cases by students working for a higher degree.

The details of work are contained in the "Jahres Bericht 1962." Early steps in the breakdown of a theta pinch have been convincingly diagnosed showing the proper drifts and X-ray production when the vector potential and the scalar potential are manipulated.

Fontenay-Aux-Roses, France

The mirror conference and the laboratory was visited here. My interest was purposely focused on the conical inductive plasma guns they are using. They (and the British [T. K. Allen] at Culham) seem to have had more satisfactory results with these guns than we in the United States have had in cases with which I am familiar.

Culham-Harwell, England

Zeta has a quiescent period of a few hundred microseconds which is being studied. T. K. Allen's conical inductive plasma gun work was especially interesting to me. He thinks he has only 0.25% impurity in his plasmas. The vacuum system uses mercury vapor pumps and no organic gaskets.

I-4. SOLAR ENERGY CONVERSION

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Solar energy is a natural resource of tremendous magnitude but one which has characteristics which make its economic application difficult. Among these characteristics are low intensity (approximately 1 kw per square yard or less), predictable variability, and intermittency due to weather. The spectral distribution of solar radiation is approximately that from a 6000°K source, with atmospheric attenuation changing the distribution of terrestrial solar radiation.

Processes for energy conversion from solar to other energy forms are roughly classified as (a) thermal, or (b) "photon" processes.

(a) Thermal Processes. In principle, any heat engine can be operated from solar energy. A problem of temperature limitation is encountered, as the low energy density dictates that high temperatures can be obtained only at the expense of added requirements on solar energy collector systems. Thus, there is a direct relationship between temperature and cost. Experimental approaches for conversion of solar to electrical or mechanical energy with heat engines for terrestrial use are concerned with input temperatures to engines ranging from 80°C to 1500°C.

(b) Photon Processes. The most common of the "photon" processes is photovoltaic conversion, which is not limited by ordinary Carnot considerations but rather by the relationship of spectral distribution of incident energy and the spectral response of the converter.

Solar-Thermoelectric Energy Converters

Systems for solar-thermoelectric conversion would probably include a focusing collector, the thermoelectric generator and the load. The variability of solar radiation dictates that the temperature of the hot junctions will also be variable, and that design must be optimized for best integrated performance for the radiation levels which are anticipated over the period of use.

Calculations of the voltage-current characteristics for a hypothetical generator using silicon-germanium alloy couples have been made at various hot junction temperatures. It is shown that good integrated performance is obtained with loads represented by load lines which are straight and pass through the origin.

Radiation Properties of Surfaces

Inherent in thermal processes are the phenomena of absorption of shortwave radiation (from the 6000°K source) and emission of relatively longwave radiation (from the collector surface at its operating temperature). Methods have been devised for preparing surfaces which have high absorptivity with shortwave radiation and low emissivity for longwave radiation; these surfaces, if they can be made stable and at sufficiently low expense, can result in improved performance of a solar-thermal conversion process.

An example of an experimental selective surface is a particulate coating of crystalline lead sulfide on aluminum which can have absorptivities in the range of 0.9 and emissivities of 0.2 to 0.4.

Photovoltaic Process for Solar Energy Conversion

The very high cost of energy conversion capacity of ordinary silicon cells has led to study of methods of increasing the output of these cells by focusing devices. An experimental study of close-gridded silicon converters indicates that electrical outputs per unit area of cell can be increased by two orders of magnitude or more.

Measurements of the voltage-current characteristics at various radiation levels in the range necessary to produce high power densities show that these converters operate nearly at the maximum power point for constant voltage loads. The same problem is encountered in design of these systems as in solar-thermoelectric systems; the design must be optimized for best integrated performance over its anticipated period of use, taking into account solar energy variability.

SESSION II

Monday, November 4, 1963

TRANSPORT PROPERTIES IN IONIZED GASES

CHAIRMAN: G. N. HATSOPOULOS
Massachusetts Institute of Technology

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II-1. DESIGN OF AN EXPERIMENT FOR PRODUCING SUPERSONIC HIGH ELECTRON DENSITY PLASMA

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This report outlines the experimental design aspects of a research program on electron recombination in "cool" supersonic (potassium seeded) plasmas which is now under development at the University of Wisconsin, Mechanical Engineering Department. The problems of producing well-defined conditions and making measurements which require a minimum of independent information for their interpretation are rather severe in plasma work. Considerable effort has been expended in these respects and, as several somewhat novel techniques will be tried, a description of our approach may be of interest.

The Honeycomb-Screen

In the design of a high enthalpy shock tube, some way of producing a short duration but steady supersonic flow of conventional gases in a moderately large diameter duct (6 inch) was needed. The long flow stabilization time in a converging-diverging nozzle of the necessary throat diameter prohibited use of this conventional method. Instead, it was proposed to use a fine mesh screen across which a supercritical pressure ratio is maintained giving a supersonic downstream flow. In an approximate sense, each of the small screen openings can be regarded as a somewhat inefficient nozzle of a very short length in which the stabilization time would also be very short. This scheme was incorporated into the shock tube design and, until a declassified NACA report by L. I. Gould¹ was found, it was thought to be a novel development. The somewhat mixed results given in this report probably account for the obscurity of this method. While there are still some incomplete areas in our experimental study, we have established that it works and have also resolved the undesirable features reported in the NACA report. A key feature of our design is the expanded stainless steel honeycomb with the screen resistance-welded to it as shown in Fig. 1. The honeycomb not only keeps the screen completely flat but permits a much finer mesh, (i.e. weaker screen) to be used so that the scale of downstream turbulence is much reduced relative to that produced in Gould's apparatus.

A schematic representation of the flow through the screen in the T-S plane is shown in Fig. 2. The initial flow state is a_1 where it enters the honeycomb and follows a slightly different Fanno line. It enters the screen at a_2 . The data reported by Cornell² show that the choked flow characteristics of woven wire screen differ only negligibly for those through a

*The design work was in connection with a project sponsored by the National Science Foundation.

converging nozzle of the same minimum-to-total-area ratio. Therefore, the transition to a_3 at $M = 1$ in the midplane of the screen is essentially isentropic. From a_3 the flow goes irreversibly to state b_1 . State b_2 represents a much further downstream state corresponding to that shown in Fig. 3. It is of interest to note that a second, subsonic, flow regime (states c_1 and c_2) is also obtainable at higher pressures, as reported by Cornell.² Inasmuch as the flow is adiabatic and the upstream and downstream areas are constant and equal, states a_1 , b_1 , b_2 , c_1 and c_2 must all lie on the same Fanno line which must also contain all previous and subsequent flow states in a duct of that area. The line b_1 to d_1 represents frictional duct flows with a divergence angle such that T and therefore M are constant.

Figure 1. Upstream and Downstream Views of the Honeycomb-Screen Assembly

Figure 2
Use of Screens for
Producing Super-
sonic Flows

Figure 3. Supersonic Duct Flow
Produced by Honeycomb-
Screen ($M = 1.68$)

Figure 3 shows a Schlieren photograph of a honeycomb-screen produced supersonic flow in our shock tube. The exposure time is less than a microsecond so that any significant turbulence or unsteady disturbances would be "stopped"; the photograph is notable for the absence of such extraneous disturbances.

One-mil Mylar strips were secured to the floor and roof of the tube (roughly 4 by 5 inches in cross section) to generate Mach lines for measuring the flow Mach number.

In the context of plasma applications certain crucial comparisons can be made between the honeycomb-screen and converging-diverging (C-D) nozzle. In an established steady flow, the transit time of a mass element through a C-D nozzle for a given exit M is proportional to the duct diameter inasmuch as the length is proportional to the throat diameter. In contrast to the C-D nozzle, with a honeycomb-screen the transit time for the same final M is many orders of magnitude less and is independent of duct size. The point is clear when a screen thickness of say 0.020 inch is compared to say the 50-inch length of a moderate size C-D nozzle.

Suppose that the honeycomb-screen assembly is made of a refractory metal such as tungsten or tantalum; then upstream total gas temperatures approaching $3000^\circ\text{K} \simeq 0.27 \text{ eV}$ are feasible, allowing for some radiation cooling of the honeycomb screen. Therefore, if we use the sonic velocity as an average velocity through the screen, for helium at 3000°K going through a screen $0.026 \text{ in} \simeq 0.066 \text{ cm}$ thick, we obtain a transit time on the order of $(0.066 \text{ cm}) / (3.3 \times 10^5 \text{ cm/sec}) = 0.2 \times 10^{-6} \text{ sec}$. Now if we assume a maximum upstream electron density, $n_e \simeq 10^{14} \text{ cm}^{-3}$, and neglect the retarding effects of the very substantial decrease in pressure, from Fig. 4 we conclude that during the $0.2 \mu\text{sec}$, the fractional changes in n_e are bounded by:

$$\Delta n_e / n_e \leq 4 \times 10^{-3} \quad \text{at } T_e = T_a = 2935^\circ\text{K (maximum } T_e)$$

$$\Delta n_e / n_e \leq 1.8 \times 10^{-1} \quad \text{at } T_e = T_b = 1286^\circ\text{K (minimum } T_e).$$

There is therefore a very sizable margin of safety in concluding that there will be a negligible change in the degree of ionization across the screen and even more negligible changes at lower electron densities since the rate is

proportional to n_e^2 . Continuity considerations, however, do cause some decrease in the absolute n_e (e.g., by a factor of about 1/5 for a change

Figure 4. Electron Recombination Rate Coefficient Dependence on Electron Temperature

$M_1 = 0.25$ to $M = 2$). Debye lengths are several orders of magnitude shorter than the screen wire diameter or any boundary layer thickness around them, so sheath effects on the flow are negligible.

Under full power conditions electron densities of about $6 \times 10^{13} \text{ cm}^{-3}$ are expected in the $M=2$ stream. This is greater by a factor of about 5×10^4 than the equilibrium value.

The Plasma Tube

A fundamental decision had to be made on how to control or contain the supersonic plasma flow. The great majority of studies of this kind have used a free jet in which the plasma is isolated from Pyrex or quartz containing walls by either cooled

plasma gas or some buffer gas. This arrangement, in fact, has been suggested to the writer several times, and it was seriously considered because of its obvious advantages of experimental simplicity and ease of observation. However, taking into account the nature of the measurements which we wanted to make, we found this method suffers decisive disadvantages. Because of rapid turbulent mixing and heat transfer, the length of the jet in a well-defined and uniform flow state was entirely too short for reliable measurements of the expected range of recombination rates. Secondly, the cool and poorly defined jet boundaries would make allowances for ambipolar diffusion tedious and uncertain.

These considerations led to the decision that the supersonic plasma flow should be contained by solid walls which, insofar as is possible, would be in thermodynamic equilibrium with the plasma. Such a design offers a number of advantages in principle:

(1) The presence of solid, nearly adiabatic walls establishes well-defined physical and thermodynamic boundaries to the flow. The large body of boundary layer literature can be brought to bear and, thermodynamically, the role of the wall as a large "third body" guarantees that the gas in contact

with it will be in thermodynamic equilibrium at a temperature approaching the recovery temperature. This is in direct contrast to a poorly defined mixing region where dilution with cool sheath gas will tend to quench the de-ionization in some non-equilibrium state.

(2) The duct geometry can be shaped to control the flow, i.e., by giving it a proper divergence, the stream static temperature can be held approximately constant (of considerable convenience in any kinetics study), and the core velocity maintained, thereby slowing the rate of boundary layer growth down the tube.

(3) The absence of a sheath potential at the wall itself (because of the equilibrium conditions there) greatly simplifies the problem of accounting for ambipolar diffusion effects. In fact, the higher boundary layer temperatures will tend to produce an inward diffusion of electrons and positive ions. Since the ambipolar diffusion coefficient is related to the seed species diffusion coefficient, D_s , by $D_s(T_e/T_n)$, the extent of ambipolar diffusion penetration relative to the boundary layer thickness can be inferred from the reciprocal Schmidt number, D_s/ν_c , in which ν_c is the kinematic viscosity of the carrier gas.

The Schmidt number is essentially independent of T and P for monatomic gases. For potassium in an argon carrier $Sc^{-1} = 1.33$ and in a helium carrier, $Sc^{-1} = 0.57$. This shows that for reasonable average boundary layer values of T_e/T_n , say 1.5, the ambipolar diffusion thickness would be roughly (for argon) twice and (for helium) 85% the boundary layer thickness. These inferences need, of course, to be verified, but they indicate that ambipolar diffusion will be troublesome only when boundary layer growth would be causing serious difficulties anyway.

From the considerations outlined above, a square 4 x 4 cm cross section, slightly diverging plasma tube was decided upon. The length (in the supersonic section) of 100 cm is a compromise between conservative estimations of minimum detectable deviations from equilibrium and the complications of excessive boundary layer growth.

After reviewing the properties of available refractory materials, we chose pyrolytic graphite for the plasma tube construction. It has an exceedingly low vapor pressure (5×10^{-4} mm Hg) relative to plasma pressures, and its ionization potential, 10 volts, is considerably higher than the 4.2 volts of potassium. With care, it is also machinable and very convenient use can be made of its highly anisotropic thermal conduction properties.

The tube will be wrapped in many layers of carbon felt insulation. Low conductivity carbon supports will hold the whole assembly inside a stainless steel 12-inch pipe, which will be clad with additional conventional

insulation. The total heat loss is estimated to be about 15%, most of which is lost through the windows. Only reasonably tight mechanical fits on the pyrolytic graphite tube will be attempted, and the annular space outside it flooded with unseeded carrier gas at about the same pressure as the plasma. The atmospheric pressure load is then taken across the pipe wall.

The windows were more troublesome since, in order to make optical measurements, they must be transparent. Quartz is the only possible material. By radiation cooling them with nearby local water cooling coils, the windows will be kept below their phase transition temperature of about 1300°K .

Figure 5 gives a schematic representation of the final design.

Figure 5. Design of the Supersonic Plasma Tunnel

Microwave Absorption and Phase Shift Measurements

The writer, who is not sufficiently familiar with microwave technique, plans to collaborate in this area with Professor J. G. VanBladel of the Electrical Engineering Department, whose principal field of interest is electromagnetic wave interactions with ionized gases. We will do preliminary experiments with on-hand microwave equipment furnished by his department. Later, when full power operations are planned, millimeter-range microwave equipment will be needed for the higher electron densities.

We plan to use a measurement technique which should dispose of the largest uncertainty usually connected with this type of measurement -

the uncertain contribution of the boundary layer and sheath to the total measured absorption and phase shift. The idea is to locate a thin metallic (tantalum) plate with a sharp leading edge in the plasma stream and parallel to the direction of flow. Several of these are shown in Fig. 5 with manual control rods extending out of the top of the apparatus. Two microwave beams generated by the same source will be beamed through opposite windows in the duct walls and reflected from opposite sides of the tantalum reflector plate, as shown in Fig. 6. The difference in attenuation and phase shift of the two reflected beams is measured. For reasons of symmetry, the effects of the boundary layers will cancel, and if the reflector is in the center of the duct, all other differences will also cancel. However, if the reflector is displaced from the center, a difference reading will be obtained which is directly attributable to the core flow, independently of the boundary layer. The shape and symmetry of the curves of attenuation and phase shift differences versus reflector position provide a direct indication of boundary layer thickness, flow asymmetry (if any), and the null point slope of the curve gives the desired specific values. The kinetic quantities which will be computed from these measurements are the electron density and collision frequency. The additional assumptions which are needed to compute the electron temperature are questionable in our case.

Figure 6. Microwave Absorption and Phase Shift with Boundary Layer Null

Temperature Measurements for Neutral Species

It is evident that the neutral gas temperature is one of the most important kinetic variables and as the flow will be largely supersonic, optical methods are strongly indicated; in particular, a line of reversal method seems appropriate in view of the potassium seeding which will be present.

The line reversal method is subject to a well recognized limitation, namely, that self-absorption (especially with the resonance lines) may be

so great that the gas is essentially opaque, and it is impossible to "see" through the boundary layer at the radiation wavelength. Reversal temperatures on these lines are then some average boundary layer temperature. There are, of course, ways of coping with the problem (local seeding, interferometric techniques), but what is thought to be a novel method (which actually occurred to the writer while in graduate school years ago) appears most suitable in this case.

If a non-uniform magnetic field is produced in the plasma duct by external coils with the maximum intensity in the midplane of the duct, then the Zeeman effect will cause a wavelength splitting of the radiation from the zone of the magnetic field. In this way, it will be possible to discriminate between boundary layer and core radiation. A potassium vapor absorption cell located external to the duct will block the undisplaced line center radiation. Actually, only a weak magnetic field (on the order of 2000 gauss) is needed as it is only necessary to displace the line somewhat beyond the normal (collision broadened) line width of the undisplaced line. If the magnetic field is made alternating, then the reversal point can be conveniently ascertained with a phototube and oscilloscope. Note that no interferometry is required as is usually the case with Zeeman effect measurements. A simple interference filter would be sufficient to eliminate radiation which is extraneous to the measurement. In our proposed setup, however, inasmuch as a spectrophotometer will be needed for other purposes, it will be used. The induced E field is about 8 V/cm and allowances may have to be made for a small disturbing effect of the field on the flow. The ratio of the induced body force to the dynamic force is estimated to be less than 0.07.

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II-2. PART I. VISCOELECTRIC MAGNETOHYDRODYNAMIC ANALOGY

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An analogy can be established between the flow of a conducting fluid in a magnetic field and a class of fluids exhibiting viscosity changes in the presence of applied electric and magnetic fields. Two of the major difficulties experienced in laboratory studies of magnetohydrodynamic flows are the production of kilogauss magnetic fields and simulation of the electromagnetic-fluid dynamic coupling. Both of these problems can be resolved, at least partially, by using the viscoelectric magnetohydrodynamic analog presented here.

The flow of an incompressible electrical neutral conducting fluid with constant scalar transport properties and negligible displacement and Hall currents is described by the following set of equations:

Conservation of Mass

$$\nabla \cdot \vec{V} = 0. \quad (1)$$

Conservation of Momentum

$$\frac{\partial \vec{V}}{\partial t} + \nabla(1/2 \vec{V}^2) - \vec{V} \times (\nabla \times \vec{V}) = -\left(\frac{p_0}{\rho V_0^2}\right) \nabla p \\ + \left(\frac{\mu}{V_0 \rho \ell_0}\right) \nabla^2 \vec{V} + \left[\left(\frac{B_0^2}{\rho V_0^2 \mu_e}\right) (\nabla \times \vec{B}) \times \vec{B}\right]. \quad (2)$$

Magnetohydrodynamic Field Equation

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B}) + \left(\frac{1}{V_0 \ell_0 \sigma \mu_e}\right) \nabla^2 \vec{B}. \quad (3)$$

The MKS system of units have been used and the symbols have their conventional connotation except that they have been non-dimensionalized with respect to arbitrary reference values, indicated by the subscript 0. The non-dimensional groupings may be readily identified as

$$Eu \quad (\text{Euler Number}) = \rho_0 / \rho V_0^2$$

$$Re \quad (\text{Reynolds Number}) = V_0 \rho \ell_0 / \mu$$

$$\text{Rem (Magnetic Reynolds Number)} = V_0 \ell_0 \sigma \mu_e$$

$$\text{Ha (Hartmann Number)} = (\sigma B_0^2 \ell_0^2 / \mu)^{1/2}.$$

It has long been known that the application of an electric field transverse to the flow of fluids with strong electric dipole moments will significantly increase their effective viscosity. A number of common fluids such as chloroform, ether, nitrobenzene, and acetone exhibit changes of up to 200 per cent at voltage gradients of the order of 2000 volts per centimeter. Effective viscosity changes of an order of magnitude or more may be obtained using viscomagnetic fluids (essentially iron in suspension in an oil base) upon application of moderate magnetic fields. Under normal conditions the fluid behaves conventionally but it takes on the consistency of potter's clay in a magnetic field.

Another class of fluids is responsive to applied electric fields, exhibiting strong increases in effective viscosity in the presence of either steady or alternating fields. This phenomenon is known as the Winslow effect. The first mention of such a viscoelectric fluid was made by Winslow in 1949. Measurements of the effective shear resistance of such a fluid were reported and it was suggested that the particles suspended in the fluid formed an oil-occluding fibrous mass in the presence of an electric field. These fibers existed on the surface of silica gel powders, about one micron particle diameter, and they extended in the general direction of the field, thus mechanically linking the individual particles and increasing their shear resistance. For concentrations of about fifty per cent by volume of silica gel in a kerosene fraction Winslow found that the effective shear resistance increased as the square of the applied voltage, the constant being associated with the particle surfaces and the type and amount of dispersing agent used in the mixture. Resistivities of the order of 10^{10} ohm-centimeter were measured and breakdown voltages as great as 40,000 volts per centimeter were obtained. The resistivity was strongly temperature dependent, decreasing more than 50 per cent with a temperature rise of 50°C .

Based upon this data it can be assumed that the Winslow stress is an algebraically additive term in the momentum equation and the equations governing a viscoelectric flow are

Conservation of Mass

$$\nabla \cdot \vec{V} = 0. \tag{4}$$

Conservation of Momentum

$$\frac{\partial \vec{V}}{\partial t} + \nabla(1/2 \vec{V}^2) - \vec{V} \times (\nabla \times \vec{V}) = - \left(\frac{P_0}{\rho V_0^2} \right) \nabla p + \left(\frac{\mu}{V_0 \rho \ell_0} \right) \nabla^2 \vec{V} + \left[\left(\frac{\alpha E_0^2}{\rho V_0^2} \right) f(\vec{E}) \right]. \quad (5)$$

Again, the variables have been non-dimensionalized. In these equations α is the constant of proportionality between the Winslow stress and the square of the applied electric field. This non-dimensional grouping will be defined as

$$Ve \text{ (Viscoelectric Parameter)} = (\alpha E_0^2 / \rho V_0^2).$$

The function, $f(\vec{E})$, can be set in an arbitrary fashion, limited only by such physical parameters as the dielectric strength of the fluid.

A comparison of Equations (1), (2), (4) and (5) shows that for geometrically similar flow systems an analogy exists between a magnetohydrodynamic flow and a viscoelectric flow if the following conditions are satisfied (the two flows are identified by the subscripts MHD and VEA respectively):

$$(Eu)_{MHD} = (Eu)_{VEA} \quad (6)$$

$$(Re)_{MHD} = (Re)_{VEA} \quad (7)$$

$$\left[\frac{Ha^2}{Re \, Rem} (\nabla \times \vec{B}) \times \vec{B} \right]_{MHD} = \left[V_e f(\vec{E}) \right]_{VEA}. \quad (8)$$

The first two conditions may be readily met by appropriate scaling. The last equation may be adjusted to fit by applying an electric field distribution corresponding to the magnetic field distribution in the magnetohydrodynamic case.

The analogy defined by Equations (6), (7) and (8) can therefore be used to verify experimentally the velocity and pressure distributions in magnetohydrodynamic flows. Since the electromagnetic-fluid dynamic coupling as embodied in the magnetic Reynolds number does not show up explicitly in the analog it is applicable for flows with arbitrary electrical conductivity.

II-2. PART II. INDUCTION COUPLED PLASMA TORCH*

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Presented by Thomas P. Anderson

Many of the problems associated with the more common arc discharge plasma torches can be avoided through the use of inductive coupling to heat the plasma. Since this configuration has no electrodes in contact with the gas there is very little contamination and a clean, stable plasma flame can be obtained. Both microwave and radio-frequency generators have been constructed successfully.

For the experiments discussed here a variable frequency, 5 to 22-megacycle, 5-kilowatt vacuum tube oscillator was used. Gas is introduced to the generator, see Fig. 1, at one end of a one-inch Pyrex tube with a swirling motion so as to provide cooling for the walls. This vortex flow then passes through the induction coil where it is ionized. Initially the flow was directed downward so that the convective recirculation would help stabilize the plasma plume but subsequent tests show that this is not necessary. Flow tracer studies have been made of the flow characteristics in the tube and show that there is considerable tangential flow in the region of the induction coil. This swirl is a maximum at the walls as was planned to provide vortex stabilization.

Figure 1. Radio-frequency Induction Coupled Plasma Torch

The magnetic fields surrounding the coil are sufficient to sustain the plasma but some other source of electrons must be used to initiate operation. In this case a carbon rod is inserted and the high resistivity material is inductively heated. The thermionically emitted free electrons are then accelerated by the oscillating axial magnetic field of the coil and an avalanche-collisional ionization initiates the plasma generation. Typical plasma operation is shown in Fig. 2.

*Supported in part by the Pure Oil Company.

Figure 2. Induction Coupled Plasma Torch in Operation

Since the plasma forms an integral part of the oscillator circuit, the coupling characteristics are strongly dependent upon the electrical makeup of the oscillator. The tuned grid-tuned plate power supply being used operates in either of two modes, see Figs. 3 and 4. For low frequency operation (5 to 15 megacycles) the tank circuit consists of a large parallel plate capacitor, C_1 , the tank coil, L_1 , and two adjustable length short circuited transmission lines, X_2 and X_3 , all in parallel. For high frequency operation (15 to 22 megacycles) the tank circuit elements are the same except that the parallel plate capacitor is short circuited so as to become a fixed length short circuited transmission line. The respective grid and mutual branch circuits differ for each mode of operation.

The frequency of a general vacuum tube oscillator may be calculated by considering a nonlinear feedback amplifier which satisfies the Barkhausen criterion of unity loop gain and has a zero loop phase shift. Using the principle of equivalent linearization a fourth order algebraic expression for the frequency of oscillation may be obtained. Since this has transcen-

dental functions of the first order an iterative computer solution was employed to determine the frequencies for variable L_2 , l , and coil configurations. The results (Fig. 5) show that for a given coil the frequency is dependent upon the tank circuit. The variable inductor, L_2 , is then used to match the reactances for an optimum oscillating condition. The calculated and measured values of the unloaded circuit frequencies agree within a few per cent.

where. L_1 - Tank coil
 L_2 - Variable inductor
 C_1 - Tank capacitor
 C_{gp} - Tube grid to plate capacitance
 C_{gk} - " " cathode "
 X_2 & X_3 - Variable length (l) short-circuited transmission lines

Figure 3. Low Frequency (5-15 Megacycle) Circuit

where X - Fixed-length short-circuited transmission line

Figure 4. High Frequency (15-22 Megacycle) Circuit

Figure 5. Unloaded Oscillator Frequency as a Function of L_2 and l for High Frequency Mode, Four Turn Coil (L_1). Results of Computer Solution.

II-3. THERMOPHYSICAL PROPERTIES OF PLASMA

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Presented by C. F. Knopp

A long range, systematic study is being conducted to determine the thermophysical properties of argon, nitrogen and air plasmas. The properties are being measured in plasmas with and without applied magnetic fields. The work is being pursued along two main lines, (1) the measurement of the electrical properties using microwave techniques, and (2) the measurement of the plasma temperature distribution and physico-chemical composition, as well as the determination of the transport properties, using spectroscopic techniques.

Arc-heated Plasma Tunnel

An investigation of the electrical properties of argon and nitrogen plasma flows has been conducted in an arc-heated plasma tunnel using microwave diagnostics. In particular, phase shift and attenuation measurements at 78 and 85.3 kmc have been made to determine the electron density and electron collision frequency of the plasma flows. The electron densities, as determined from the phase shift measurements at the two frequencies, agree quite well and when compared with theoretical predictions indicate that the plasma flows are not in equilibrium. An experimental program has also been undertaken in which a DC magnetic field is applied to the argon plasma flow and phenomena such as Faraday rotation and the ellipticity of the transmitted wave are being investigated.

Wall-stabilized Arc

A wall-stabilized arc seems to offer the most rewarding results in the investigation of the transport properties of an argon plasma. This device has the advantage of producing a laminar flow, steady state, stable plasma of cylindrical geometry. The present facility has been operated successfully over long periods of time. At present, the temperature profile in arc columns of various radii is being investigated by spectroscopic techniques. Coincidentally, an estimate of radiation effects is being made. These measurements, combined with experimentally determined values of electric field, velocity field, and pressure gradient permit an accurate determination of the viscosity and thermal conductivity of the plasma as a function of temperature.

Electromagnetic Shock Tube

The thermodynamic state generated in argon in the laboratory's conical type electromagnetic shock tube has been determined from time-integrated and time-resolved spectroscopic observations. The time-resolved intensity variations of atom and ion lines, and the associated continuum radiation have been measured by placing photomultipliers behind appropriate slits in the focal plane of a Hilger glass-prism spectrograph. The shape of the luminous front was investigated with photomultipliers placed in a plane perpendicular to the shock expansion tube. The luminous front velocity was measured with photomultipliers placed along the axis of the expansion tube.

The electron temperature, atom, ion, and electron densities were calculated by the two-line method. The electron densities were also calculated from the intensity of the continuum and Stark broadening of the hydrogen $H\beta$ impurity line.

The tests were conducted at ambient pressures of 50, 300 and 1 mm Hg and capacitor voltages of 18 to 23 kv. Measurements were made at various positions downstream from the ring electrode. Luminous front velocities ranged from 12,000 to 27,000 fps, electron temperatures from 13,000 to 17,000°K, and electron densities from 10^{16} to 10^{17} cm⁻³. The data indicates thermodynamic equilibrium in the region near the luminous front. There are indications of a high impurity level, particularly to the rear of the luminous zone. In all tests the temperatures were significantly higher than those predicted by the shock equations assuming a cold gas ahead of the luminous front.

II-5. TRANSPORT PROPERTIES AND ACOUSTIC WAVE PROPAGATION IN PLASMAS

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Presented by M. B. Lewis

Research is in progress on the general problem of solving the Boltzmann equation for the transition region between the collisionless description of a gas and the near-equilibrium, or hydrodynamic regime. At present, the analysis is being done for non-ionized gases, but it is expected that in the future the method will be extended to plasmas. This method of expansion of the distribution function in a series of orthogonal polynomials has shown considerable success in the problem of sound propagation in a rarefied gas; other problems are being considered.

SESSION III

Monday, November 4, 1963

FUEL CELLS, THERMOELECTRIC DEVICES AND SOLAR BATTERIES

CHAIRMAN: R. C. VOGEL
Argonne National Laboratory

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III-1. LIQUID METAL CELLS

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Potassium-mercury liquid metal cells have been studied both theoretically and experimentally at the Allison Division, General Motors Corporation. These cells appear to be desirable because they have high heat transfer capability and high current density and are capable of thermal and electrical regeneration.

The open circuit voltage for such a cell is given in Equation 1.

$$E_0 = - \frac{RT}{nF} \ln \frac{a_1}{a_2} \quad (1)$$

where a_1 and a_2 are the activities of K at the anode and cathode (Hg rich electrode) respectively.

A schematic of a Hg-K cell is shown in Fig. 1. By incorporating mass flow relations the K activity into anode and cathode can be expressed as a function of x , the distance along the cell length. The cell voltage as a function of x can then be given by Equation 2.

Figure 1. A Mercury-Potassium Cell.

M_{Ci} = Mass flow rate into cathode.

M_{Ai} = Mass flow rate into anode.

M_K = Mass rate of potassium moving through the electrolyte.

$$V = \frac{RT}{nF} \ln \frac{a_{Kx}}{a'_{Kx}} - I_x R_x w dx \quad (2)$$

where

x = distance in direction of metal flow

a'_{Kx} = activity of K at x in cathode

a_{Kx} = activity of K at x in anode

R_x = resistance at x

w = cell width

I_x = current density at x

I_x is related by the Faradaic relationship to M_K . Thus Equation 2 can be written in the form of Equation 3 wherein V is a function of M_K .

$$V = \frac{RT}{nF} \ln \frac{\gamma_{A(x)} \left[\frac{M_{Ki} - \int_0^x M_{Kx} dx}{M_{Ai} - \int_0^x M_{Kx} dx} \right]}{\gamma_{C(x)} \left[\frac{M'_{Ki} + \int_0^x M_{Kx} dx}{M_{Ci} + \int_0^x M_{Kx} dx} \right]} - \frac{nFM_{Kx}}{39} R \quad (3)$$

where

M_{Ki} and M'_{Ki} = mass flow of K into anode and cathode respectively

γ = activity coefficient.

This equation was solved by means of a digital computer. Typical results are shown in Fig. 2.

In order to check this theory a cell of the type shown in Fig. 3 was operated. The results of this operation are shown in Fig. 4. The dotted points represent theoretical calculations while the continuous lines represent data. The lack of agreement during the early portion of operation is thought

to be due to diffusion characteristics between potassium and mercury. The model is presently being expanded to include this effect.

Figure 2. Typical Results of the Solution of Equation 3

Figure 3. Arrangement of the Mercury-Potassium Cell.

Figure 4. Results of Operation of the Cell.

III-2. HYDRIDE AND BIMETALLIC REGENERATIVE EMF CELLS

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Presented by C. E. Crouthamel

The objective of the studies on the regenerative emf cells is to produce a device which would operate continuously in a closed Carnot cycle. In this cycle, heat would be consumed in one isothermal leg and useful elec-

trical energy would be produced in the second isothermal leg. Such a thermodynamic cycle is illustrated by a temperature-entropy diagram in Fig. 1. In the diagram, a galvanic cell is arbitrarily placed in the isothermal path 3-4, where the cell reaction $A + B \rightarrow AB$ occurs at temperature T_1 . The temperature of the cell product AB is raised to T_2 along the path 4-2. The product AB is dissociated along the isothermal path 2-1 at temperature T_2 to produce the cell reactants A and B .

Since spontaneous recombination of A and B would occur in a homogeneous system at T_1 , it is necessary to separate the reactants at or near T_2 .

The reactants A and B are returned

to their respective anode and cathode compartments in the cell and the temperature of the reactants is returned to T_1 along the path 1-3. The maximum overall efficiency of this cycle is the Carnot efficiency $[(T_2 - T_1)/T_2]$ where T is the Kelvin scale. Although the regenerative cell is not expected to be more efficient than a conventional steam plant (overall conversion efficiencies of about 40 percent have been achieved with conventional generating systems), some of the anticipated advantages of the cell are compactness, versatility with respect to size, low mass to power output, and elimination of most of the mechanical parts which should result in a cell that is long-lived and trouble-free.

Two types of regenerative emf cells are being studied: the hydride cell and bimetallic concentration cell.

Regenerative Hydride Cell Studies

The first cell selected for study was the lithium hydride cell (see Fig. 2). In operation, the chemical reaction at the molten metal lithium

Figure 1. Temperature-Entropy Diagram in the Regenerative EMF-Cell Cycle

anode is the oxidation of the metal to lithium ions and the reaction at the cathode is the reduction of hydrogen gas to hydride ions. The overall cell reaction is

The selection of this cell for initial investigation was made after a careful study of the available, though scant, literature.¹ From this study, it appeared that the lithium hydride cell held considerable promise if the difficulties associated with the use of porous metal frits for the hydrogen gas electrode could be eliminated, i.e., the occurrence of variable catalytic activity at the surface of the frits and alternate flooding of the frits by hydrogen gas and fused salt electrolyte. Despite these difficulties, a current

Figure 2. Lithium Hydride Cell

density of 200 amp/sq ft of electrode area at 0.3 volt at a cell operating temperature of 570°C was achieved with a cell developed by the Mine Safety Appliance Corporation.² The cell consisted of a liquid lithium anode, a lithium fluoride-lithium chloride eutectic as an electrolyte, and a stainless steel cathode. The cathode was in the form of a screen or a porous micro-metallic gas electrode. The duration of this current and the conditions under which it was achieved are not known.

Studies on hydride cells have also been carried out by Thompson Ramo Wooldridge, Inc.³ (TRW) in Cleveland, Ohio, for the U. S. Air Force. The results of the work at TRW led to the conclusion that iron and niobium are the only materials which possess the requisite characteristics for use as hydrogen diffusion diaphragms, i. e., the rates of diffusion of hydrogen through both materials at 400 to 500°C were appreciable and both materials were compatible with the salt-alkali metal environment of the hydride cell. Most of the work at TRW was carried out with iron diaphragms. However, the results of a single 45-minute run in which a niobium diaphragm was utilized have also been reported by TRW. This run indicated that current densities of over 1000 amp/sq ft of electrode could be achieved by a lithium hydride cell utilizing a niobium diaphragm. Considerable effort, however, was required to provide a niobium diaphragm free of oxide coating at the operating temperature of the cell. In this respect iron diaphragms offer an advantage inasmuch as the iron oxides formed are reduced to the metal by hydrogen at the cell temperature.

In experiments at Argonne, current densities of about 10 amp/sq ft were achieved using a lithium hydride cell with a 5-mil thick Armco iron diaphragm at a cell operating temperature of 500°C. This value is a factor of ten lower than the current density of 100 amp/sq ft which is usually regarded as being the minimum standard of acceptability. The low current density obtained in these experiments is attributed to the low rate of hydrogen diffusion through the pure iron diaphragm (see Figs. 3 and 4). To achieve a satisfactory current density, a tenfold increase in the rate of diffusion of hydrogen through the diaphragm is necessary.

Consideration has been given to three methods whereby this increase might be achieved. The first depends upon the ionization of the hydrogen gas stream behind the diaphragm; the second depends upon finding a more suitable diaphragm material; and the third depends upon the fabrication of a gas electrode with a sufficiently large area to bring about the tenfold increase in diffusion rate.

The effect of ionization of hydrogen on its rate of diffusion through an Armco iron diaphragm was tested in two experiments. In each experiment, an alpha source (plutonium in the first run and curium in the second) was placed in the hydrogen gas stream about 2 inches behind the diaphragm.

The intensities of the alpha sources differed by a factor of about ten. The results of the tests indicated that an increase (about twofold at 400°C) in diffusion rate was obtained by the use of the alpha sources. No appreciable dependency of the diffusion rate on the intensity of the alpha sources was observed. From these results, it was concluded that the ionization of the hydrogen stream could not in itself bring about the required tenfold increase in the rate of diffusion of hydrogen through the iron diaphragm.

Figure 3. Effect of Temperature on Hydrogen Diffusion through a 10-mil Armco Iron Diaphragm (Unannealed)

Figure 4. Effect of Temperature on Hydrogen Diffusion through a 10-mil Armco Iron Diaphragm (Annealed at H_2 at 900°C for 2 hr)

The second possibility, namely, the utilization of other materials for the construction of gas electrode diaphragms, is now being investigated. Some of the more promising materials, such as molybdenum-iron alloys, niobium, and vanadium, have presented fabrication problems, but Battelle Memorial Institute (BMI) has undertaken the fabrication of some diaphragms for Argonne National Laboratory. BMI has thus far supplied diaphragms of 5 and 10 weight percent molybdenum-iron alloys and of pure nickel, tantalum, and niobium. A high-purity vanadium foil has been supplied by Ames Laboratory. In evaluation tests conducted at Argonne, it was found that the rate of

diffusion of hydrogen through the 10 weight percent molybdenum-iron alloy was slightly lower than the rate through pure iron. The rate of diffusion of hydrogen through the pure vanadium foil supplied by Ames was determined to be 1.16×10^{-1} cc/(sq cm)(sec) at 550°C. This value would allow the achievement of a current density of about 500 amp/sq ft at the hydrogen electrode. The permeability value obtained at Argonne differs widely from the value of 5.0×10^{-5} cc/(sq cm)(sec) at 550°C reported in the literature.⁴ The reason for this large discrepancy is not known. Evaluation studies are now being carried out on the other diaphragms received from Battelle.

The possibility of achieving the desired current density at the hydrogen gas electrode by constructing an electrode with a large surface area has also been considered. Preliminary calculations,⁵ which were based on the utilization of 5-mil thick tubes ($\frac{1}{16}$ -in. OD) of pure iron for the construction of the electrode, indicated that the achievement of a suitable cathodic current density in a lithium hydride cell would require an electrode comprised of 3400 tubes arranged in a 10 x 30 x 30 cm bundle. Although the problems associated with the fabrication of this electrode could be solved, it was concluded that the expense and effort involved in such a venture were unwarranted until other avenues of research were more thoroughly investigated.

Some basic research is being carried out in support of the studies of the lithium hydride cell. Cooling-curve studies have been made to de-

lineate the phase diagram of the lithium hydride-lithium chloride system. The very reactive salts were weighed in a helium atmosphere glove box, which is described later, and the experiments were conducted in a furnace well attached to the floor of the box. The furnace well was isolated from the rest of the system and the experiments were carried out in a hydrogen atmosphere in order to stabilize the lithium hydride. A eutectic melting at 494°C was found at 35 mole percent lithium hydride. The phase diagram of the lithium hydride-lithium chloride system is shown in Fig. 5.

Regenerative Bimetallic Cell Studies

Figure 5. Phase Diagram of the Lithium Hydride-Lithium Chloride System

Experiments with bimetallic cells were continued. These are concentration cells of the type

pure M_1 metal	ionic electrolyte containing ions of M_1 (valence Z_1)	M_1 dissolved in M_2 metal
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The emf of this cell is given by the equation

$$\epsilon = - \frac{RT}{Z_1 F} \ln a$$

where ϵ = electromotive force

Z_1 = valence of metal M_1 in ionic electrolyte

F = Faraday

a_1 = activity of M_1 in M_2

The overall cell reaction is M_1 (pure metal) $\rightarrow M_1$ (solution in M_2).

The study of bimetallic cells is being restricted to cells containing three liquid phases. A diagram of a bimetallic concentration cell is shown in Fig. 6. The advantages of cells of this type are their simplicity, low internal resistance, and ability to operate at very high current densities. This is in contrast to the lithium hydride cell in which the achievement of high current densities is the key problem. The regeneration of bimetallic cells, however, may prove to be considerably more difficult than the regeneration of the lithium hydride cell.

Figure 6. Bimetallic Concentration Cell

The current-voltage characteristics of six cells utilizing different bimetallic combinations were determined and are given in Table I. The lithium-bismuth cell was chosen for further study because of the high current density (450 amp/sq ft

at about 0.46 volt) produced in the cell and because the lithium-bismuth system presented fewer containment problems than some of the other cell systems, e.g., the lithium-tellurium system. The relationship between the saturated lithium-bismuth cell voltage and temperature is given by the following equation:

$$\epsilon = 0.4064 + 10.0212 \times 10^{-4} T - 7.8388 \times 10^{-7} T^2.$$

TABLE I Characteristics of Bimetallic Cells

System	Highest-Melting Intermetallic Compound	Melting Point of Highest Melting Compound (°C)	Open-Circuit Voltage (volt)	Current Density at 1/2 Open-Circuit Voltage (amp/sq ft)
Li-Te	Li ₂ Te	(unknown)	1.94	230
Li-Bi	Li ₃ Bi	1145	0.931	450
Li-Sn	Li ₇ Sn ₂	783	0.789	375
Li-Pb	Li ₁₀ Pb ₃	726	0.687	200
Li-Zn	Li ₂ Zn ₃	520	0.675	225
Li-Cd	LiCd	549	0.659	350

The emf's of the lithium-bismuth bimetallic system as a function of temperature and composition are shown in Fig. 7. The liquid bismuth

Figure 7. Characteristics of Lithium-Bismuth Cell. Smooth curves are computer derived least squares quadratic functions, σ = standard deviation, and X_{Li} = mole fraction of Li in Bi. Each curve includes about twenty data points at intervals of 50° or less.

metal cathode saturated with lithium was operated against pure lithium anodes to obtain the lower emf-temperature plot shown in Fig. 7. The saturated lithium-bismuth electrode was then used as the anode and secondary standard electrode to obtain the other curves. Irreversible transfer of lithium in cells utilizing pure lithium anodes changed the composition of the cathode too rapidly to permit temperature cycling.

In early studies, attempts were made to use the lithium chloride-potassium chloride eutectic as the electrolyte. It was found, however, that cell voltages became unstable at temperatures above 450°C. This instability was attributed to the reduction of potassium to the elemental metal by lithium. When the cell electrolyte was changed to the lithium chloride-lithium fluoride eutectic mixture, the voltages of the saturated lithium-bismuth cell remained stable at cell-operating temperatures as high as 825°C. Above this temperature, the cell voltages again became unstable. The reason for the instability above 825°C is not clearly understood. It is believed, however, that the instability is due to the rapid, irreversible transfer of lithium metal to the cathode. This transfer of metal may be caused by a considerable increase in the solubility of lithium in the fused salt electrolyte as the operating temperature of the cell is increased. That such an increase in solubility is likely is given credence by the work of Bredig *et al.*⁶ who found that the solubility of lithium metal in lithium chloride varies from 0.005 mole percent at 600°C to 0.02 mole percent at 1000°C.

Because of the instability of the cell voltage above 825°C and the relatively low emf-temperature coefficient of the cell, electrical regeneration of a cell using a pure lithium metal anode does not appear promising. It is possible, however, that these difficulties may be eliminated by using an anode of bismuth saturated with lithium (in equilibrium with solid Li_3Bi) and a cathode of bismuth containing about 0.01 to 0.05 mole fraction of lithium in bismuth. This cell would allow the use of many electrolytes which are not thermodynamically stable with respect to pure lithium and, therefore, it may be possible to find a lower melting mixture for use as the electrolyte. Moreover, it may be possible to operate the cell at higher temperatures and thus produce higher voltages. Both of these changes in operating conditions are made possible because of the lower activity of lithium in the anode.

Regeneration of the lithium-bismuth cell by means of a spontaneous thermal regeneration may also prove to be feasible. This method would involve raising the temperature of the lithium-bismuth alloy to an extent that would allow the separation of the lithium from the alloy by vaporization. By extrapolation of cell data from 825°C to 1000°C, it is possible to estimate the activity of lithium in the saturated lithium-bismuth cell at 1000°C. This value was estimated to be 2.4×10^{-2} . Since the vapor pressure of pure lithium at 1000°C is 40 mm Hg, the vapor pressure of lithium over a saturated lithium-bismuth alloy is about 0.8 mm Hg. By sweeping lithium with helium and condensing the vapor at a lower temperature, it may be possible

to achieve thermal regeneration of the cell. The vapor pressure of pure bismuth at 1000°C is about 2 mm Hg. The activity of bismuth in the saturated lithium-bismuth alloy would have to be of the same order of magnitude as that of the lithium, if very little bismuth is to appear in the gas phase. This is possible but is not known from experimental data at this time. Since the question of thermal regeneration cannot be settled completely by cell studies, it will be necessary to perform a transportation experiment at about 1000°C to determine the relative quantities of lithium and bismuth removed and their rates of removal in the vaporization process.

Although the calculations suggest that thermal regeneration of the lithium-bismuth cell is barely possible at 1000°C, it is likely that the chance of regeneration may be increased by using alkali metals heavier than lithium in the cell. These heavier alkali metals have greater vapor pressures and greater solubilities in their fused halide salts than does lithium. The disadvantage of the greater solubilities of the heavier alkali metals in the cell electrolyte may be offset by limiting the quantity of common ion halide salts in the cell electrolyte.

The availability of suitable materials of construction may very well become the overriding consideration in the selection of a cell for practical use. Very little data are available on the corrosion of structural materials by metals and fused salts at the high temperatures contemplated for the operation of the cell. In addition, corrosion data collected in stagnant systems may not be applicable to a circulating system. It is anticipated that a considerable research effort will be required in this area before the regenerative emf cell program can be successfully concluded.

Recirculating Helium Atmosphere Glove Box

The systems of interest in the regenerative emf cell program involve the use of fused salts and liquid metals that are not compatible with an ordinary atmosphere. An important development during the past year has been the design and construction of a recirculating helium atmosphere glove box. Prior to the completion of the box, experimental work was seriously compromised by contamination of the systems under study with impurities such as hydroxides, oxides, and nitrides. The helium atmosphere in the glove boxes (see Fig. 8) that are now being used contains less than 1 ppm water and 10 ppm oxygen and nitrogen. Experimental furnace wells have been attached to the metal floor of the glove boxes by means of water-cooled O-ring seals. These wells can be isolated from the rest of the glove-box system by an O-ring-sealed interior cap. Experiments may thus be set up in the furnace well in the purified helium atmosphere of the box; however, by placing the interior cap on the well, a high vacuum or other atmosphere may be maintained in the well during experimentation. Details of the design and specifications of the glove box helium purification system have been published in report ANL-6652.⁷

Figure 8. Recirculating Helium Atmosphere Glove Box. (Furnace wells are attached to the floor of the box. The helium purification system is located behind the glove box.)

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III-3. PHOTOVOLTAIC ENERGY CONVERSION AND FUEL CELL RESEARCH AT IIT RESEARCH INSTITUTE

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Several aspects of photovoltaic energy conversion are being pursued at IIT Research Institute. Since CdTe (1.4 eV) has a larger band gap than silicon (1.1 eV) and falls nearer the maximum theoretical efficiency for solar conversion (Fig. 1), it is being investigated as a material for solar energy converters. Silicon, the present solar converter material, has a more slowly changing absorption edge (Fig. 2) than does either GaAs or CdTe. This means that the absorbing layer can be thicker and the series resistance of the cell due to this layer can be smaller. This, however, requires long lifetimes and long diffusion lengths for optimum utilization. The thicker absorption layer also reduces the effect of the surface recombination upon the efficiency of the cell. GaAs has a very sharp absorption edge, which means that the sun's photons are absorbed near the surface and the junction must be closer to the surface. This increases the series resistance and increases the effect of surface recombination on the efficiency, but allows one to produce a junction with a high carrier collection efficiency with less stringent requirements on lifetime and diffusion length. As shown by Fig. 2, CdTe is a compromise between Si and GaAs in this respect.

Figure 1. Efficiency Versus Band Gap
at Different Temperatures

Figure 2. Plot of Absorption
Constant α Versus
 $h\nu$ for Ge, Si,
GaAs and CdTe

While the CdTe devices which we have produced have had very low efficiencies (less than 3 per cent), we have recently produced very good CdTe - lifetime, 25 microseconds; resistivity 3000 ohm-cm p type; hole mobility, 100 cm²/volt sec; electron mobility, greater than 2000 cm²/volt sec. Also, there has been much less degradation in the cells at 500°K than anticipated. Silicon cells, of course, are inoperable at 500°K.

A device to convert radioactive energy to electricity has been devised which converts beta rays to light and uses a silicon photovoltaic converter to produce electricity. The radioactive sample was promethium-147 with a half life of two and one half years. A 60% ZnS-40% CdS phosphor with a copper activator was chosen because its light output most nearly fitted available silicon solar cells. The phosphor light output was 0.1 milliwatt/cm² and the overall efficiency of the device was less than one per cent.

IITRI fuel cell research is concentrated in two primary areas. One is the use of inorganic ion exchange membrane for fuel cells, and the other system involves the development of cells based on methanol as the fuel.

The inorganic ion exchange membrane fuel cells used hydrogen as the fuel and oxygen or air as the oxidizer. They can also utilize propellant materials such as hydrazine as the fuel and nitrogen tetroxide as the oxidant. These cells have advantages of simplicity, stability, a lack of liquid, and excellent performance at both room and elevated temperature.

The cells based on methanol have been developed to the point where values such as 300-500 amp per sq ft have been obtained for the methanol electrode. Development of novel electrode and catalyst systems have made these extremely high densities possible. Work is now in progress on the oxidant electrode to match the fuel electrode values.

III-4. SOME NEW APPROACHES TO THE HYDROGEN-OXYGEN FUEL CELL

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Conventional hydrogen-oxygen fuel cells generally involve two flat-plate porous electrodes separated by an electrolyte and perhaps a membrane. The basic problems in such cells are that the structure leads to difficulties in maintaining liquid-gas interfaces, eliminating pressure differentials, hot spots, electrolyte dilution, and the like.

Attempts are being made to simplify these problems in the following way: Conformal transformations from the flat parallel plate structure are being used to design new electrode configurations that allow operations at high pressures which do not have gas-liquid interface problems and which do not permit differential pressures to build up. Analytical and experimental work of this nature is underway.

Another experiment in which electron flow and ion flow are controlled by magnetic fields, thereby eliminating the electrolyte, is being carried out.

III-5. ELECTRO-OSMOTIC ENERGY CONVERSION

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Energy conversion by the mechanism of electro-osmosis has been investigated, and a device capable of converting either electrical power into pumping power or pumping power into electrical power in the steady state is being studied. The basic equations coupling voltage, pressure, current and flow rate are established and simplified in the light of existing experimental evidence. Operating characteristics for both the fluid pumping and the electrical generation mode (Fig. 1) are determined and illustrated by example problems. The results indicate that with water as the working fluid, conversion efficiencies of only a fraction of one per cent are possible.

Figure 1. Electro-osmotic Energy Converter
in Pumping Mode

III-6. GERMANIUM CELLS FOR RADIANT ENERGY CONVERSION*

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Until recently photovoltaic energy conversion was associated mainly with the conversion of solar energy to electrical energy. Silicon solar cells are used for this purpose and are commercially available. They have capabilities of converting 8 to 10% of the radiant energy falling on their surfaces to electrical power output.

According to Prince¹ and Wolf² theoretical efficiencies of the order 22% are predicted from ideal behavior of the silicon cells. Under ideal behavior the silicon solar cells are assumed to follow the rectifier equation of Shockley³ based on his diffusion theory.

The Shockley rectifier equation for a P-N junction in the dark is

$$I = I_0 (e^{qV/kT} - 1) \quad (1)$$

where

I_0 is the reverse saturation current

I is the current flowing through the junction

q is the electronic charge ($= 1.6 \times 10^{-19}$ coulombs)

k is the Boltzmann constant in joules/°K

T is the temperature in °K

V is the applied voltage.

When the junction is illuminated, the radiant energy produces a current by generating electron-hole pairs in the cell. The electrons and holes are swept by the electric field inside the P-N junction and a radiant energy current results. If this current is I_R and the cell is connected across a load with a voltage V , the Shockley equation (1) can be rewritten for the cell as

$$I = I_R - I_0 (e^{qV/kT} - 1) \quad (2)$$

*Work performed during summer employment with Allison Division of General Motors Corp.

The discrepancy between the theoretical and experimental efficiencies of silicon solar cells has been attributed by Wolf² to shunt and series resistance. However, a more fundamental property of silicon may be the cause. Shockley, Sah and Noyce⁴ show statistically that silicon solar cells are very sensitive to impurities, which form traps in the forbidden energy gap. Besides the diffusion current, the silicon solar cells have a comparable amount of recombination and generation current due to traps. This modifies the behavior of the silicon cells from the ideal equation (2). Investigations to determine the exact equation followed by silicon solar cells are in progress.

Quiesser⁵ concluded that commercial solar cells contain unnecessary defects which cause the strange characteristics which impair the efficiencies theoretically attainable from the cells. Nevertheless silicon cells, because they are cheap and readily available, continue to be the only ones used for solar energy conversion. In addition, the solar spectrum requires for optimum power that the energy gap in the semiconductor should lie between 1 and 1.6 electron volts. Thus silicon, with a room-temperature energy gap of 1.08 electron volts, is ideally suited for solar energy convertors, but it gives inferior performance in a cell.

Attempts are in progress to obtain photovoltaic energy conversion from incandescent sources burning fossil fuels. The semiconductor materials required for cells to convert this radiant energy at high efficiencies are different from those for solar radiation cells. In this connection germanium is a potentially good material for converting energy from an incandescent source operating at approximately 2000°K. This report discusses the maximum available power densities, the efficiency for a black body source operating at 2000°K, and the conversion efficiency for solar radiation of germanium cells.

Operational Characteristics of a Germanium Solar Cell

According to Shockley and Quiesser⁶ germanium solar cells would follow the ideal Shockley equation (2) for photovoltaic energy conversion

$$I = I_R - I_0 (e^{qV/kT} - 1) \quad (2)$$

where

$$I_0 = \left[q p_N \left(\frac{D_p}{\tau_p} \right)^{1/2} + q n_P \left(\frac{D_n}{\tau_n} \right)^{1/2} \right] \cdot \text{Area} \quad (3)$$

p_N is the equilibrium hole density in the N-region

n_P is the equilibrium electron-density in the P-region

D_p and τ_p are the diffusion and lifetimes of holes in the N-region

D_n and τ_n are the diffusion and lifetimes of electrons in the P-region

q is the electronic charge.

The open circuit voltage, $V_{o.c.}$, is

$$V_{o.c.} = \frac{kT}{q} \ln \left(\frac{I_R}{I_o} + 1 \right). \quad (4)$$

In all practical cases, $I_R/I_o \gg 1$. Therefore,

$$V_{o.c.} = \frac{kT}{q} \ln \frac{I_R}{I_o}.$$

Expressing I_R and I_o in terms of current densities

$$J_R = \frac{I_R}{A} \text{ and } J_o = \frac{I_o}{A},$$

where A is the cross-sectional area of the cell. Then

$$V_{o.c.} = 2.3 \frac{kT}{q} \log \frac{J_R}{J_o}$$

and at room temperature

$$V_{o.c.} = 0.0575 \log \frac{J_R}{J_o}. \quad (5)$$

The short circuit current, $I_{s.c.}$, is

$$I_{s.c.} = I_R. \quad (6)$$

The power obtained from the cell is

$$P = I^2 R = \left[I_R - I_o (e^{qV/kT} - 1) \right]^2 \cdot R \quad (7)$$

where R is the load resistance. In order to obtain the maximum power

$$R = \frac{kT}{qI_o} e^{-qV/kT}.$$

The voltage at maximum power is

$$V_{mp} = \frac{kT}{q} \ln \left[\frac{kT}{qI_o} \cdot \frac{1}{R} \right] \quad (8)$$

and the current at maximum power is

$$I_{mp} = \frac{kT}{qR} \ln \left[\frac{kT}{qI_o} \cdot \frac{1}{R} \right]. \quad (9)$$

The maximum power is

$$P_{max} = \left\{ \frac{kT}{qR} \ln \left[\frac{kT}{qI_o} \cdot \frac{1}{R} \right] \right\}^2 \cdot R. \quad (10)$$

Prince¹ gives the expression for maximum power

$$P_{max} = 0.8 \times V_{o.c.} \times I_{s.c.} \quad (11)$$

which, although approximate, gives us a good basis to compare materials.

Now according to equations (5) and (6), for a given material I_o is constant and thus both $V_{o.c.}$ and $I_{s.c.}$ are functions of I_R , the current due to radiant energy. Therefore

$$P_{max} = f(I_R, I_o).$$

Limit on Power Densities from Germanium Cells

From equation (1)

$$\frac{P_{max}}{A} = 0.8 \times V_{o.c.} \times \frac{I_{s.c.}}{A} = 0.8 V_{o.c.} \times J_R$$

or

$$\frac{P_{max}}{A} = 0.8 \times \frac{kT}{q} \times 2.3 \left(\log \frac{J_R}{J_o} \right) \times J_R = \sigma_P. \quad (12)$$

The power density σ_P would increase with increasing J_R and decreasing J_o .

A limitation on the value of J_o is expressed as

$$J_o = q p_N \left(\frac{D_p}{\tau_p} \right)^{1/2} + q n_P \left(\frac{D_n}{\tau_n} \right)^{1/2}.$$

When a heavily doped P region is in contact with a moderately doped N region, $p_N \gg n_P$ and, hence,

$$J_o \approx q p_N \left(\frac{D_p}{\tau_p} \right)^{1/2}.$$

Using the relationship

$$p_N = n_i^2 / n_N$$

where n_i is the intrinsic carrier density and

$$n_i^2 = 2.23 \times 10^{31} e^{-E_g/kT} \cdot T^3.$$

Where E_g is the energy gap of the material in electron volts, it develops that

$$J_o = \frac{q \times 2.23 \times 10^{31} \times e^{-E_g/kT} \times T^3}{n_N} \times \left(\frac{D_p}{\tau_p} \right)^{1/2}.$$

Now

$$n_N = \frac{1}{\rho_N \cdot q \cdot \mu_n}$$

therefore

$$J_o = q^2 \cdot \rho_N \cdot \mu_n \times 2.23 \times 10^{31} \times e^{-E_g/kT} \cdot T^3 \cdot \left(\frac{D_p}{\tau_p} \right)^{1/2}$$

and at room temperature

$$J_o = 15.4 \rho_N \mu_n e^{-E_g/kT} \cdot \left(\frac{D_p}{\tau_p} \right)^{1/2}$$

where ρ_N is the resistivity of N-type material and μ_n is the mobility of electrons.

In order to decrease J_o and thus a higher open-circuit voltage and, hence, a higher power density, we use a material of low resistivity, low mobility and high lifetime. In N-type germanium τ_p is practically independent of concentration between $n_N/n_i = 10^3$ to 10^5 and equals $100 \mu\text{sec}$.

$$D_p = \frac{kT}{q} \mu_p$$

where μ_p is the mobility of holes. For germanium

$$\mu_p = 1900 \text{ cm}^2/\text{volt-sec}$$

$$\mu_n = 3900 \text{ cm}^2/\text{volt-sec}$$

$$kT = \frac{1}{39} \text{ ev at room temperature}$$

$$D_p = \frac{1900}{39} = 49 \text{ cm}^2/\text{sec}$$

$$\tau_p = 100 \mu\text{sec}$$

$$(D_p/\tau_p)^{1/2} = 7 \times 10^2.$$

Taking

$$\rho_N = 0.01 \text{ ohm-cm},$$

$$J_o = 2.17 \times 10^{-6} \text{ amperes/cm}^2.$$

The value of J_R is limited by the number of photons falling on the junction and having an energy greater than or equal to E_g . From a practical point of view we have for a black body at 2000°K about 2.39×10^{20} photons per second of wavelength shorter than 1.77μ , corresponding to an energy gap of $\text{Ge} = 0.67 \text{ ev}$, falling on the cell surface and affecting the volume. If we assume these photons to be useful, we have,

$$J_R = q \times 2.39 \times 10^{20} = 37.9 \text{ amperes/cm}^2.$$

Hence

$$V_{o.c.} = 0.0575 \log (J_R/J_o) = 0.416 \text{ volts}$$

and thus

$$\sigma_P = 0.8 \times 0.416 \times 37.9 = 12.6 \text{ watts/cm}^2.$$

This assumes a 100% quantum efficiency of photon absorption.

The Efficiency of Conversion for a Black Body Source at Temperature T°K

We assume it is possible to maintain the cells at room temperature 300°K by some sort of cooling arrangement, say water cooling. The efficiency of conversion of radiant energy:

$$\eta = \frac{\text{electrical power output}}{\text{input (radiant energy/sec at source)}} = \frac{0.8 \times V_{o.c.} \times J_R}{\int_0^\infty W_\lambda \cdot d\lambda}$$

where W_λ is the spectral radiant emittance in watts/cm²/micron. Now $J_R = J_{s.c.}$. Substituting the value of $V_{o.c.}$ at 300°K

$$\eta = \frac{0.8 \times 0.0575 J_R}{\int_0^\infty W_\lambda \cdot d\lambda} \log \frac{J_R}{J_o}$$

where

$$J_R = qN_p \text{ amperes/cm}^2$$

N_p is the number of photons having energies $h\nu \geq E_g$ and

$$J_o = 15.4 \rho_N \mu_n e^{-E_g/kT} \left(\frac{D_p}{\tau_p} \right)^{1/2}.$$

Putting in data for germanium and a source at 2000°K

$$J_R = 37.9 \text{ amperes/cm}^2$$

$$J_o = 2.17 \times 10^{-6} \text{ amperes/cm}^2$$

$$\int_0^\infty W_\lambda \cdot d\lambda = 90.86 \text{ watts/cm}^2 \text{ at } 2000^\circ\text{K}$$

$$\eta = 13.9\%.$$

The above calculations assume that the amount of photons emitted per square centimeter by the source are received by a square centimeter area of the cell.

Assuming the shape of the source to be cylindrical with length ℓ and diameter d_s (Fig. 1) and assuming the diameter of the collector surface - also cylindrical - to be $2x + d_s$ we shall have for a total reflectance of 1 for end plates:

$$J_R(x) = qN_p \cdot \frac{d_s}{d_s + 2x} = J_R \cdot \frac{d_s}{d_s + 2x}$$

$$V_{o.c.} = 0.0575 \log \frac{J_R(x)}{J_o}.$$

If

P_o = power output

$$P_o(x) = 0.8 V_{o.c.} J_R(x) \cdot \pi(d_s + 2x) \cdot \ell$$

$$P_i = \text{power input} = \left[\int_0^\infty W_\lambda \cdot d\lambda \right] \cdot \pi d_s \cdot \ell$$

$$\eta = \frac{0.8 \cdot 0.0575 \cdot \left[\log \frac{J_R(x)}{J_o} \right] \cdot J_R \cdot \frac{d_s}{d_s + 2x} \cdot \pi(d_s + 2x) \cdot \ell}{\left[\int_0^\infty W_\lambda \cdot d\lambda \right] \cdot \pi d_s \cdot \ell}$$

$$\eta(x) = \frac{0.8 \cdot 0.0575 J_R \cdot \log \frac{J_R(x)}{J_o}}{\int_0^\infty W_\lambda \cdot d\lambda}.$$

Figure 1 shows the variation of η with x in the case of a black body source at 2000°K and germanium cells at room temperatures as collectors.

Figure 1
Variation of η with $2x/d_s$ for Germanium Cells and a Black Body Source at 2000°K

The above calculations assume or suggest no means of utilizing those photons that do not have sufficient energy to produce electron hole pair and the excess energy of photons having energies greater than E_g . Any such means would certainly increase the efficiency of conversion of the fuel energy to electrical energy.

Conversion Efficiency of Germanium Cells for Solar Energy

The efficiency as shown before is

$$\eta = \frac{\text{output power/cm}^2}{\text{input power/cm}^2}$$

$$\eta = \frac{0.8 \times V_{o.c.} \times J_R}{100 \times 10^{-3}} = \frac{0.8 \times 0.0575 \left[\log \frac{J_R}{J_o} \right] J_R}{100 \times 10^{-3}}.$$

According to Fig. 4 in Wolf's publication,²

$$J_R = 6.5 \times 10^{-2} \text{ amperes/cm}^2 \text{ and } J_o = 10^{-6} \text{ amperes/cm}^2.$$

Thus

$$\eta = \frac{0.8 \times 0.0575 [\log 6.5 \times 10^4] \times 6.5 \times 10^{-2}}{100 \times 10^{-3}} \times 100 \text{ or } 14.4\%.$$

Conversion Efficiency of Silicon Cells for Solar Energy

Taking ideal behavior of a silicon solar cell and the data from Wolf,²

$$J_R = 4.5 \times 10^{-2} \text{ amperes/cm}^2 \text{ and } J_o = 10^{-12} \text{ amperes/cm}^2.$$

Then by the equation above,

$$\eta = \frac{0.8 \times 0.0575 [\log 4.5 \times 10^{10}] \times 4.5 \times 10^{-2}}{100 \times 10^{-3}} \times 100 \text{ or } 22\%.$$

This theoretical efficiency of 22% in a silicon solar cell is possible provided the silicon P-N junction has ideal V-I characteristics according to Shockley's equation (1). In practice it has been possible to obtain efficiencies only from 8-10%.

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III-7. THE TEMPERATURE DEPENDENCE OF THE CONTACT RESISTANCE OF AN IRON PLATED LEAD TELLURIDE CONTACT

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Presented by W. B. Berry

The two major problems confronting the development of solid state thermoelectric generators are the preparation of suitable materials and the bonding of these materials to suitable electrodes.¹ This paper is concerned with the latter. The specific item of interest is the temperature dependence of metal-semiconductor contact resistance. The contact of particular interest is one of electrodeposited iron on lead telluride. The results of the experimental investigation will be presented first and followed by the discussion of simple idealized two-carrier models in an effort to explain the experimental results.

Basic Formulation of Contact Resistivity and Its Relation to the Design Problem

Contact resistivity as considered is a planar resistivity. That is, it is the resistance of a plane through which a charge carrier must pass. While this is a convenient description for a model, the physical problem necessitates consideration of the regions near the position where this contact is assumed to exist and relating the disturbances in these regions to the model. The basic formulation for the contact resistivity is

$$\rho_0 = \int_0^L (\rho_{\text{actual}} - \rho_{\text{bulk}}) dy = R_a - R_B \quad (1)$$

where L is the equivalent length of the disturbed region and unit area is assumed. The contact resistivity as such is given in units of ohm-meters squared ($\Omega\text{-m}^2$). The analytical problem is to determine R_a .

The contact resistivity appears in the design problem as a degradation of the figure of merit, Z . The ideal maximum power efficiency equation is²

$$\eta = \eta_c \left\{ 2 - \frac{\eta_c}{2} + \frac{4}{Z T_h} \right\}^{-1} \quad (2)$$

where η_c is the Carnot efficiency and T_h is the hot junction temperature.

Considering the contact resistance evenly divided between the hot and cold junctions, the degraded figure of merit is³

$$Z' = Z\theta \quad (3)$$

$$\theta = [1 + R_0/R_B]^{-1} = [1 + \rho_0/\rho_B l]^{-1}. \quad (4)$$

If the magnitude of the contact resistance is ten per cent of the bulk resistance, the figure of merit is reduced by approximately ten per cent.

Experimental Procedures and Results

Lead telluride of room temperature resistivities 500 and 680 $\mu\Omega$ -cm was used as the basic element. Contacts were prepared on these materials in three steps: electropolishing the surface prior to electroplating to minimize residual oxidation, electrodeposition of iron on the lead telluride pellet in a ferrous sulphate bath, and abrasive polishing in preparation for measurement. The measurements, taken in a reducing atmosphere of 95% argon-5% hydrogen, are obtained over the temperature range of room temperature to 800°K. A pressure of approximately 100 psi is applied along the axis of the plated pellets. The method employed to obtain the data is a modified traveling probe method. This method obtains the potential profile along the semiconductor up to and across the contact by

measuring the potential difference between fixed and movable probes. The fixed probe contacts the metallic plate. The frequency at which the a-c measurements are taken is 100 cps and the signal amplitude is one ampere. Contact resistivities were positive and ranged from 0.3 to 20 $\mu\Omega$ -cm². The temperature dependence was found to be positive of the form $\rho_0 \propto T^x$ with x between 2 and 3.

Figure 1 indicates the measured temperature dependence of the contact resistivity.

Analysis of the Contact Resistivity

Two models are employed in the determination of contact resistivity. The first is a minimum resistance study which considers only conduction by local carrier concentrations.

Figure 1. Measured Contact Resistivity.
#3a - 500 $\mu\Omega$ -cm and
#1a - 680 $\mu\Omega$ -cm

The second study considers only the zero current resistance, but takes into account both conduction and diffusion in the barrier layer, but does not consider tunneling through the barrier. In both models, the contact resistance is the additional resistance contributed by the barrier, which is restricted to the semiconductor.

The contact resistivity is studied as a function of temperature and contact potential. Impurity concentration is an inherent variable, however, the calculations are presented for concentrations of 10^{25} m^{-3} only. A separate investigation led to the choice of an impurity band conduction model for the bulk resistivity calculation. This calculation is not presented here, however, the basic assumptions are an effective mass of one-fourth the electron rest mass, an energy gap of 0.18 eV at 0°K with a positive linear temperature dependence of $2.5 \times 10^{-4} \text{ eV/}^\circ\text{K}$ to a maximum of 0.32 eV, and a mobility ratio which varies from 1.35 at 0°K to 2.5 at 900°K.

In the interest of brevity the two derivatives will be outlined instead of fully and completely presented. The resulting equations for the contact resistivity will be presented at the end of each outline. The equations which are basic to both will be listed first, however. These are:⁴

$$\text{Total current} \quad j_t = j_n + j_p \quad (5)$$

$$\text{Total electron current} \quad j_n = e \mu_n n \frac{d(\psi/\alpha)}{dy} + e D_n \frac{dn}{dy} \quad (6)$$

$$\text{Total hole current} \quad j_p = -e \mu_p p \frac{d(\psi/\alpha)}{dy} - e D_p \frac{dp}{dy} \quad (7)$$

$$\text{Electron continuity} \quad \frac{\partial n}{\partial t} = g - r + \frac{1}{e} \frac{dj_n}{dy} \quad (8)$$

$$\text{Hole continuity} \quad \frac{\partial p}{\partial t} = g - r - \frac{1}{e} \frac{dj_p}{dy} \quad (9)$$

$$\text{Electron concentration} \quad n = N_i F(\psi - \phi_n) \quad (10)$$

$$\text{Hole concentration} \quad p = N_i F(\phi_p - \psi) \quad (11)$$

$$\text{Donor level occupation} \quad n_d = N_d \left(1 + \frac{1}{2} e^{(\phi_d - \phi_n + \psi)^{-1}} \right) \quad (12)$$

$$\text{Poisson's equation} \quad -\frac{d^2\psi}{dy^2} = \frac{e^2}{\epsilon K T} (p - n + N_d - n_d) \quad (13)$$

Local conductivity
$$\sigma = \frac{1}{\rho} = e\mu_n(n+n_d) + e\mu_p p \quad (14)$$

where the addition of a subscript B implies bulk equilibrium magnitudes.

The electric field
$$E = - \frac{d\psi}{dy} . \quad (15)$$

The contact resistivity equation for the minimum resistance model is found by substituting the bulk and local conductivity expressions, as in Equation (14), and Equation (15) solved for the differential distance after the electric field solution has been found from Equation (13), into Equation (1). The resultant contact resistivity expression is

$$\rho_0 = (-) \int_0^{V_0} \left\{ \frac{e\mu_n (n_B + n_{dB}) + e\mu_p p_B}{e\mu_n (n + n_d) + e\mu_p p} - 1 \right\} \left\{ \left(- \frac{e^2}{\epsilon K T} \right) \int_0^V (p - n + N_d - n_d) d\psi \right\}^{-1/2} dV. \quad (16)$$

The constant temperature characteristics are given in Fig. 2.

Figure 2
Minimum Contact Resistivity for
the Impurity Concentration
of 10^{25} m^{-3}

The general approach requires the solution of Equation (13). The solution of this equation is more easily expressed in terms of position variable, that is

$$\int_0^L dy = - \int_0^{V_0+V_a} \frac{dV}{E(V)}. \quad (17)$$

The partial derivative of Equation (17) with respect to total current yields the zero current total resistance, R_a , in the form of $\frac{\partial V_a}{\partial J_t}$, in the limit as the total current approaches zero. Equations (5) and (9), after being integrated, are substituted into the resultant expression to form the solution. The boundary condition in the final expression is supplied by the total current equation under the assumption that the partial derivatives of the electron and hole quasi-Fermi levels with respect to total current in the limit as J_t approaches zero are the same. The resultant expression for the contact resistivity is obtained by subtracting the equivalent bulk resistance. That is,

$$\rho_0 = (-) \left(\frac{1}{2e\mu_n N_d} \right) \left(\frac{kT}{eL_D} \right)^2 E(V_0) \int_0^{V_0} \frac{1}{E^3} \left\{ \int_{-\infty}^Y \left[1 - \frac{1+b}{\mu_n \tau_p} \int_{-\infty}^X \frac{\partial p}{\partial \xi_p} \right. \right. \\ \left. \left. \cdot \left(\int_{-\infty}^Z \frac{1}{n + p/b} \partial U \right) dZ \right] dX + \frac{(n-p)}{e\mu_n N_D} \int_{-\infty}^Y \frac{1}{n + p/b} dX \right\} d\psi - \rho_B L. \quad (18)$$

The constant temperature characteristics are shown in Fig. 3.

Summary of the Calculations

The first contact resistivity model is a minimum resistance model which considers conduction only. This model indicates possible temperature dependencies for the contact resistivity in the range of $\rho \propto T^1$ to T^2 . These temperature dependencies are obtained for three assumed contact potential models. Two of the surface contact potential models assume respectively that the surface Fermi level is at the valence band edge and at one-third the energy gap from the valence band edge. The third surface contact potential model assumes a charge balance between the bulk semiconductor and surface states which are one per atom in population and assumed evenly distributed throughout the gap. The contact resistivity magnitudes indicated by this model and these concentrations are in the neighborhood of $10^{-12} \Omega\text{-m}^2$.

The second contact resistivity model considers both conduction and diffusion effects and employs quasi-Fermi levels in the formulation. The same surface contact potential models are applied as in the first model and contact resistivity temperature dependencies in the range of $\rho_0 \propto T^2$ to $T^{2.5}$ result. The magnitude of the contact resistivity is of the order $10^{-11} \Omega\text{-m}^2$.

The contact potential intercepts with the constant temperature contact resistivity vs. contact potential curves are shown on Figs. 2 and 3. The temperature dependence of the contact resistance is plotted on Fig. 4 for both models.

Figure 3. Diffusion Model Contact Resistivity for the Impurity Concentration $N_d = 10^{25} \text{ m}^{-3}$

Figure 4. Calculated Temperature Dependence of Contact Resistivity $N_d = 10^{25}$

Conclusions

The principal conclusion is that the electrodeposited iron on lead telluride contact resistance is positive and increases with increasing temperature. The experimental results indicate the temperature dependence is positive and may be simply represented as $\rho_0 \propto T^x$, where x is in the range of 2 to 3.

Care must be exercised in the use of the design equation (4) if room temperature contact resistance is used. The acceptable ratio if $\rho_0/\rho_B \ell$ must be modified by an appropriate factor for each material to insure acceptable performance.

Nomenclature

A	Cross-sectional area
b	Mobility ratio
D_n, D_p	Electron and hole diffusion coefficients respectively
e	Magnitude of electronic charge
$E(x)$	Electric field
E_v	Valence band-edge energy
E_g	Energy gap
E_{FS}	Fermi energy at the surface
$F(\eta), F_{1/2}(\eta), F_{3/2}(\eta)$	Fermi Dirac integrals
g	Generation
j_t	Total current
j_n	Electron current
j_p	Hole current
k	Boltzmann constant
L_D	Debye length
L	Equivalent length of space charge region
ℓ	Length of semiconductor
n	Local electron concentration
n_B	Bulk electron concentration
n_d, n'_d	Occupied and unoccupied donor impurity site concentration respectively
N_d	N-type impurity concentration
N_i	Intrinsic equivalent degeneracy at the band edges
p	Local hole concentration
p_B	Bulk hole concentration
r	Recombination

r	As above, or convenience parameter for condensing one of the thermoelectric efficiency expressions
R_a	Total resistance for an applied voltage
R_0	Contact resistance
R_B	Bulk resistance
t	Time
T	Temperature
T_c, T_h	Cold and hot junction temperatures respectively
V	Electrostatic potential
V_a	Applied potential
V_0	Contact potential
x	Exponent
y	Position
X, Y, Z, U	Position variables in Equation (18)
Z	Figure of merit for a thermoelectric material
Z'	Degraded figure of merit
α	Seebeck coefficient or potential normalization constant
ϵ	Permittivity
γ_0	Ratio of hole to total current
η	Efficiency, Fermi integral variable
η_c	Carnot efficiency
μ_n, μ_p	Electron and hole mobility respectively
ρ	Electrical resistivity
ρ_s	Bulk electrical resistivity
ρ_0	Contact resistivity
θ	Figure of merit degradation factor
σ_B	Bulk electrical conductivity
σ	Electrical conductivity
ψ	Electrostatic potential, dummy variable
ζ_p	Hole chemical potential

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SESSION IV

Tuesday, November 5, 1963

CHAIRMAN: H. S. ISBIN
University of Minnesota

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IV-1. CHARGED PARTICLE PROPULSION; A DOUBLE ENERGY-CONVERSION PROBLEM

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The electric propulsion of space vehicles is a problem which, at first glance, is rather straightforward and simple. In actuality as well as in principle, a beam of charged particles is formed, accelerated by an electric field, neutralized, and permitted to leave the vehicle in much the same manner as does the high-velocity gas from a jet engine of a chemical rocket. Thus, in the most simple statement of the problem, we have merely substituted electrical means of accelerating the particles for chemical means and changed the particles from hydrocarbons, water, oxides of carbon or nitrogen, and other molecules to atoms or ions of cesium, rubidium, or other alkali metals or to multiatomic particles of carbon, mercury, glycerol, or other convenient material. Indeed, as seen from a first glance, the problems seem almost trivial and certainly straightforward from the classical mechanics point of view.

Energy Conversion Concept

The primary objective of the propulsion system is to convert stored energy in one form or another (chemical, nuclear, electrical, photo, thermal) to kinetic energy of the vehicle itself. Such an objective is certainly not unique; indeed, it is the same general objective present in any vehicular system be it automotive, locomotive, horsedrawn, or man powered. How then, does an electric propulsion system differ from other propulsion systems? Figure 1 is a schematic diagram of an elementary nuclear-electric propulsion system. If this diagram is modified to point only to the energy conversion problem we have Fig. 2.

Figure 1. Block Diagram of a General Electric Propulsion System

Figure 2. Block Diagram of a Possible Energy Conversion System for a Propulsion System

It should be noted that in the most simple case, we have a double energy-conversion problem: nuclear-electrical-mechanical. In a more complicated case (and perhaps more realistic) the energy conversion problem may become much more complex.

Electrical-Mechanical Conversion

The final electrical-to-mechanical energy conversion system is comprised of several fundamental parts, as shown in Fig. 1. Roughly these are: (1) the charged particle production system, (2) the beam forming system which may be part of (1), (3) the acceleration system, and (4) the neutralizer. Of these four units, we are most concerned in our laboratory, at present, with (1) and (2), i.e., the charged particle production and beam formation units.

Methods of Producing Charged Particles

A source of charged particles must be reliable over long periods of time and be capable of producing particles of suitable specific charge (q/m) in numbers sufficiently high to be useful. Many sources have been proposed. Some of these are: (1) cesium-tungsten contact ionization sources; (2) electron-bombardment ion sources (similar to PIG discharge gauges); (3) duoplasmatron sources; and (4) other plasma-extraction sources. It should be noted that such sources produce primarily monatomic or diatomic ions. A second class of sources produces multiatomic ions or "heavy" ions. Such particles may be as large as several microns in diameter. Four main types of heavy particle sources are currently under investigation. They are: (1) electrically sprayed liquid droplet sources, (2) sources of solid charged particles condensed from the vapor phase on a substrate and subsequently removed, (3) sources producing charged particles by condensation from an ionized vapor phase,

and (4) sources producing uncharged particles by condensation from vapor phase and subsequently charging the particles by corona means.

Efficiency Considerations

To understand the relative merits of the two types of particles - ions and heavy particles - we must examine the production, acceleration, and use of the particles in a thrust unit. In order to be able to compare two systems using different particles, let us assume an exit velocity for the particles of v relative to the vehicle. The momentum imparted to the vehicle per nucleon will then be Mv where M is the mass per nucleon. In the case of an atomic ion of cesium, the momentum per ion would then be Mv and the directed kinetic energy would be $\frac{1}{2}Mv^2$ per ion (or atom). To form this ion from a cesium atom requires energy equal to $e\phi$, where e is the electron charge and ϕ is the ionization potential of cesium. In addition, to maintain the tungsten at suitably high temperatures ($T = 1200^\circ\text{K}$) requires, say, W_T energy per cesium atom. Thus, if we lump all losses into W_L , to get $\frac{1}{2}Mv^2$ energy into the beam we must supply a total energy

$$\frac{1}{2}Mv^2 + e\phi + W_L.$$

Of this energy only $\frac{1}{2}Mv^2$ is recoverable as vehicular energy, and the remainder is lost. It is thus possible to calculate a rough efficiency of transfer of energy from the supply to the vehicle. We may define efficiency as, approximately,

$$\text{eff.} = \frac{\frac{1}{2}Mv^2}{\frac{1}{2}Mv^2 + e\phi + W_L} = \frac{1}{1 + [(e\phi + W_L)/(\frac{1}{2}Mv^2)]}.$$

The energy given to the particles by the accelerating fields, i.e., the beam energy per particle, is

$$\frac{1}{2}Mv^2 = qV$$

where q is the charge per particle and V is the potential through which the particle is accelerated. Thus, the efficiency becomes

$$\text{eff.} = \frac{1}{1 + [(e\phi + W_L)/qV]}$$

and approaches unity as V becomes large. However, under the assumption that the exit velocity remain fixed, if V is increased, the specific charge of the particle must decrease. From this point of view, high efficiencies may be obtained by the use of high accelerator potentials and large particles,

i.e., those with low specific charge. For present cesium ion thrusters, the quantity $e\phi + W_L$ is about 1000 ev per ion.

It is of significance that we have made the assumption of a fixed exit velocity regardless of the particle specific charge. This assumption is made as a result of optimization studies which show that for a given mission, payload, power supply capability, etc., there is an optimum velocity with which the working fluid should be ejected. For many methods of computation and various assumptions, the optimum value of v is in the range 20×10^3 meters/sec to 50×10^3 meters/sec. The exit velocity is often converted to specific impulse I_{sp} which, after some discussion, can be found to equal v/g , where g is the acceleration due to gravity at the earth's surface. For purposes of discussion, 3000 seconds is here taken as an optimum value of specific impulse toward which we strive. In Fig. 3 we have plotted specific impulse as a function of accelerating potential with specific charge as a parameter. From these curves we see that for a specific charge of 7.5×10^5 coulombs/kilogram (cesium ions) and an accelerating potential of 600 volts, a specific impulse of 3000 seconds is obtained. Since the formation energy and losses are about 1000 ev we see that the efficiency as we have defined it is rather low (about 37.5%). If we examine the efficiency for particles of lower specific charge, 5000 coulombs/kilograms for example, we find the accelerating potential is 1.8×10^5 volts and the efficiency has become 99.5%. Because of the marked increase in efficiency with decreasing specific charge, we are interested in producing beams of particles with specific charge in the range 500-10,000 coulombs/kilograms.

Figure 3. Specific Impulse as a Function of Accelerating Potential with Specific Charge, q/m , as a Parameter

Electrical Spraying of Liquids

If a liquid is permitted to issue from the open end of a hollow conducting tube maintained at a suitably high potential, the surface of the liquid will become unstable and spraying from the surface may result. Figure 4 is a cross-sectional view of what may be happening at the surface. The spray from the liquid surface consists of charged droplets of various sizes. To be useful as a working fluid in a thruster the droplets should have a uniform specific charge and be formed into a beam.

Figure 4. Cross Section of the Possible Configurations of a Spraying Capillary. Equipotentials are shown as dotted lines.

Figure 5 is a schematic diagram of the general system used to study the electric spraying of liquids. The physical phenomena associated with the spraying process are not well enough understood to enable us to state the parameters of an ideal liquid for propulsion purposes. Figure 6 is a photograph of an actual system as it is set up to study the spraying of liquids. Since the particle specific charge is an important parameter in a propulsion system, we need to determine the distribution of q/m as the liquids are sprayed. Such determinations are accomplished by using mass-spectrometer techniques and by measuring particle velocity after acceleration through a known potential. The mass spectrometers used most often in our work are of the time-of-flight and electric, high-frequency quadrupole types.

Specific-Charge Distributions

Time-of-flight measurements are made using relatively standard techniques and give results such as those shown in Fig. 7. The system

giving these results is diagramed schematically in Fig. 8. This system is simple to build and use and enables us to determine the specific charge of spraying drops during very short time intervals.

Figure 5. Schematic Diagram of System Used to Study Spraying Liquids

Figure 6. Typical System Used to Study Spraying Liquids. Liquid reservoir and manometer for measuring reservoir pressure is shown on left of picture.

Figure 7

Data Obtained from Time-of-flight Mass Spectrometer. Upper trace is capillary current pulse produced by spraying liquid. Lower trace is detector output as function of time. Time increasing from left to right.

Figure 8. Time-of-flight Mass Spectrometer Schematic Diagram

The quadrupole mass spectrometer is essentially a strong focussing lens excited at a high frequency. Since general strong-lens theory is reasonably well documented and since Paul, Steinwedel and others have discussed the theory of the "massenfilter," nothing is to be gained by going into great detail on this device. However, it should be noted that the potential surfaces should have the configuration indicated in Fig. 9. These

Figure 9. Ideal Potential Surfaces Needed for Quadrupole Mass Spectrometer. The z axis is perpendicular to the paper.

are produced approximately by circular cylinders as shown in Fig. 10. The detector used in the Q-pole spectrometer is a current measuring device and thus results in a time integrated result for the specific charge distribution. By properly setting driving voltage and frequency, the particles getting through to the detector may be selected according to specific charge. The distribution of specific charges may be obtained by holding the driving voltage fixed and varying the frequency. A typical spectrum of ions produced in a vacuum system which has a slight leak is shown in Fig. 11. (Helium was being sprayed on the deck.) In Fig. 12 we have typical spectra of very low specific charge particles. The spectra of Figs. 11 and 12 were obtained by using the same spectrometer but widely varying frequencies to drive the quadrupole lens elements. We have found that with a single instrument we are able to cover a range of specific charge from 10^8 coulomb/kg (hydrogen ions) to 10^{-3} coulomb/kg (very large particles). The electronics to cover such a range is shown in Fig. 13.

Figure 10. Dimensions and Configuration of a Typical Quadrupole Mass Spectrometer

Figure 11. Mass Spectrum of Gases in a Vacuum System into Which a Small Amount of Helium was Introduced through a Small Leak

Figure 12

Specific Charge Distributions of Particles Sprayed from a High Potential Capillary. The curve on the left was for liquid (glycerol) at 25°C and the curve on the right was for glycerol at a temperature of 55°C.

Figure 13. Oscillators and other Circuitry for Quadrupole Mass Spectrometer

Much of our work has been concerned with the unraveling of the physical processes involved in spraying liquids electrically. The parameters which affect the spraying process are: flow rate, capillary diameter, spraying potential, conductivity (electrical), viscosity, temperature, and surface tension. The manner in which each of these parameters affects the spraying process is not well understood, however. As an example, Fig. 12 shows the specific charge distribution of glycerine at 25°C on the left and that of glycerine at 55°C on the right at higher specific charge. From consideration of Rayleigh's theories of spraying as extended by Zeleny, one would expect the center of the distribution to shift to lower values of q/m .

The two curves shown in Fig. 12 were obtained with the spraying capillary at a potential of about 4 kv and a capillary 0.008 inches

diameter. Figure 14 shows on the left a distribution of sprayed pure glycerine using a 0.024 inch capillary at 16 kv. The curve on the right was obtained under the same conditions except the glycerine contained 2.0% carbon particles. The carbon had a mean particle diameter of about 0.8 micron. From the comparison of Figs. 12 and 14, we see that higher potentials lead to higher specific charges as one might expect. By comparing the curves of Fig. 14, we see that addition of small conducting particles to the glycerine leads to a shift of an order of magnitude in specific charge at the peak of the distribution and an apparent narrowing of the distribution. We have no suitable explanation for such results.

Figure 14. Specific Charge Distributions of Glycerine and Carbon-Glycerine Sprays

The distribution shown in Fig. 15 was obtained using dibutyl phthalate sprayed at 18.2 kv. We see from this that it is possible to obtain q/m values suitable for propulsion purposes by electrical spraying methods.

Figure 15
Specific Charge Distribution of Dibutyl Phthalate Sprayed at a Capillary Potential of 18 Kilovolts

To say these are "suitable" implies that the power source will provide electrical energy at "suitable" potentials for accelerating the particles.

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IV-2. HIGH TEMPERATURE SHOCK RESEARCH AT CASE INSTITUTE OF TECHNOLOGY*

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The energy balance of an annular electromagnetic shock tube has been investigated. The total energy to the shock tube was measured and compared with the effective energy in the shock wave after the driving current vanished. The difference between these two energies is explained by losses during the first half cycle of the discharge.

Simultaneous measurements of the magnetic field and luminous front indicate that these two fronts are coincident over a major part of the half cycle of the total current. Only at a time when the total current to the shock tube is considerably smaller than the peak current does a separation exist. Fluctuations in the magnetic field between the electrodes and significant trapped magnetic fields in the plasma ejected from the end of the electrodes are observed and a tentative explanation is presented for this phenomenon.

Data extracted from smear camera pictures indicate that either a current piston shock wave model or a model based on simple momentum considerations predict the velocity of the luminous front at the exit of the electrodes, and that a blast wave model closely approximates the attenuation of the shock wave down the tube.

Spectroscopic measurements of the electron density behind the shock wave are in approximate agreement with the electron density computed with the Hugoniot relationships. Open shutter spectrograms show that both iron and nitrogen impurities are present in the hydrogen gas ejected from the electrodes.

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IV-3. REVIEW OF MHD POWER GENERATION*

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During the past six years, the study of magnetohydrodynamic (MHD) power generation has been pursued intensively by several research organizations in the United States and elsewhere. The principles involved in the direct generation of electrical power from a flowing, electrically conducting fluid were established by Faraday and are indicated in Fig. 1. His initial experiment on Waterloo Bridge, London, failed because he had (1) insufficient magnetic field, (2) a low-conductivity working fluid, and (3) electrode

contact difficulties. These three factors, together with the effects introduced by actual machine configurations and materials requirements imposed by MHD system operating temperatures, represent the basic problems of the MHD power generation field at the present time.

Figure 1. Linear MHD Generator Geometry

The feature which distinguishes MHD generators from other energy conversion devices is that a body force, rather than a surface force or effect, is involved in the basic conversion process. Since

losses are essentially area dependent, the efficiency of MHD generators may be expected to increase with increasing size and accordingly MHD generation should be most favorable where large amounts of electrical power are involved.

Work on MHD power generation was initially directed towards the development of large scale central installations using fossil fuel and open cycle operation. In this case, the MHD generator serves as a topping unit and enables the maximum temperature to be raised substantially above the limits imposed by current steam turbine technology. A simplified diagram of a fossil fuel MHD system is shown in Fig. 2 for a 500-megawatt installation. The economics of MHD central stations are compared in Fig. 3 with

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Figure 2. Fossil Fuel Combined MHD and Turbine Cycle (From Ref. 7)

conventional power plants and non-MHD nuclear installations. Capital and fuel costs considerations lead to the shaded triangle in Fig. 3 defining the requirements for economically favorable MHD power generation. The conditions under which this triangle may be obtained have not yet been fully determined but appear to require the use of superconducting field systems.

Figure 3
Comparison of
Central Station
Power Cycles

The development of high temperature nuclear reactors has reached a point where it is worthwhile to consider the possibility of coupling an MHD generator to a nuclear heat source for central station power generation and accordingly to achieve thermal efficiencies considerably in excess of those available from nuclear-steam turbine installations. A tentative layout for a 500-megawatt power plant operating with a 3000°F gas cooled reactor is shown in Fig. 4. Reactors suitable for sustained operation at this temperature have yet to be developed and the success of a gas or Brayton cycle MHD-nuclear system depends on progress with reactor technology. Helium would be used as the working fluid in a scheme of this

Figure 4
Gas-Cooled Reactor
with Combined MHD-
Steam Plant Cycle
(From Ref. 9)

type and seeding with cesium is proposed to render it electrically conducting in the MHD generator duct. The conductivity obtained with this arrangement under conditions of thermal equilibrium is probably too low for satisfactory generator operation and a method of extra-thermal ionization is required. Fission products released by the fuel elements would provide some extra ionization but this would have to be supplemented either by electrode injection or by electron field elevation of electron temperature.

The generation of electrical power from a space vehicle nuclear heat source offers a further potential application for MHD generators. As heat rejection by radiation is involved, a high temperature cycle is required to minimize radiator area and hence power system weight. Reactor outlet temperatures in the range 1500° to 3000°F are required and both gas cooled and liquid metal cooled types are under consideration. In principle, both Brayton cycle and condensing or Rankine cycle systems are possible; the latter offers substantial advantages in radiator performance but requires the use of an alkali metal as the working fluid. In the case of Rankine cycle systems, the working fluid can be used either in its vapor or liquid state in the MHD generator duct and three such schemes are given in Fig. 5. In each case, lithium transfers heat from a liquid metal cooled reactor, such as the SNAP 50, to the boiler or heat exchanger in the power loop and, for liquid metal generators, the conversion of thermal energy to liquid kinetic energy is required. In Fig. 5b, a single working fluid is used and this thermal-kinetic energy conversion is achieved in the condensing-ejector device shown in Fig. 6. Two immiscible working fluids may also be employed in conjunction with a nozzle-separator arrangement as indicated in Fig. 5c. While liquid metal generator systems enable a high conductivity working fluid to be used in the MHD generator duct, their overall efficiency is likely to be considerably lower than in the vapor generator case.

The transmission and utilization of electric power is generally done under A-C conditions and use of D-C is confined to very small scale or special installations. This will probably prove to be the case in applications where MHD generators are involved and thus it is useful to investigate the prospects for the direct generation of A-C power in MHD machines. It should be noted, however, that the geometry of a linear MHD machine is naturally suited to D-C operation and most of the development of MHD generators to date has been for this mode of operation.

Direct A-C power generation may be obtained by alternating the magnetic field while keeping the flow steady, by varying the flow properties or conditions or by a combination of these two methods. In all A-C MHD generators, the performance depends on a magnetic Reynolds number based on an axial length characteristic of the machine and useful values of this parameter are obtained only with liquid metal flows. Direct A-C generation

with ionized gas flows in the conductivity range at present attainable does not appear to be feasible but the situation is more promising in the case of liquid metals.

Figure 5a
Vapor MHD Generator

Figure 5b
Single Fluid with Liquid
Metal MHD Generator

Figure 5c. Two Fluids with Liquid Metal Generator

Figure 6. Schematic Drawing of Condensing-Ejector

A straightforward method of A-C generation is simply to alternate the field of a D-C machine. One disadvantage of this approach on liquid metal flows is that the generated voltage is quite low. Use of an induction generator as shown in Fig. 7 enables the excitation system to be wound for higher voltages and also eliminates the need for electrodes. The annular geometry of Fig. 8 is an alternative ar-

range ment which avoids the edge losses inherent in the flat linear machine. Variation of conductivity offers one means of modulating the fluid properties and Fig. 9 gives an electrodeless generator operating on this principle. A succession of conducting slugs maintain the coil and its associated capacitor in oscillation parametrically in a manner analogous to conventional variable reluctance machines.

Figure 7
Linear MHD Induction Generator

Figure 8. Annular MHD Induction Generator

Figure 9
Parametric MHD
Generator

Magnetohydrodynamic power generation has now progressed to the point where several applications are receiving detailed attention and others are in prospect. Many factors outside the realm of magnetohydrodynamics are involved and economic considerations will undoubtedly play a large part in determining the time at which MHD power generation enters the commercial field. For special applications, some of the characteristics associated with MHD systems may prove favorable but a lengthy period of research and development will probably ensue before the final outcome of this work can be clearly evaluated.

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SESSION V

Tuesday, November 5, 1963

PLASMA DIAGNOSTICS AND THERMIONICS

CHAIRMAN: L. GOLDSTEIN
University of Illinois

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V-1. PLASMA DIAGNOSTICS USING ELECTROMAGNETIC WAVES

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The development of microwave techniques for the study of ionized gases was a direct result of the technological advances in this part of frequency spectrum during World War II. Probably the greatest advantage of using electromagnetic waves for plasma diagnostics is that one is able to use extremely small amplitudes for the probing signal and thus impart negligible perturbation on the energy state of the plasma. Usually the electromagnetic energy interacts only with charge constituents of the plasma, and if the frequency is high enough it interacts primarily with the electron gas. However, the electron gas in a plasma interacts with the other constituents of the plasma; with the ions via the long range Coulomb force and with the neutrals by binary collisions governed by very short range forces.

There are exceptions to the statement that the em waves interact only with the electron gas. For instance, Buchbaum at Bell Laboratories has been performing experiments involving the interaction of em waves with ions, whereas Marshall at Illinois has used electron spin resonance techniques for the interaction of em waves with some of the neutral products of a gaseous plasma. In the remainder of this discussion, I will restrict my attention to the energy exchange between the em wave and the electron gas and the resulting relaxation processes occurring between the electrons and the other constituents. My primary aim is to discuss how electromagnetic waves may be used for plasma diagnostics. The first half of my talk will be devoted to the interaction of microwaves with a plasma; the last half will discuss one use of the laser for similar studies on plasmas of high charge density.

The Microwave Technique

When an em wave impinges upon an electron gas, the electrons exhibit ordered simple harmonic motion in addition to their disordered thermal motion. This coherent motion, if not interfered with, represents a continual energy exchange between the electron gas and the em wave. As a consequence of this absorption of em energy and reradiation, the velocity of propagation of em waves in such a media differs from that in a vacuum.

However, this ordered motion is interrupted by collisions of the electrons with the other gas constituents and part of this excess energy

obtained from em wave is irretrievably lost insofar as coherent energy is concerned, and this excess energy is transferred to the other constituents. Thus, the electromagnetic wave suffers an attenuation while propagating through a plasma.

In its simplest mathematical form, this problem involves the simultaneous solution of Maxwell's equations coupled to the Lorentz force equation:

$$\nabla \times \vec{H} = -ne\vec{v} + j\omega\epsilon_0 \vec{E}$$

$$\nabla \times \vec{E} = -j\omega\mu_0 \vec{H}$$

$$m \frac{d\vec{v}}{dt} = -e(\vec{E} + \vec{v} \times \vec{B}) - m\vec{v}\nu$$

where n is the number density of electrons and ν is the effective collision frequency for momentum transfer. It is convenient to rewrite the first equation in terms of a relative dielectric constant composed of real and imaginary parts, which are related to the plasma parameters by the following equations:

$$\nabla \times \vec{H} = j\omega\epsilon_0(\epsilon' - j\epsilon'') \vec{E}$$

where

$$\epsilon' - j\epsilon'' = 1 - \frac{\omega_p^2}{\omega^2} \cdot \frac{1}{1 - j\nu/\omega}$$

$$\omega_p^2 = ne^2/m\epsilon_0 = \text{plasma frequency.}$$

The theory given above is deficient in that it neglects the fact that the collision frequency depends upon the thermal velocity of the electrons, and in general one has a distribution of electron velocities. A more correct approach is to solve the Boltzmann equation. Fortunately, this approach can be related to the prior simple theory and is shown in Fig. 1.

Assuming that the electron gas has a Maxwellian velocity distribution prior to the application of the electromagnetic field, one can relate the real and imaginary parts of the dielectric constant to the electron number density, and elastic cross section. Thus, any circuit that can measure the phase velocity and the absorption of em energy is suitable for plasma diagnostics.

$$\epsilon' - j\epsilon'' = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\nu}$$

$$\omega_p^2 = \frac{n_e e^2}{m\epsilon_0}$$

$$\nu (\text{sec})^{-1} = \frac{\omega\epsilon''}{(1 - \epsilon')}$$

$$n_e = \text{ELECTRON NUMBER DENSITY}$$

$$\omega = \text{SIGNAL ANGULAR FREQUENCY}$$

$$\nu = \text{COLLISION FREQUENCY FOR MOMENTUM TRANSFER}$$

$$n_e (\text{cm})^{-3} = \frac{\omega^2}{3.182 \times 10^9} (1 - \epsilon') \left[1 + \left(\frac{\epsilon''}{1 - \epsilon'} \right)^2 \right]$$

$$\frac{\nu\omega}{\nu^2 + \omega^2} = \frac{4}{3\sqrt{\pi}} \left(\frac{N_A^2 2kT_e}{\omega^2 m} \right)^{1/2} \int_0^\infty \frac{x^2 e^{-x} Q(x) dx}{1 + \left(\frac{N_A^2 2kT_e}{\omega^2 m} \right) x Q^2(x)}$$

$$x = \frac{mv_e^2}{2kT_e}$$

$$m = \text{ELECTRON MASS}$$

$$T_e = \text{ELECTRON TEMPERATURE}$$

$$N_A = \text{NEUTRAL ATOM NUMBER DENSITY}$$

$$Q(x) = \text{CROSS-SECTION AS A FUNCTION OF } x; \text{ ASSUMED ISOTROPIC}$$

$$\frac{\nu}{\omega} \lim_{\frac{\nu^2}{\omega^2} \rightarrow 0} = \frac{4}{3\sqrt{\pi}} \left(\frac{N_A^2 2kT_e}{\omega^2 m} \right)^{1/2} \int_0^\infty x^2 e^{-x} Q(x) dx$$

Figure 1. Equations Relating Electron Number Density and Collision Frequency to the Complex Dielectric Constant and the Elastic Scattering Cross Section

There are two primary techniques in vogue today; namely, the "cavity" technique and the "transmission" technique. In the cavity technique, the plasma is created in a resonant circuit, and the pertinent parameters measured are the change in resonant frequency and decrease in the "Q" of the circuit, which in turn are related to the real and imaginary parts of the dielectric constant respectively. Because of the ease in making precise frequency measurements, one can use this to measure very small perturbations in the resonant conditions of the circuit.

The primary advantage of the transmission technique is its broad-band character. Here one makes direct measurement on the insertion loss and phase shift introduced by the plasma in the path of em wave propagation. A circuit for making this measurement with guided waves is shown in Fig. 2 and represents, in my opinion, a circuit which is pushing the state of the art. It is technique presently being used by P. D. Goldan of Illinois in his study of plasmas at liquid helium temperatures (and up).

This is a microwave bridge circuit that can perform many functions. By splitting the microwave at the first "T," allowing the microwave energy to traverse the two arms of the bridge, and recombining the energy at the "magic T," one can compare the phase shift and the

attenuation introduced by the plasma to that of the reference arm. Thus the collision frequency and the electron density can be determined.

Figure 2. A Transmission Technique Circuit

Furthermore, one other measurement is possible with this circuit. It was found by Mumford at Bell Laboratories that a gas discharge emitted noise in the microwave spectrum; indeed, this forms the basis of the standard noise source. This phenomenon was then explained by Parzen and Goldstein to be related to the electron temperature by the relation:

$$P(f)df = kT\epsilon df$$

where

ϵ = emissivity = absorptivity.

Hence, this can be turned around and used as a diagnostic tool for the measurement of electron temperature. The use of a calibrated low-noise superheterodyne receiver, employing a ruby maser as the front end, allows one to make radiation measurements down to noise limit of the maser - approximately 80°K in this case.

Typical procedures and results are shown next.

Figure 3 shows the experimental procedure. (a) The gas to be ionized is located in a glass container inside the WR-90 (X-band) wave guide. (b) It is ionized by the application of a high-voltage pulse to electrodes located externally to the waveguide. Upon removal of the source of ionization, the gas relaxes back to unionized state. (c) The bottom two pictures show the effect of the decaying plasma upon the transmission of a CW microwave signal as well as the use of a pulsed-on wave delayed with respect to the breakdown pulse. (d) The whole operation is repeated at a rate of 10 times per second.

Figure 3. Diagram of the Experimental Procedure

Figure 4 shows how the phase information can be displayed. The detector on one arm of the "magic T" displays the unbalance in phase of the signal entering the opposite arms. The circuit is initially balanced with no plasma for a null. As the plasma state changes in time the phase of the energy traversing the plasma also changes and the bridge becomes unbalanced. When this phase change reaches 360° , the situation is a gain favorable for a null, and the signal is a minimum. In analogy with optical interferometers, one says that there is "one fringe" shift at this first null.

Figure 4. Phase Information Display

Figure 5 shows some typical results involving the absorption of electromagnetic energy. (a) The top trace shows the transmission with no plasma. (b) The smooth trace represents the transmission of the microwave signal in the presence of the plasma. The difference between this and the top represent the absorption introduced by the plasma.

MICROWAVE CROSS MODULATION
PROBING WAVE 8.53gc @ .5mwatts
HEATING WAVE 8.8gc @ 50mwatts
TIME SCALE - 5 μ sec/cm
PERFORMED AT 1000 μ sec IN
AFTERGLOW

MICROWAVE CROSS MODULATION
DISPLAY OF PORTION IN CIRCLE ABOVE
TIME SCALE 1 μ sec/cm

Figure 5. Typical Results Involving the Absorption of Electromagnetic Energy (Helium, 2.50 Torr, 4.2°K)

(c) Recall that " ν " was a function of electron temperature. We can change this electron temperature by using higher power "heating" microwave signal at a different frequency from that of the low power microwave "probing" wave. Furthermore we tune our detector so as to observe only the probing signal. (d) As we heat the electrons, ν increases in this case, and the absorption on the probing signal increases. When the disturbing wave power is turned off, the electron gas relaxes back to its initial energy state. (e) The

time interval to reach this final energy state is a measure of how tightly coupled the electrons are to the other constituents of the plasma.

Figure 6 shows typical radiometric measurements of the electron temperature as a function of time in the afterglow. One sees that the electron gas temperature falls much faster than the electron disappears through various loss mechanisms. Hence the previous measurements were performed on an electron gas essentially at the parent gas temperature.

Figure 6. Electron Temperature Variation with Afterglow Time

There are some obvious limitations to the microwave method however. The frequency of the electromagnetic wave must be greater than the plasma frequency for wave motion to take place. Thus the non-availability of very high frequency sources limits the electron density measurable with this technique to roughly 10^{14} per cm^3 or less.

One very common technique for the study of high density plasma is the use of optical interferometric techniques. Here the frequency is quite high enough to propagate through any gaseous plasma. A moment consideration will show that interferometers operating in the visible is limited by the plasmas of practical lengths for lowest density measurable to $n_e \geq 5 \times 10^{15} \text{ cm}^{-3}$ for one fringe shift and a 20-cm path. Thus a gap in density range exists.

Recently Dr. Gerardo and I described an interferometric technique using a laser which reduces this gap, with great promise of closing it. Furthermore, it appears to allow the possibility of some very interesting and fundamental studies being performed. I would like to describe this technique.

Investigation of Dense Plasmas by Laser Radiation

(J. B. Gerardo and J. T. Verdeyen)

The use of a laser for interferometric studies, in the manner first expounded by Ashby and Jephcott, has considerable application in the study of high density plasmas. It was very beautifully demonstrated by these workers that the laser acts as the source for the interferometer as well as the detector. The phase information, usually found in "fringe shifts" in conventional interferometers shows up as amplitude modulations of the laser output. Following their initial work, we have shown and will show today that the sensitivity can be improved considerably by using spherical mirrors for the cavity containing the unknown plasma.

The principles of the laser itself are well known and need not be discussed here in detail except to remark the following: The number of transitions from the upper state of the laser to the lower state per unit of time is proportional to the intensity of radiation inducing these transitions. Thus, if we add radiation at the same frequency as the laser to that already existing inside the laser, then the laser output will increase or decrease depending upon the phase of the external radiation with respect to the initial laser field. The means for doing this is shown in Fig. 7. The output of the laser at M_2 is reflected by mirror M_3 back to the laser cavity M_1 and M_2 . If $I_1 = I_0$ with mirror M_3 removed, then $I_1 = I_0 + \Delta I$ if the feedback adds in phase with the initial laser field, and correspondingly $I_1 = I_0 - \Delta I$ if the phase is 180° .

$$\frac{2nd}{\lambda_0} = \left\{ q + \frac{1+m+p}{\pi} \cos^{-1} \left[1 - \frac{d}{b_3} \right]^{1/2} \right\}$$

where: m, p, q = mode indices of $TEM_{m,p,q}$ mode

n = index of refraction

λ_0 = operating wavelength of laser

Figure 7. Means for Modulating the Amplitude of the Laser Output

Now to follow a single wave train bouncing back and forth between M_2 and M_3 is difficult if not misleading. A more correct way of stating

this is that the mirror system $M_2 - M_3$ forms a high Q optical cavity, whose resonant frequency depends upon the index of refraction of the optical path of E_2 and the geometry of the cavity. The phase and the amplitude of the signal fed back to the laser cavity depends upon the proximity of the laser frequency to resonant frequencies of the reference cavity. The resonant frequencies for such optical cavities were derived by Boyd, Gordon, and Kogelnik and are given by the formula on Fig. 7. The quantities (m,p,q) are mode indices describing the field configuration of the $TEM_{m,p,q}$ mode inside the reference cavity. The quantity n is reserved for the index of refraction of the medium. Thus if we change d or n with time, the resonant frequencies of the passive cavity will shift past the laser frequency, and the laser output will be amplitude modulated.

Figure 8 shows what type of signal can be expected. Here the distance d is changed slightly by placing a cheap loudspeaker on the bed supporting the mirrors. The output I_1 is detected by a FW-118 photomultiplier and presented on the oscilloscope as the bottom trace. The scope itself was triggered by the audio voltage, (shown as the top trace) and the bottom trace represents the laser output synchronized to the driving force. Note that the pattern is symmetrical with respect to the place where the mirror changes its direction of motion. The second picture is the same as the first but with an expanded time scale. Each time the distance d changes by a suitable amount so that a different mode is excited in the reference cavity, the laser output exhibits one cycle of modulation. In analogy to the microwave bridge interferometer, this modulation is referred to as "fringes."

Figure 8. Laser Output Modulated by Audio Frequency Vibration of the Mirrors

One can also observe these modulations by changing the refractive index of the medium between M_2 and M_3 . This is the technique used for plasma diagnostics and is shown in Fig. 9. Here the gas to be ionized is located in a quartz cylinder, surrounded by a one-turn coil, and placed in

the reference cavity described previously. The discharge of a capacitor bank through the one-turn coil forms the well-known "theta pinch" producing nearly total ionization in gas. The plasma then relaxes back to its un-ionized state. The previous formula for the resonant frequencies of the passive cavity can be written as shown for the particular case described here. As the electron density changes with time, the various resonant frequencies of the passive cavity sequentially coincide with the laser frequency, and I_1 exhibits the modulations described previously. Going backwards, then, we count the number of "fringes" relative to $t = \infty$ after the plasma has been produced and equate this to the changes in mode indices m, p, q of the passive cavity. Thus the plasma frequency and the electron number density are determined.

$$2 \left\{ \frac{n_p L + n_g (d-L)}{\lambda_0} \right\} = q + \frac{1+m+p}{4}$$

$$n_p \cong 1 - \frac{1}{2} \frac{\omega_p^2}{\omega^2}$$

$$\omega_p^2 = \frac{N e^2}{m \epsilon_0}$$

$$\frac{\omega_p^2}{\omega^2} = \left\{ \Delta q + \frac{\Delta m + \Delta p}{4} \right\}$$

Δ = change in mode indices

Figure 9. Laser Modulation Technique
for Plasma Diagnostics

However, there is an uncertainty here. If these fringes are due to a change in q , then one fringe is equivalent to a change in electron density of $4.84 \times 10^{15} \text{ cm}^{-3}$. On the other hand, if the changes are due to m or p , the change in electron density is $1.2 \times 10^{15} \text{ cm}^{-3}$. This is quite important; changes in m and p are 4 times as sensitive as changes in q , if and only if the following applies.

- (1) The transverse modes are resolvable, i.e.,

$$\frac{f_{m,p,q}}{Q} < f_{m+1,p,q} - f_{m,p,q}$$

Q = quality factor of the cavity.

- (2) The transverse modes are excited!

These are questions which can only be answered through laboratory experimentation. The results of using hydrogen gas at 0.3 mm Hg base pressure is shown in Fig. 10. The top trace represents the current through the theta-pinch coil, whereas the bottom trace represents the laser output. The difference in the character of the fringes here and previously shown is due to the fact we have introduced extra-surfaces in this geometry, and the resonances are not as sharp.

(a)

(b)

Figure 10

Fringe Information Display for
a Theta-pinch in Hydrogen Gas
at 0.3 Torr Base Pressure

In both pictures, the increase of the photomultiplier output near the active portion of the discharge is due to the incoherent light emitted by the hydrogen plasma. The bottom picture was taken under the same conditions as the top. The periodic variations of the laser output are the "fringes." The relatively smooth curve in this bottom picture represents laser plus plasma light when the Q of the reference cavity was spoiled by inserting a diffusive material between M_3 and the theta-pinch tube. That fringes are observed is clearly seen; however, one cannot easily distinguish between change in the longitudinal mode index q and the transverse indices m, p . An independent measurement must be performed.

Fortunately, in hydrogen at these pressures, an independent measurement of electron density is available - Stark broadening of the hydrogen. Such a comparison was made at 0.2 mm Hg utilizing the broadening

of H_{β} , and the results are shown in Fig. 11. As one can see, an agreement can only be obtained if one associates these fringes with the changes in transverse mode indices. Hence this technique can be used in a straightforward manner to measure electron densities in any plasma; the "if's" have been answered in the affirmative.

TIME 10 ⁻⁶ sec	ELECTRON DENSITY in 10 ¹⁸ cm ⁻³		
	STARK BROADENING	LASER	
		TRANSVERSE MODES	LONGITUDINAL MODES
60	51	51	20.4
70	37	3.8	15.2
80	25	2.5	10.0
90	205	1.87	7.48
100	1.2	1.19	4.76

Figure 11. Comparison of Measured Electron Densities in Hydrogen at 0.2 Torr

Finally, Fig. 12 shows the character of the fringes when the plasma is located in a tube 30 cm long with Brewster angle windows. The plasma here was produced in xenon at 1 Torr, with a sweep speed of 50 μ sec/cm. If we associate the fringes with the electronic contribution to the index of refraction, then each fringe equals a change of 8.7×10^{14} cm⁻³ electrons. There are 21 fringes here from $t = \infty$ to $t = 50$ microseconds, after the initiation of the discharge; hence $N = 1.82 \times 10^{16}$ cm⁻³ at $t = 50$ microseconds.

Figure 12
Fringes in Tube 30 cm Long
with Brewster Angle Windows
for Xe Plasma at 1 Torr

Let me close by a few remarks:

1. The factor 4 in the formula presented earlier is only one of many choices. For the particular case for our laser, cavity, and mirrors,

this represents a condition of high degeneracy in frequency between the possible modes in the reference cavity, as well as a degeneracy between the laser frequencies and the reference cavity. By suitable selection of the distance d in the reference cavity, the arc cosine term can yield non-integral values, and the frequency degeneracy between the various modes in the reference cavity is destroyed. Under these circumstances, the nearest neighbors, in a resonant frequency plot versus frequency, need not possess the identical longitudinal mode indices. As a consequence, the frequency separation between adjacent modes in the reference cavity is much less than the frequency separation between modes with the same q or longitudinal mode index. Thus even smaller values of the change in index of refraction can be measured using this variation. Very recently we have succeeded in making measurements down to $2 \times 10^{14} \text{ cm}^{-3}$ over a 30-cm path using this technique. The details will be published in the near future.

2. Finally, let me remark that this technique can only measure changes in the total index of refraction integrated along the optical path. The index of refraction is related to the number of electrons; and the number and polarizability of the remaining constituents in the plasma, i.e., the neutral atoms in the ground and/or excited states as well as the corresponding states in a multielectron ion. The contribution of the neutrals, excited atoms, and ions to the index of refraction of the hydrogen plasma can be neglected. The validity of this neglect for xenon is debatable.

3. Very small losses of electromagnetic energy at optical frequencies are extremely difficult to make. It appears feasible at the present time to measure both the real and imaginary parts of the index of refraction. For a 20-cm path, the limits are:

$$n = n_r - j\psi$$

$$\Delta n_r = \frac{\lambda_0}{8\ell} \sim 7.25 \times 10^{-7} \text{ (1 "fringe")}$$

$$\Delta \psi = \frac{\lambda_0}{4\pi\ell} K \sim 4 \times 10^{-9} \text{ (double the loss)}$$

where K = fixed losses in the cavity, $\sim 1\%$.

This work has been supported by the Signal Corp.

V-2. EXPERIMENTAL DATA FOR ANALYSIS OF THERMIONIC CONVERTERS*

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The thermionic converter family tree is shown in Fig. 1. Although several modified configurations have been suggested, the cesium vapor converter reigns supreme at the moment. The terminology used to describe the various modes of operation of such a converter is not well standardized at the present time. In this paper the definitions given by R. Breitwieser are used, and include "space-charge," "ignited," and "arc."¹

THERMIONIC CONVERSION

Figure 1. Family of Thermionic Converters

*Partially supported by the Research and Technology Division, Air Force Systems Command.

While the space-charge and ignited modes are comparatively well understood theoretically, the arc mode is not.^{2,3} References 2 and 3 treat the ignited mode by Breitwieser's definition even though the authors use the term "arc." In the space-charge mode the saturation current is limited by space charge effects when the emitter is electron rich; at the very close electrode spacing (5-10 microns) space charge theory can be used to calculate current voltage curve. When the emitter is ion-rich, the saturation current is given by the data due to J. M. Houston and as extrapolated by W. B. Nottingham for a given emitter material, emitter temperature, and cesium reservoir temperature.^{4,5}

In the ignited mode the emitter is electron-rich. Volume ionization effects, either gradual or abrupt, reduce the electron space charge and permit the saturation current to flow. However, in the arc mode volume ionization effects produce a condition in which the current may exceed the saturation value by an order of magnitude as reported by V. C. Wilson and J. Lawrence.⁶ This behavior is not well understood, but such reasons as the effect of a strong field on the surface which is composed of work function patches, and an increased arrival rate at the emitter due to high ion currents from the plasma, have been suggested.

Figure 2 shows the potential diagram for the space-charge mode with an electron-rich emitter condition. Figure 3 shows the potential diagram for the ion-rich space-charge mode, the ignited mode, and the arc mode. The only difference in the diagram for the various mode conditions would be the magnitude of ion sheath at the emitter surface.

Figure 2. Potential Diagram for Space-Charge Mode

Figure 3. Potential Diagram for Ignited and Arc Modes

Typical Converter Data

Typical current-voltage (I-V) characteristics for a tantalum emitter at 1775°K are shown in Fig. 4. At 513°K an ignition voltage is required to trigger the arc mode. All of the curves indicate arc mode because the currents in the steep portion are greater than the saturation values given in Reference 5 for an ion-rich emitter. Figure 5 shows all three modes - space-charge, ignited, and arc. High frequency oscillations exist where the traces are unsteady.

Figure 4
Typical Low Temperature Current-Voltage Characteristic

Figure 5. Typical High Temperature Current-Voltage Characteristic

In the analysis of converters it is useful to measure the reverse current at large negative voltages because, if made under the proper conditions, this data can yield information about the emitter work function, the collector work function, and the sheath condition at the emitter surface. Figure 6 shows some typical data taken at constant cesium temperature, T_{CS} , and collector temperature, T_C , as a function of emitter temperature, T_E .

Figure 6
Reverse Current
Data

High frequency oscillations are observed at some conditions of operation - Fig. 7 shows a typical oscillogram. The frequency of oscillation

Figure 7. Oscillogram of Plasma Oscillations.
 $T_E = 1800^\circ K$; $T_{CS} = 473^\circ K$; $d = 1.0$ mm.

can be shown to be related to ion transient time. The peak excursions in voltage and current of some recent data have been plotted on the steady state I-V curve in Fig. 8. The study of oscillations gives useful information on the type and magnitude of potential distributions which exist within the interelectrode space.⁷

Date - 7 May 1963

$T_E = 1800^\circ\text{K}$

$T_{Cs} = 473^\circ\text{K}$

$d = 1.0 \text{ mm}$

$T_C = 425^\circ\text{C}$

R (Ω)	V (v)	I (ma)	R (Ω)	V (v)	I (ma)
10.036	1.57	156	0.936	0.35	374
9.036	1.50	166	0.836	0.34	407
8.036	1.44	179	0.736	0.32	434
7.036	1.33	189	0.636	0.30	473
6.036	1.20	199	0.536	0.29	540
5.036	0.94	187	0.436	0.28	640
4.036	0.76	189	0.336	0.27	801
3.036	0.62	204	0.236	0.26	1100
2.036	0.49	241	0.136	0.25	1840
1.036	0.36	348

Figure 8. Current-Voltage Characteristic with Oscillations Present

Another potentially useful tool for analysis of the converter is the spectrograph. Figure 9 shows some typical spectrograms taken in the various modes of operation:

- A - space-charge with wide slit
- B - space-charge with narrow slit
- C - space-charge with oscillations present
- D - arc

Details of this work are published in the literature.^{8,9}

Figure 9. Spectra for Various Operating Modes

Research Devices

The ideal research device for study of the conversion process should be flexible to permit the types of measurements described previously over a wide range of T_E , T_{CS} , T_C , and electrode spacing, d . The emitter should have a guard ring to define accurately the emission area. A window or windows should be provided for spectroscopic studies. The insulator design should permit the measurement of small reverse currents by eliminating leakage currents. Figure 10 shows one design of such a device which has all of these features. It would also be desirable to have demountable emitter and collector assemblies to increase further the flexibility of the device.

Figure 10. Flexible Research Device

Analysis of Some I-V Characteristics

Recently I-V characteristics have been obtained on a planar molybdenum emitter and a slotted tantalum emitter. The emitters were compared in an experimental converter as shown in Fig. 11. The converter was heated by an electron gun as shown in Fig. 12. The slotted emitter was investigated on the basis of previous results obtained on a capillary type emitter structure as shown in Fig. 13.^{1,9,10,11} The slotted emitter is shown in Fig. 14 - there were 40 slots, 0.35 mm wide and 2 mm deep, across the 2 cm diameter emitter surface. The excess area factor was 8.9.

Figure 11. Experimental Device for Comparison of Planar and Excess Area Emitters

Figure 12. Heating Arrangement for Experimental Device

Figure 13. Capillary Emitter. Tantalum Multicapillary (X12)

Figure 14. Slotted Emitter

Typical data from the planar emitter are shown in Figs. 15 and 16. In the ion-rich condition there is a lack of sensitivity to spacing. In marked contrast, the electron-rich condition is quite sensitive to spacing.

Figure 15. Effect of Spacing in the Ion-Rich Condition

(a)

(b)

Figure 16. Effect of Spacing in the Electron-Rich Condition

Results are summarized in Fig. 17 - the current values plotted are the zero voltage or short circuit values from the data. The "zero field" line is indicated - at this emitter temperature the ratio of electron to ion current from the emitter is theoretically 492, exactly as required to eliminate any space charge effect.

Figure 17. Comparison of Theory and Experiment on Planar Molybdenum Emitter

Typical data from the slotted emitter are shown in Fig 18. If these curves are compared with Fig 15, it can be seen that the slotted emitter, for a given T_{CS} , remains electron-rich to a higher emitter temperature than the planar surface. Also other data shows that, for the same T_E and T_{CS} , the electron currents are higher. If the electron current data are plotted in the same form as Fig 17, the performance of the slotted emitter is seen to be limited by the excess area factor as seen in Fig 19. Also electron-rich operation is seen to extend about 300°K above the zero field temperature of 1375°K.

Figure 18 Current-Voltage Characteristic for Emitter Temperature of 1600°K and Cesium Temperature 473°K

Figure 20 shows the results at a higher cesium temperature, 523°K. From this data it appears that the slotted emitter emission is governed by a random current theory when not limited by the excess area factor. In the random current theory it is postulated that a thermal plasma of cesium vapor exists within the slotted emitter cavities. The electron current which can be extracted is then:

$$I_e = (N_e e \bar{v})/4$$

where

N_e = plasma density determined by the cesium atom density and the Saha equation

e = electronic charge

$\bar{v}$ = average kinetic velocity based upon the emitter temperature

Details of this theory may be found in the literature 9,10,12

Figure 19. Comparison of Theory and Experiment at $T_{Cs} = 473^{\circ}K$

Figure 20. Comparison of Theory and Experiment at $T_{Cs} = 523^{\circ}K$

Conclusion

It appears that the electron emission from a cesiated cavity type emitter is governed by a random current theory when the total wall current is equal to or greater than the random current leaving the cavity. It is planned to obtain additional data on ion currents; by comparing the experimental values with the random current theory and the theoretical Saha-Langmuir values, additional information will be obtained on the theory of operation of the cavity type emitter in a thermionic converter.

Acknowledgement

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V-3. EXTENDED SURFACE THERMIONIC CONVERTERS*

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Among the devices for direct energy conversion, the thermionic system has been considered to be most promising in terms of low weight-to-power ratio and conversion efficiency.¹⁻³

Since the use of extended surfaces has been commonplace in the apparatus for energy transfer in the form of heat,⁴ it is logical to expect that further improvement in the weight-to-power ratio of a thermionic system can be achieved through the use of extended surface electrodes as shown in Fig. 1. The feasibility of such a system is further strengthened by the fact that the current density in the metallic electrodes J_m is limited by the thermionic current density in the gap J_g . It is readily shown that for a metal, the ratio of permissible current densities is given by:

$$\begin{aligned} J_g/J_m &= [(4\pi me/h^3)k^2T^2 \exp(-e\phi/kT)]/[(\pi me/2h^3)\mu_F^2] \\ &= (8k^2T^2/\mu_F^2) \exp(-e\phi/kT) \end{aligned} \quad (1)$$

as a maximum, where m is the electronic mass, e is the electronic charge, h is the Planck constant, k is the Boltzmann constant, T is the absolute temperature, ϕ is the thermionic potential, and μ_F is the Fermi level of the solid. For tungsten at 3000°K, $J_g/J_m \sim 10^{-8}$.

Figure 1. Extended Surface Electrode

It is also to be expected that due to the temperature gradient in the fins constituting the extended surface, additional irreversibility is introduced into the system when compared to that with plain electrodes.

*Patent pending, University of Illinois Foundation.

Therefore the price to be paid in reduced efficiency toward achieving increased output in a given cross sectional area of electrodes has to be carefully analyzed.

Basic Considerations

When applied to an element of an extended surface cathode of variable cross-sectional area $A(x)$ (Fig.2) with simultaneous heat and electron transfer, the method of irreversible thermodynamics⁵⁻⁷ gives the following energy equation:

$$\frac{d}{dx} \left(A \kappa \frac{dT}{dx} \right) + \frac{J^2 A}{\bar{\sigma}} - \tau J A \frac{dT}{dx} - (eV_c + 2kT - TS^*) \frac{1}{e} \frac{d(JA)}{dx} - P\bar{\epsilon} \sigma T^4 + P(W_g - W_h) = 0 \quad (2)$$

where x is along the plane of symmetry of the fin, κ is the thermal conductivity, T is the absolute temperature, J is the electric current density, σ is the electrical conductivity, τ is the Thomson coefficient, S^* is the Seebeck coefficient of the solid, $P(x)$ is the periphery, $\bar{\epsilon}$ is the emissivity of the surface, σ is the Stefan-Boltzmann constant, W_g and W_h are the energy flux of back radiation from the anode and the heat conducted by the cesium in the gap (Fig. 1) respectively. J can be obtained from

$$\frac{d(JA)}{dx} = p A_0 T^2 \exp(-eV_c/kT) \quad (3)$$

where A_0 is the coefficient of the Richardson-Dushman equation, V_c is the cathode potential shown in Fig. 3. The boundary conditions are: $x = 0$, $T = t_0$, $x = \ell$, $T = T_\ell$, $J_\ell = A_0 T_\ell^2 \exp(-V_c/kT_\ell)$. Solution of Eqs. (2) and (3) satisfying the boundary conditions gives the current and heat flow through a fin.

Figure 2
Element of Finned Electrode

Figure 3. Potential Diagram of a Thermionic System

Because of the distribution of temperature and current density over a fin, the efficiency of a system with finned electrodes can be calculated from (Fig.3)

$$\eta_f \sim \frac{(V_c - V_a) \int_s J_c dx}{\int_s \{J_c [V_c + 2(kT/e)] + \bar{\epsilon} \sigma T_c^4\} dx} \quad (4)$$

where subscripts c and a are for cathode and anode respectively and s is the surface of a complete pitch. This is to be compared to the efficiency of a system with plain electrodes,⁸⁻¹⁰

$$\eta_p \sim \frac{J_c (V_c - V_a)}{J_c [V_c + 2(kT/e)] + \bar{\epsilon} \sigma T_c^4} \quad (5)$$

with similar degree of approximation as made by Houston.⁹ It is seen that for a finned system, the temperature gradient along the fin contributes additional irreversibility. It can be further shown by the mean value theorems¹¹ that $\eta_f < \eta_p$ for either $T_{cm} \geq T_{co} > T_{cl}$ or $T_{co} > T_{cm} > T_{cl}$, where T_{cm} is the optimum cathode temperature for a system with plain electrodes as shown in Fig. 4.

Fins of Simple Geometry

It is shown in Fig. 5 that for practical operating conditions, the function in Eq. (2)

Figure 4. Typical Performance of a Converter with Plain Electrodes

Figure 5. $F(T)$ and Its Linearization

$$F(T) = A_0 V_c T^2 \left(1 + \frac{2kT}{eV_c}\right) \exp(-eV_c/kT) + \bar{\epsilon} \sigma T^4 \quad (6)$$

can be linearized, or

$$F(t) = aT + b. \quad (7)$$

When applied to a straight fin of thickness 2δ as shown in Fig. 6, and $W_g, W_h \sim 0$, Eq. (2) reduces to:

$$\frac{d^2T}{dx^2} = \frac{1}{\delta\kappa} F(T) = \frac{1}{\delta\kappa} (aT + b) = \left(\frac{\beta}{\delta}\right)^2 (T - T^*) \quad (8)$$

where $\beta^2 = h\delta/\kappa$ is a Nusselt number including electron transfer, h is the corresponding transfer coefficient, $a = h$, $-b/a = T^*$ (a characteristic temperature). Eq. (8) can be solved by introducing $\theta = T - T^*$, or

$$\frac{d^2\theta}{dx^2} = \left(\frac{\beta}{\delta}\right)^2 \theta \quad (9)$$

with $x = 0$, $\theta = \theta_0 = T_0 - T^*$; $x = \ell$, $-\kappa \frac{d\theta}{dx} \Big|_{\ell} = h \theta_{\ell}$. Eq. (9) gives a solution analogous to that of a heat exchanger fin.⁴

Figure 6
Straight Rectangular Fin

The current density per unit projected area of a finned system J_f can be expressed in terms of a ratio with that of a plain electrode system J_p

$$j = \frac{J_f}{J_p} = \frac{I_f}{2\delta J(T_0)} \frac{1}{2 + (d/\delta)} \quad (10)$$

where I_f is the current of a fin, d is the gap between electrodes, T_0 is the temperature at the root of the cathode. The efficiency of a finned system can also be expressed as

$$r = \frac{\eta_f}{\eta_p} = \frac{I_f}{2\delta J(T_0)} \frac{1}{\nu + 1 + (d/\delta)} \quad (11)$$

where $\nu = [\gamma \exp(2\Lambda) - 1]/\beta [\gamma \exp(2\Lambda) + 1]$; $\gamma = (1 + \beta)/(1 - \beta)$, $\Lambda = \beta \ell / \delta$, and

$$\frac{I_f}{2 \delta J(T_0)} = \frac{\ell \int_0^\ell J(x) dx}{\delta J(T_0)} + \frac{J(T_\ell)}{J(T_0)} + \left(1 + \frac{d}{\delta}\right). \quad (12)$$

The results of computations for a tungsten cathode with 100°K temperature drop at $T_{oc} = 3050^\circ\text{K}$ are shown in Figs. 7 and 8. Figure 8 further shows r' , the efficiency ratio for a radiant heat source including back radiation from the cathode. The efficiencies η'_p and η'_f are given by, for the same degree of approximation as in Eq. (5),

$$\eta'_p \sim \frac{J_c(V_c - V_a)}{J_c[V_c + 2(kT/e)] + \bar{\epsilon} \sigma T_c^4 + \bar{\epsilon}' \sigma T_c^4} \quad (13)$$

where $\bar{\epsilon}'$ is the emissivity of the back of the cathode, and

$$\eta'_f \sim \frac{(V_c - V_a) \int_s J_c dx}{\int_s \{J_c[V_c + 2(kT/e)] + \bar{\epsilon} \sigma T_c^4\} dx + s' \bar{\epsilon}' \sigma T_c^4} \quad (14)$$

Figure 7. Fin Height and Current Density Ratio

Figure 8. Efficiency Ratios for Various Fin Proportions

where s' is the projected area of each complete pitch s . Therefore

$$r' = \frac{\eta_f'}{\eta_p'} = \frac{I_f}{2\delta J(T_0)} \frac{1 + \bar{\epsilon}' \sigma T_0^4 / F(T_0)}{\nu + 1 + (d/\delta) + [2 + (d/\delta)] \bar{\epsilon}' \sigma T_0^4 / F(T_0)} \quad (15)$$

Figures 7 and 8 show that it is entirely feasible to have a large improvement in current output for a given projected area of electrodes which suffers little loss in efficiency; a typical combination would be with fins 0.5 mm thick and 1.5 mm long with the tungsten cathode at 3000°K and the anode at 600°K with a tip to root temperature drop of 100°K, giving $j = 2.1$, $r = 0.86$ for $d = 0.4$ mm.

It is also feasible to design for profiled fins (Fig. 9). Equation (2) now becomes:

$$y(x) \frac{d^2\theta}{dx^2} + \left(\frac{dy}{dx}\right) \frac{d\theta}{dx} - \frac{h}{k} \theta = 0 \quad (16)$$

where the profile is given by the function $y(x)$. Improved performance has been demonstrated by using trapezoidal fins instead of straight fins.

Figure 9
General Shape Profile
of a Straight Fin

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V-4. THERMIONIC ENERGY CONVERSION FOR DC AND HIGH FREQUENCY POWER OUTPUT

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The investigation of thermionic energy conversion shall provide information for in-pile experiments to utilize the fission heat for production of electrical power. Since the temperature for efficient conversion will be about 2000°C or higher, the choice of the reactor material is very limited. Probably uranium-zirconium carbide will be used. This material is also a very good electron emitter, but it disintegrates slowly by surface depletion of uranium. Materials like tungsten, tantalum or molybdenum might be used and are under investigation. Since the space charge of the electron emitter has to be neutralized, cesium, rubidium or potassium are used for ion production.

The resulting plasma is frequently the source of high frequency oscillations. The following investigations include the interaction of the plasma oscillations with the DC characteristics, as well as the comparison of cesium with potassium as ion sources.

Experimental Setup

In the experimental arrangement (Figs. 1 and 2) an electron gun is used to heat a tantalum button of 0.5 inch diameter to temperatures between 1700 and 2500°K. The tantalum button is welded to a tantalum diaphragm that separates the gun from the cell. Opposite the button is a molybdenum collector and guard ring. The emitter-collector distance is variable from zero to one-half inch by means of bellows and a micrometer head. The cell can be filled with alkaline vapor, the pressure of which is regulated by the temperature of an alkaline trap. An X-Y recorder permits one to apply a voltage from +6 to -6 volts at the collector, while the emitter remains grounded. A network of capacitances and RF chokes separates the high frequency or RF components from the direct current output. Identical networks were inserted for collector and guardring. The RF section was connected to an oscilloscope and a VTV voltmeter. The RF section could have an open circuit, or a short circuit to ground or be loaded with an inductance free resistance, in order to measure the RF power production.

Experiments and Results

Preliminary results with a potassium cell have been reported in a paper, "RF Oscillations and Power Output in Alkaline Thermionic Converters," by H. K. Richards, Symposium on Thermionic Power Conversion, Colorado Springs, May 1962, and the publication in "Advanced Power Conversion," Vol. 2, pp. 613-621 (1962).

Figure 1
Direct Conversion Cell
with Variable Emitter-
Collector Distance

Figure 2. Circuit Diagram of the Experimental Arrangement

The following tables and graphs use the symbols as given below.

EM T°K	emitter temperature in °K
N(Cs) or N(K)	atomic density of Cs or K
EM-COLL-DIST or ECD	emitter collector distance
J_E/J_i	emitter to ion current density
+3, 1, 0, -1 V	DC voltage applied to collector
KC	kilocycles of RF frequency
RMS	root means square voltage of RF
PM-DC, PM-RF	power maximum of DC and RF out- put in milliwatt (mw) or watt (w)
J_M/J_C	measured to calculated emitter current

Figures 3 and 4 show the results for cesium vapor, Figs. 5 and 6 for potassium vapor. The tables give the details for the graphs. In Fig. 7 some photographic pictures show the variation of frequency and amplitude as a function of emitter temperature and applied DC voltage.

NO EM-T°K	N(Cs)	EM-COLL. DIST-mm	$\frac{J_M - \text{ma}}{J_C - \text{ma}}$	J_E/J_i	0-V		-1-V		MP DC-mw	MP RF-mw
					KC	RMS-V	KC	RMS-V		
A 2160	$8 \times 10^{13}?$	1.5	46/48	79	220	1.6	?	0.5	43	-
B 2310	"	"	220/220	110	90	2.5	72	1.0	260	25
C 2371	"	"	390/420	140	85	3.0	70	1.2	450	50
D 2528	"	"	1300/1600	434	40	2.3	?	?	1275	160
E 2613	"	"	2600/3200	?	?	?	?	?	3012	400
F 2743	"	"	4800/7000	1200	?	?	?	?	5200	250

Figure 3. Results of Cesium Cell Experiments

NO EM-T°K	EM-COLL DIST-mm	N(Cs)	J/cm ² ma	J _E /J _I	0-V		-1-V		PM-DC mw	PM-RF mw
					KC	RMS-V	KC	RMS-V		
A 2445	2	6.8 x 10 ¹²	540	123	?	2.1	80	1.0	500	55
B "	1	"	"	108	200	2.0	200	1.4	500	40
C "	0.5	"	"	108	?	1.0	?	?	"	-
D 2571	2	8.2 x 10 ¹²	1000	124	1300	1.8	1200	1.1	960	60
E "	1	"	1200	156	220	2.0	?	1.2	1150	40
F "	0.5	"	1200	210	350	1.3	310	8	1150	-

Figure 4. Results of Cesium Cell Experiments

NO EM-T°K	N(K)	EM-COLL. DIST-mm	J_M/J_C	J_E/J_I	0-V		-I-V		PM-DC mw	PM-RF mw
					RF-KC	RMS-V	RF-KC	RMS-V		
A 2123	5×10^{12}	2.0	48/31	60	230	2.8	190	2.0	46	8
B "	"	1.0	58/31	92	270	1.8	230	1.0	67	3
C "	"	0.5	54/31	45	300	1.7	120	0.7	63	12
D 2341	6×10^{12}	2.0	280/310	93	?	2.6	50	1.8	322	60
E "	"	1.0	" "	70	?	0.5	2800	1.6 ⁴	325	16

Figure 5. Results of Potassium Cell Experiments

NO EM-T°K	N(K)	EM-COLL. DIST-mm	$\frac{J_M - m_a}{J_C - m_a}$	J_E/J_i	0-V		-I-V		PM-DC mw	PM-RF mw
					KC	RMS-V	KC	RMS-V		
A 2400	6×10^{12}	2	1000/320	131	?	2.6	?	1.4	1035	225
B 2453	"	1	1400/830	105	2000	1.9	1800	1.8	1500	40
C "	"	0.5	" "	87	?	?	?	?	"	9
D 2560	1.6×10^{13}	2	4200/2100	161	?	?	?	?	2600	120
E "	"	1	5000/2100	185	?	?	?	?	3400	-
F "	"	0.5	4800/2100	240	?	?	?	?	3600	-

To - EM: Mo - COLL.
COLL. ONLY

Figure 6. Results of Potassium Cell Experiments

Figure 7. Variation of Frequency and Amplitude as a Function of Emitter Temperature and Applied DC Voltage

As the graphs and tables show, emitter-collector distances, emitter temperatures, cesium or potassium densities were varied. The experimental results can be summarized as follows:

(1) The pressure did not exceed 10^{-2} mm Hg. As long as the electron density remained very much lower than the ion density, no oscillations were observed. The DC curves showed a knee at about -2.6 or -2.7 volts. Assuming a tantalum work function of about 4.2 ev, the collector work function would be 1.5 to 1.6 volts for the cesium layer on the molybdenum. The emitter-collector distance was first set at about 2 mm.

(2) At constant vapor pressure the emitter temperature and electron density were increased. RF oscillations were measured and portions of the voltage-current characteristics became negative. The wave shape, frequency, rms voltage and amplitudes were recorded. At low RF amplitudes the DC characteristics were identical for RF open (o) and RF short circuited (s).

(3) An increase in emitter current increased the negative characteristics. The DC characteristics varied now with the RF "o" or "s." Usually the DC characteristic with RF "o" showed a higher current, but in some instances RF "s" resulted in higher DC characteristics. At the same time the ratio of RF to DC power output increased, sometimes up to 20%.

(4) Ion currents were measured with a negative voltage on the emitter. The ratio of ion to electron current gave a certain indication as to whether the cell operated with a positive sheath or negative space charge. Even at high oscillation amplitudes the ratio was usually much larger than 1:500, i.e., a positive region.

(5) With further increase in emitter temperature the relative RF power output decreased again. At pressures of 10^{-4} - 10^{-3} mm Hg the emitter current remained much lower than saturation and the ratio of ion to emitter current decreased, indicating a negative space charge region. The maximum RF power output appears to be a function of the ratio ion to electron density.

(6) As the emitter collector distance is decreased to 1.0 mm, 0.5 mm and less, the RF amplitude, power output and effect on the DC characteristics decrease rapidly.

(7) With cesium densities higher than 10^{-2} mm the oscillations became weaker and disappeared completely.

(8) Observation of frequencies gave the following results: (a) The frequencies decreased if the voltage applied to the collector decreased. (b) The frequencies increased, as expected, with decreasing emitter collector distance. (c) Frequencies doubled or tripled sometimes as a function of applied DC voltage.

(9) The frequencies changed from nearly sinusoidal to pulses. The pulse amplitudes were frequently 5-10 volts, therefore, higher than the cesium and potassium ionization voltages.

(10) Comparison of cesium and potassium cells showed only very slight differences for tantalum emitters.

SESSION VI

Tuesday, November 5, 1963

ENERGY RESEARCH AND CONVERSION DEVICES

CHAIRMAN: M. HAMERMESH
Argonne National Laboratory

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VI-1. EVALUATING POWER SOURCES

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The task of selecting a power source or of comparing one device with another is not as simple as one might expect. One reason for this is the varying extents of development to which the new systems have been carried. More important, however, is the lack of common yardsticks to measure the virtues of a power source. Until the industry can come to some kind of an agreement on what characteristics everyone is to measure and as to how they are to be measured, exchange of really meaningful information in this field will continue to be impeded for lack of a suitable vocabulary.

One result of the variable or vanishing yardstick is that industry is slower than it might be to develop new power sources. Another result is that the really outstanding characteristics go unnoticed for lack of comparisons. A third result is a tremendous waste of manpower as scientists throughout the world try unsuccessfully to compare new results with inadequate, old information.

More often than once a year review articles appear on energy sources and how to evaluate them. On the subject of batteries alone, at least eight articles have appeared since 1960, and no two authors tackle the problems alike. One author says, "Some characteristics are difficult or impossible to measure." And, although most scientists agree that comparisons are desirable, there are a few who believe them unnecessary or even undesirable. Comparisons are deemed to be undesirable when they bring about an unwarranted emphasis of a device's weak points. For example, why consider the weight of a central power station when its uniqueness rests in low cost power?

A list of "Ten Characteristics Most Commonly Asked about Electrical Power Sources" is appended. Its purpose is to provide a check off list of questions with a few suggested answers. The list of characteristics is a result of years of experience with users of power sources. These are the properties asked about. The suggested answers in the listing are seldom given, however. Answers to inquirers seem to be unique with each inquiry. Some sort of flexible standardization is needed. Even the questions are far from exhaustive. Many more questions are asked and even the same questions are asked in different ways. Hence, any general agreement on the most important characteristics would be a scientific advance.

Notice also two broad classifications of characteristics: (a) those to which numbers can, or should, be assigned, and (b) those to which numbers are difficult or impossible to assign. Convenience items (No. 10) give examples of abstract characteristics. The "I like it" attitude is sometimes as real with power sources as it is with clothing and cannot be ignored. Sometimes the convenience items are the most important. Nevertheless, future efforts should be made to supply scientific dimensions for all characteristics.

One means for easing evaluations would be to include the dimensions of power and energy with each characteristic. Thus, sizes should be specified with more than cubic feet. Sizes should be specified also as ratios of power per unit size and energy per unit size. Sometimes this scheme is used but wider use would bring about more complete evaluations.

A common example of incomplete information is temperature coefficient of voltage for electrochemical devices. This has great thermodynamic significance but one should recognize that voltage coefficients alone are an incomplete evaluation. Voltages change only a few tenths of a per cent, or less, for each degree change in temperature. At the same time, current density might change several per cent per degree of temperature. Seldom can one find data on watts per degree or ergs per degree for various power sources. And yet these power and energy dimensions are essential for "Evaluating Power Sources."

Where possible, measuring dimensions are suggested for the tabulated characteristics. These dimensions are far from complete and they are oversimplified. Nevertheless, they illustrate the need for common yardsticks.

Ten Characteristics Most Commonly Asked about Electrical Power Sources

1. Size - Total power source, controls, fuel supply available space, auxiliary equipment, active materials (watts/ft³) or (kwhr/ft³)
2. Weight - Ditto for size. (watts/lb) or (kwhr/lb)
3. Cost - Ditto for size plus maintenance, fuel, replacement parts (\$/kw) or (¢/kwhr)
4. Temperature - Maximum and minimum for operation, storage, or starting (degrees)
 - Temperature coefficient, (volts/degree), (watts/degree), and (watt-hrs/degree)

5. Rate - Maximum power from a given system (kw/kwhr)
 - Start up time (minutes)
6. Life - How many kwhrs can be obtained from a kw of capacity (kwhr/kw)
 - Does power source change or deteriorate when not being used - Shelf life (years)
 - Does life depend on the way the power source is used (whrs delivered x hours used/whrs capacity) or (number of cycles)
7. Quality of Power - Constancy of voltage with constant or varying load or with varying temperature. (volts/watt) and (volts/watt-hr)
 - Voltage tolerance (maximum and minimum volts)
8. Reliability - Confidence that system will deliver necessary power without failure throughout the required time interval (failures per thousand devices per year)
 - Sensitivity to impurities in fuel, air, or the system (maximum weight per kwhr)
 - Ability to withstand vibration or shock (g's to cause failure)
9. Efficiency - Thermal or overall (electrical kwhr out/heat energy in)
 - Electrical or ideal (electrical kwhr out/free energy in)
 - Utilization (unconsumed fuel out/total fuel in)
10. Convenience - Primary energy source, noise, vibration, heat, noxious fumes, explosion, availability of material and parts, unattended operation, mobility, multiple use, skill required for operation and maintenance, interchangeability of power source.

VI-2. AN ACOUSTICALLY RESONANT STIRLING ENGINE

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An MHD generator which would produce an alternating current electrical output can be realized if a conducting working fluid is made to oscillate in a duct passing transversely through an external magnetic field. One possible means for obtaining an oscillating gas column is provided by the phenomenon of thermoacoustical resonance which utilizes thermal energy to produce an oscillating gas.

It was observed almost one hundred years ago that sustained acoustical oscillations can be produced when heat is supplied near one end of a column of gas.¹ More recently, such thermoacoustical oscillations have been observed by many investigators.²⁻⁵ One particular type of thermoacoustical oscillator has been examined by us in the light of its similarity to a single-cycle Stirling engine. A conventional single-cycle Stirling engine and its idealized pressure-volume and temperature-entropy diagrams are illustrated in Fig. 1. The regenerator portion of the engine serves to store heat such that a constant temperature expansion and compression occur in the ideal cycle. The analogous two-cycle piston loaded thermoacoustical engine is shown in Fig. 2. This engine is essentially comprised of two Stirling engines operating back-to-back. As in the conventional Stirling engine, the working piston is 90° ahead of the displacer piston in the operating cycle. If the pistons were replaced with an ionized gas, or any conducting fluid, work could be removed by MHD coupling. A four-cycle version of the thermoacoustical engine illustrated in Fig. 2 has been successfully operated, but with low efficiency.

Figure 1. Conventional Single-cycle Stirling Engine

Figure 2. Proposed Thermoacoustical Two-cycle Stirling Engine

The fundamental elements of an unloaded thermoacoustical converter are illustrated in Fig. 3. Heat is added at each end of the closed

tube and is removed in the center section, creating a large thermal gradient across the "regenerator." Maximum amplitude oscillations occur at the center plane of symmetry. It was experimentally observed that the amplitude of the oscillations was increased markedly when water vapor was present in the oscillating air.* The water droplets are vaporized by the heat in the closed end of the tube. After passing through the regenerator nozzles the vapor is condensed on the cool tube wall near the center. In Fig. 4 a proposed thermoacoustical converter is shown which takes advantage of the increased amplitude of oscillations resulting from the use of a condensable vapor in the working gas. Fluid return tubes cycle the condensed fluid back to the heated end to be revaporized in order to improve the efficiency of the conversion. Figure 5 illustrates two simple

Figure 3. Closed Thermoacoustical Converter

Figure 4. Thermoacoustical Converter with a Condensable Working Fluid

Figure 5. Thermoacoustical Converters

*This effect was first observed by Mr. R. Wren of the University of Missouri glass shop.

single-cycle thermoacoustical oscillators which are currently under investigation. Heat is supplied to the closed end by a gas flame in the case of the upper tube, and by an internal electric heater in the lower tube. The regenerator nozzles shown in the lower tube are found to be necessary for the sustainment of oscillations. Best performance is observed when short, small diameter glass tubes are used for the regenerator nozzles. For a two-inch diameter straight tube 44 inches long, oscillations of eighty cycles per second frequency and one inch peak to peak amplitude occur at the open end for a heater temperature of about 700°F. Maximum amplitude oscillations occur when the heat source and the regenerator nozzles are placed close together in the tube at about one-fourth to one-half of the length of the tube from the closed end. Increasing the heater temperature increases the amplitude of the oscillations while the frequency remains constant. The frequency of oscillations is primarily dependent on the configuration of the tube, that is, lengthening the tube decreases the frequency. Through heat balances taken first with the tube oscillating and then with the oscillations damped, the operating efficiency of the converter was determined to be on the order of 5%.

Figure 6. Idealized Thermoacoustical Converter

Analysis of the thermoacoustical resonance phenomenon to a first order approximation is depicted in Fig. 6. Here, the oscillator is broken into its acoustical components - a Helmholtz resonator and an organ pipe or simple tube. While this simple analytical approach is

intuitively attractive, it yields results which differ by a factor of two from observed values. Another instructive analog is found in an electrical oscillator circuit made up of a capacitance, inductance and a vacuum triode amplifier. In this electrical analog the triode displacement current corresponds to the movement of gas mass and the electron current corresponds to the energy transport. In common with the electronic oscillator, the detailed theory of the thermoacoustical conversion phenomenon depends on nonlinear relationships which must be carefully selected in order to obtain an analytical solution.

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VI-3. CONVERSION OF ALPHA PARTICLE KINETIC ENERGY INTO ELECTRICITY

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In 1958 Battelle initiated a study of a concept for converting the kinetic energy of fission fragments directly into electricity. With both in-house and industrial support, Battelle has since been conducting experiments and theoretical studies on this concept which has been named the "Triode" since three electrodes make up a unit cell - an emitter, a grid, and a collector. In 1961 Battelle initiated studies on an alpha-particle version of the Triode which was an offshoot of the fission fragment converter. The alpha electric cell experiments were first planned as a means to determine design parameters for the Triode. These experiments not only served the purpose intended but also showed that the alpha cell itself might prove to be a useful power source.

Introduction

An alpha-electric cell converts the kinetic energy of alpha particles directly to a high electric potential. Figure 1 is a sketch of the alpha-

Figure 1. Cylindrical Alpha Electric Cell

electric cell with cylindrical geometry. A source material, such as polonium-210 or other high-energy alpha emitter, is distributed in a thin layer over a surface which will be called the cathode. The emitting surface is capable of charging a collecting electrode, which will be called the anode. In time a retarding electric field is established and the positively-charged alpha particles do work against this field, i.e., their kinetic energy is transformed to available electrical energy.

The discovery that charged-particle emission can build up a voltage on a properly insulated electrode may be traced to work by Mosely in 1913.¹ The direct

application of this idea for a high-voltage generator has been considered by others during the past several decades, for example, the work of Linder and Christian at RCA.² However, a critical problem exists in reducing the concept to practice. Along with the emergence of the positively-charged alpha particles come secondary electrons which have opposing charge. Although these secondary electrons have very low energy (approximately 97% have energy less than 100 ev), they are produced in such abundance that their total negative charge more than offsets the positive charge buildup. Thus, under passive conditions a low-energy net negative charge, rather than the desired positive high-energy charge, is emitted from the cathode. The use of a properly designed control grid placed close to the cathode appears to be a method to overcome this difficulty. A negative potential applied to the grid can be utilized to repel the secondary electrons back to the cathode, as illustrated in Fig. 1. The grid can be designed to be almost completely "open," i.e., to intercept only a small fraction of the alpha particles traveling from the emitter to the collector.

Some Characteristics of the Alpha Electric Cell

Generator Efficiency. A cell with coaxial-cylinder geometry and polonium-210 source material has several operational features of meriting discussion. First, the maximum theoretical conversion efficiency as a function of anode voltage is

$$P = \frac{1}{2} \frac{VZ_0}{E_0} \sqrt{1 - \frac{VZ_0}{E_0}}$$

where E_0 , Z_0 are the initial energy and charge of the alpha particles leaving the cathode and V is the anode voltage. P is shown graphically as a function of the dimensionless voltage parameter $\beta = (VZ_0)/E_0$ in Fig. 2.

Figure 2
Efficiency Versus Voltage
for a Cylindrical Cell

It is seen that a maximum efficiency of about 19 per cent occurs for $\beta = 2/3$. Using as characteristic values $Z_0 = 2$ charges and $E_0 = 5$ Mev, the voltage at maximum efficiency in this ideal case is 1.7 megavolts, illustrating the voltage characteristic of the device. (It should be noted that the E_0/Z_0 ratio for alpha particles is approximately equal to that for fission fragments.)

Generator Size. Cylindrical cell size can be roughly estimated by considering the obtainable power density. One square centimeter of cathode surface with a 4-micron coating of polonium-210 contains about 16 curies. This provides a total possible charging current of

$$I_0 = 2 \text{ charges/disintegration} \times 0.5 \text{ particles emitted radially outward} \times 3.7 \times 10^{10} \text{ disintegrations per second per curie} \times 16 \text{ curies/cm}^2 \times 1.6 \times 10^{-19} \text{ ampere-second per charge} = 0.95 \times 10^{-7} \text{ ampere/cm}^2.$$

Operation at an average voltage of 10^6 volts (efficiency of about 10 per cent as shown in Fig. 2) will thus yield electric power of about 0.1 watt/cm² of cathode. For a cathode 2 cm in diameter by 30 cm in length, the power output of the cell would be about 20 watts. By using thicker coatings of alpha emitter, larger cathode area per cell, or multiple cells, one may readily increase the output to the 100-watt range with reasonable generator volumes.

Concept Limitations. An actual system would not perform as the ideal system which has been discussed. The ideal efficiencies are reduced by several factors, including (1) interception of a small fraction of alpha particles at the grid; (2) escape of a fraction of the secondary electrons formed at the grid (leakage to the anode); (3) attenuation of charge and energy of alpha particles in passing out of the emitter surface layer; (4) spread in energy of alpha particles due to varying degrees of attenuation in passing out of the emitter surface layer; and (5) ionization of residual gas between electrodes.

Several problems are presently recognized which might make the concept impractical. Such problems include (1) loss of alpha-emitter material as the alpha particles emerge from the surface. Studies of such "vaporization" by fission fragments have indicated that use of an oxidized surface may reduce this loss.³ Further, use of a thin barrier of non-emitting material deposited over the emitting surface may greatly reduce this loss; (2) attaining and maintaining high voltages (in the megavolt range) in the presence of alpha-particle bombardment and with a relatively low current may present problems not yet fully recognized; and (3) the safety and containment requirements associated with kilocurie quantities of alpha emitter.

The degree to which these problems will affect cell design and output will depend largely on the outcome of further experiments and analyses. At present, efforts are being concentrated on getting a working device on a laboratory scale. The results of the Battelle experiments to date have been encouraging and will be summarized.

Initial Experiments with the Alpha Cell

Apparatus. Preliminary proof-of-principle experiments using a polonium alpha emitter were performed in late 1962. Several curies of polonium-210 were distributed uniformly on a cathode $1/2$ inch diameter by 12 inches long. To minimize contamination of the equipment a thin gold foil (0.0001 inch thick) was wrapped over the bare polonium surface.

The cathode was surrounded by a squirrel-cage grid of 40 stainless steel wires 10 mils in diameter equally spaced on a 1.25-inch-diameter grid circle and supported at the ends. As shown in the photograph of Fig. 3, the grid-cathode assembly was installed into a concentric 4-inch ID anode cylinder electrically insulated by a quartz tripod. A vacuum chamber lowers over the apparatus and fastens to the base plate.

Figure 3. Experimental Arrangement

Figure 3 also shows the components of the high-voltage measuring apparatus. The measurement of anode potential is complicated by the fact that the measurement must be made without appreciable current drain, and that the voltage information must be transmitted outside the vacuum. Considerable effort was devoted to a study of different methods for voltage measurement until a satisfactory method was found. This method determines the anode voltage by measuring the increase in

energy of an alpha particle accelerating through the electric field set up by the anode. A description of this technique is given in the report AECU-3989.⁴ For the measurements, a 2-millicurie polonium-210 alpha source is mounted on the outer surface of the anode. A small gas-filled chamber (with variable gas pressure) containing a thin mica window and

a silicon-gold charged-particle solid-state detector is placed so that the detector can "see" the alpha source through the mica window. The small chamber is vacuum-sealed and connected by a 1/4-inch line through the test chamber base plate to a separate evacuating system. With this arrangement the pressure in the small chamber can be varied from a few microns to one atmosphere without affecting the vacuum in the large test dome. Measurements with the solid-state detector as the pressure is varied in the small chamber determine the range in air of the alpha particles from the anode. From the measured range and the well-known range-energy relationships,⁵ the energy of the alpha particle can be determined. The anode voltage is then simply the energy at this voltage minus the energy with the anode grounded divided by the charge on the alpha particle. This technique has the advantages that the measured energy increment, ΔE , is not very sensitive to either the initial energy of the alpha particle or the physical dimensions of the detector. While it is true that the voltage determination comes from taking the difference between two large numbers, analysis of the data and techniques indicate an accuracy of better than $\pm 10\%$. This accuracy is competitive with any other high-voltage measurement in the 10^5 to 10^6 volt range.

Alpha Cell Currents. The initial measurements consisted of measuring cell currents as a function of grid bias at zero anode voltage. To predict the cell currents, the following simplified relations for a large negative bias on the grid are useful.

$$I_{\text{cathode}} = [1 - (1 - x) f N_g] I_0$$

$$I_{\text{grid}} = -f (1 + N_g) I_0$$

$$I_{\text{net}} = [(1 - f) - x f N_g] I_0 = [1 - f (1 + x N_g)] I_0$$

where

I_0 = current carried from cathode by positively charged alpha particles,

f = fraction of alpha particles emerging from the cathode which strike the grid wires,

x = fraction of secondary electrons produced at the grid which escape the grid-cathode assembly,

N_g = charge ratio; the magnitude of the ratio of the secondary electrons produced at the grid to the charge of alpha particles striking the grid.

These relations are derived as follows. Considering first the grid current, the fraction f of the alpha particles striking the grid carry a current of positive charges of (fI_0) to the grid. These alpha particles striking the grid produce secondary electrons, so that a secondary electron current of $(fN_g I_0)$ is produced. Since the grid is at a large negative bias, all of these escape from the grid. The total current from the grid is the sum of these two components: $I_{\text{grid}} = - (fI_0) - (fN_g I_0) = - f(1+N_g) I_0$. The minus sign is assigned to this current according to the convention that a flow of positive charges from the cathode is a positive current. The cathode current also consists of two components. A current I_0 of alpha particles leaves the cathode, but a fraction $(1-x)$ of the secondary electrons produced by the few alphas which strike the grid returns to the cathode. The cathode current is then $I_{\text{cathode}} = I_0 + (1-x)(fN_g I_0) = [1 + (1-x)fN_g] I_0$. The net current from the grid-cathode assembly is the algebraic sum of the grid and cathode currents and represents the current available to charge up the anode. It will be noted that this charging current is diminished from the original alpha particle current I_0 by two factors. First, because of the physical interception of some alpha particles by the grid, only $(1-f)$ of the alpha particles escape from the grid-cathode assembly. Second, a fraction x of the secondary electrons formed at the grid escape to the anode and reduce the net flow of positive charge. Note that the loss in charging current is proportional to $f(1+xN_g)$. It is apparent that the interception fraction at the grid, the f -factor, must be as small as possible to minimize losses in the charging current.

Figure 4 shows how these currents would be expected to behave as a function of grid bias. Below about 100 volts on the grid, the energy distribution of the secondary electrons will affect the currents. At high negative grid bias, these currents should be independent of grid bias. Of course, it would be hoped that the grid current is small enough so that a positive net current is obtained from the device, i.e., $I_{\text{cathode}} + I_{\text{grid}} > 0$.

Figure 4
Variation of Current
with Grid Voltage for
an Ideal Triode Cell

The measured currents are shown in Fig. 5. As seen from these data, the cell currents were found to behave very nearly as expected in the ideal case. At grid bias greater than -500 volts, the currents are essentially independent of grid voltage. The cathode current is greater than the net current; and the charging current (the net from the grid-cathode assembly) is a positive current so that buildup of anode voltage could be expected.

Figure 5
Current as a Function
of Grid Bias

Other Experimental Results

Energy Distribution of Secondary Electrons. The energy distribution of secondary electrons formed at the cathode as the alpha particles emerge is reflected by the grid bias curve shown in Fig. 6. As seen from these data, more than half of the secondary electrons produced by the alpha particles are collected at the grid with a positive potential of 10 volts and nearly all are collected with 100 volts on the grid.

Voltage Buildup Experiments. To determine the high-voltage buildup limits of the apparatus, prior to inserting the alpha source, a special anode was installed on the quartz tripod inside the vacuum chamber with small cerium-144 - praseodymium-144 beta sources attached to the top of the anode. With beta emission, the anode charged up to 50,000 volts. At this voltage, microdischarging began which abruptly terminated further voltage buildup. Thus, prior to the alpha experiments, it was determined that the apparatus was capable of sustaining 50,000 volts without breakdown.

Figure 6. Grid Current Versus Grid Bias for Positive Grid Bias and Zero Anode Voltage

Voltage buildup with the alpha cell was measured for a variety of grid biases. A maximum of 50,000 volts was obtained in these initial experiments which was the upper limit of the equipment and sufficient to prove the principle of operation. A grid voltage of -800 volts was sufficient to maintain this potential. It was observed that microdischarges were again responsible for the limitation in voltage buildup, but the experiments have not progressed to the point where it can be said with surety whether these microdischarges are occurring across the vacuum gaps in the apparatus or down the quartz legs supporting the anode. Observations have shown that this microdischarging is a threshold phenomenon, i.e., essentially no microdischarges occur until the voltage attains a critical value, at which voltage the microdischarging is initiated with a frequency such that the current leakage in the discharging just matches the charging current.

Effect of Pressure on Voltage Buildup. The effect of test chamber pressure on the maximum voltage buildup was briefly examined and some rather interesting phenomena observed. Figure 7 shows the effect of pressure on voltage buildup using a beta emitter to charge up the anode. As seen from these data, the anode voltage was independent of pressure below about 10^{-4} mm Hg. Between 10^{-4} and 10^{-3} mm Hg the voltage dropped to zero. Then at 10^{-3} mm Hg, it increased rapidly to about twice the high-vacuum value. Further increase in pressure caused a rapid decrease to zero voltage again. This rather anomalous behavior is roughly the same as that which was observed by Linder and Christian at RCA using a beta emitter.² The peak in voltage may be due to a surface condition effect on secondary electron and ion emission. The rapid decrease in voltage above 10^{-3} mm Hg is apparently due to ionization of the gas.

Figure 7. Anode Voltage Variation with Pressure

The same experiment was repeated with the alpha cell, with results as shown in Fig. 8. As seen from these data, again below 10^{-4} mm Hg pressure the anode voltage was constant. The behavior above 10^{-4} mm Hg was qualitatively the same as observed with the beta device, i.e., with increasing pressure, the voltage first decreased, then peaked and finally dropped to zero above 10^{-3} mm Hg. However, near 10^{-3} mm Hg a few gross discharges were observed, and the pressure-voltage curve contained additional peaks.

Figure 8. Alpha Cell Anode Voltage Variation with Pressure

Except for these studies of voltage behavior with pressure, all experiments have been performed at pressures in the 10^{-7} to 10^{-6} mm Hg pressure range. However, it appears from the data accumulated to date that only 10^{-4} mm Hg pressure is required for the operation of the alpha cell.

Although the f -factor and amplification factor are critical to grid design, several other factors may have significant influence on grid design. Examples of such factors are:

(1) Dependence of secondary electron yield at the grid on grid wire material. [Since losses are proportional to $f(1 + xN_g)$, in addition to minimizing f , it is desirable to choose grid wire material to minimize N_g , or hence the secondary electron yield at the grid.]

(2) Dependence of secondary yield on electric field. For secondaries produced at the grid wires at locations exposed to the anode field, a significant increase in electron emission might occur due to the electric field. Depending on the importance of this effect, it might be desirable to use wire shapes other than cylindrical.

(3) Gamma-induced secondary electron emission. For alpha emitters such as polonium-210 which have very weak associated gamma radiation, the electron production due to the gamma radiation can generally be ignored.

(4) Structural strength of grid. At large anode voltage, the electrostatic force of attraction between anode and grid is sufficiently strong to deflect the grid wires if they are constrained only at the ends of the grid. The use of containing rings spaced along the squirrel-cage grid minimizes this deflection.

In general, further experiments will be required to determine the importance of these effects to grid design.

Microdischarges

The present theoretical and experimental status of high-voltage breakdown across a vacuum gap indicates that a critical current of the order of 10^{-4} amps is required to initiate breakdown.⁶ Interchange of current between electrodes at values below the critical current occurs in the form of microdischarges. It has been suggested⁷ that the microdischarges are due to particles or clumps of foreign material ejected from the electrode surfaces by the electric field. Whatever the mechanism, simultaneous observation of microdischarges with voltage buildup with betas indicated that the discharges first occur at about 50 kilovolts, and then occur with increasing frequency up to a limiting voltage of

approximately 100 kv. Presumably, at this voltage, the leakage current contained in the microdischarges offsets the charging current. In the alpha cell experiments, the voltage never exceeded the threshold voltage for onset of microdischarging of about 50 kilovolts. The appearance of the very definite threshold voltage for microdischarging explains the sudden stop in voltage buildup with time in the initial experiments.

Summary of Alpha Cell Experiments

To summarize the experiments with the alpha cell, the initial experiments gave a voltage buildup of 50,000 volts, which was very encouraging. This was sufficient to prove the principle of operation and to permit extraction of values of design parameters. Required future studies are to determine and eliminate the source of microdischarging and to extend the voltage buildup to the megavolt range.

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VI-4. THE LIQUID METAL LINEAR GENERATOR

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The utilization of nuclear heat energy in the production of electricity for specialized purposes, such as satellite power supplies, suggests the application of liquid metals to this task. Conceivably our technology will be capable of producing reactor cores operating at temperatures in the range 1000 - 1100°C in the near future. At such temperatures the physical properties of liquid metals make the operation of vapor cycles possible. If the vapor cycle is applied to producing motion in a liquid metal stream, the moving liquid metal can be passed directly through a magnetic field where electrical energy can be extracted.

For example, in Fig. 1 the vapor pressure of sodium is plotted as a function of absolute temperature.¹ At 1100°C the vapor pressure for sodium is equal to 6 atmospheres (88.2 psia). For potassium the corresponding pressure is estimated to be about 140 psia. From this it is apparent that one can apply a heat source of this type to produce a supply of moderate pressure vapor. The vapor can now be expanded through a nozzle to convert a portion of the enthalpy of the vapor into kinetic energy. Conventionally, the high speed vapor could be used to drive the blades of a turbine to supply motive power to a generator. On the other hand, the vapor expanded through the nozzle can be used to directly propel a column of liquid metal. Such a

scheme is shown diagrammatically in Fig. 2. Here we can see the heat source used to produce the vapor which is led to an expanding nozzle in a jet pump or injector. In this device, the vapor impinges upon and condenses in a liquid metal stream in a constricted region and the fluid achieves a relatively high velocity. In this region, if a proper condensing shock is formed, one may take advantage of the high fluid velocity to extract electrical energy by allowing the liquid to pass through the generator. Following this, the fluid enters a diffuser where its velocity drops to moderate values. The fluid is then passed at some

Figure 1. Sodium Vapor Pressure as a Function of Temperature

Figure 2. Schematic Diagram of an MHD Circuit

velocity through a heat rejection unit after which it re-enters the jet pump region. The details of the jet pump are shown in section in Fig. 3. In this figure, one can see the annular arrangement surrounding the periphery of the vapor nozzle portion. This region is the one where the liquid velocity is increased before the fluid enters the combining section. A portion of the fluid is drawn off beyond the jet pump and returned to the heat

source as makeup for the vapor introduced into the circuit.

Figure 3. Cross Section of a Jet Injector

Although it is recognized that the traditional efficiency of an injector has always been low, the recirculating system is being studied with the objective in mind that if reasonably good liquid velocity can be attained it may be possible to increase the efficiency. This possibility is suggested from an examination of turbine efficiency curves as a function of bucket-to-steam-velocity ratio.² The efficiency of a turbine rises as this ratio is increased and reaches a maximum in the vicinity of 0.5. That is when the bucket is moving at half the speed of the impinging steam. It is apparent, of course, that for this type of a ratio, the hydraulic losses would become very important and the design of the system would have to take this into account.

The experimental effort to study this configuration has been started and equipment constructed to operate initially with steam and water. The apparatus is shown in Fig. 4. The jet pump is located at the top with the heat exchanger mounted below. The equipment was designed to permit changes in the relative positions of components and the positioning of the loop. A turbine flowmeter is located in the system to measure the flowrate of water and thermocouples are positioned throughout to provide proper

heat balances. In addition, a throttling valve has been incorporated in the line to simulate the effect of the generator.

Figure 4. Photograph of Laboratory Equipment

If one considers the operation of a circuit of the type described during operation at equilibrium a force balance taken over the system yields the function:

$$F_u = F_e + F_f$$

where F_u is the vapor impact force, F_e the electrical retarding force, and F_f the additive hydraulic force. Then,

$$\frac{W}{g} = \frac{u_1 - u_2}{A_n} = \frac{6.357 \times 10^{-11} B^2 \ell^2 u_2}{RA_n} + \frac{0.1 (u_2^2 - u_3^2) \rho}{144g} + \frac{2fLu_3^2 \rho}{144gD}$$

where $f = 0.04 (\text{Re})^{-0.16}$.

Here, the term on the left is equal to the driving pressure of the impinging steam. The first term on the right is the total electrical load, while the second is the loss load in the two sections of changing cross section. The final term is simply the hydraulic loss in the remainder of the circuit. If this equation is applied to the simple pumping circuit, the term for electrical force can be dropped and a comparison of experimental data can be made. At the time of writing a preliminary run was made. The measured velocity of fluid showed that the liquid attained a velocity of 78 ft/sec in the constriction of the test section. The corresponding vapor velocity for this is equal to 420 ft/sec. It appears that this velocity is lower than one would expect. Estimates indicate that this velocity should be at least 914 ft/sec. On this basis, the conversion of steam kinetic energy to liquid kinetic energy is of the order of 20%. Further tests of this unit will be made before operation with liquid metal is begun.

The inefficiency encountered in a system of this type can come from several sources. Primarily, the major losses may be caused by: (1) decrease in steam enthalpy due to heat loss, (2) turbulence in nozzle and impact area, and (3) slip between vapor and liquid. These are in addition to the hydraulic losses. The first step in the program, consequently, is aimed at optimizing the conditions to produce the flow.

Finally, when the experiments are converted to liquid metal operation it appears that a number of techniques can be used in an effort to decrease hydraulic losses. Primarily, these are: (1) boundary layer injection of vapor to reduce wall friction, (2) ultrasonic cavitation produced at the boundary in an effort to induce the liquid to supply its own lubricating vapor,³ and (3) reduction of flow turbulence loss by magnetic fields parallel to the flow direction.^{4,5}

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