Int. J. Heat Mass Transfer. Vol. 14, pp. 1927–1949. Pergamon Press 1971. Printed in Great Britain

# HEAT TRANSFER IN THE SEVENTIES

**R. H. SABERSKY**
California Institute of Technology, Pasadena, California, U.S.A.

(*Received* 15 *April* 1971)

## TABLE OF CONTENTS



## ACKNOWLEDGEMENTS

The survey reported herein has been conducted under the auspices of the National Science Foundation whose support is gratefully acknowledged.

This survey has been made possible through the cooperation of the many persons whose advice I sought and who have responded most generously by supplying information and offering suggestions. The subsequent listing is to be a token of my sincere thanks and appreciation.

Contributors who supplied information through extensive written memoranda and prepared statements

| | |
|---|---|
| K. J. Bell | F. Landis |
| H. Brauer | S. Levy |
| J. A. Clark | A. L. London |
| A. E. Duckler | A. V. Luikov |
| E. R. G. Eckert | T. Mizushina |
| K. T. Feldman | A. C. Mueller |
| T. H. K. Frederking | S. Ostrach |
| R. J. Goldstein | W. M. Rohsenow |
| U. Grigull | R. A. Seban |
| R. Greif | J. H. Seely |
| W. B. Hall | M. C. Shaw |
| G. F. Hewitt | E. M. Sparrow |
| F. C. Hooper | K. Stephan |
| N. Ishiiki | A. M. Stoll |
| E. K. Kalinin | J. Taborek |
| J. G. Knudsen | G. J. Trezek |
| R. L. Kramer | J. W. Westwater |
| F. Kreith | R. D. Zerkle |
| S. S. Kutateladze | |

Contributors who supplied information in discussions and through correspondence

| | |
|---|---|
| A. J. Acosta | D. F. Dipprey |
| W. J. Adams | R. M. Drake |
| M. Altman | N. Dunning |
| L. H. Back | R. H. Eustis |
| D. J. Carney | W. H. Giedt |
| K. L. Coulson | P. M. Githinji |
| R. W. Graham | S. R. Morrison |
| T. J. Hanratty | J. H. Munier |
| J. C. Harper | R. N. Norris |
| J. P. Hartnett | J. W. Palen |
| E. G. Hauptmann | F. H. Shair |
| R. C. Hendricks | J. L. Shapiro |
| Y. Y. Hsu | R. J. Simoneau |
| D. Q. Kern | J. M. Smith |
| S. P. Kezios | P. T. Vickers |
| A. D. Kraus | N. Zuber |
| P. Kyropoulos | E. E. Zukoski |

Special thanks are due to Professor E. Brun, who graciously arranged for the Round Table Session at the Fourth International Heat Transfer Meeting which gave an opportunity for discussion of the subject matter of the report.

## INTRODUCTION

In the present study an attempt was made to collect the opinions and ideas of workers in the field of heat transfer as to the future course of research in this area and its relation to applied problems. Interviews were conducted and memoranda were obtained from those actively engaged in research as well as from persons concerned with the design and operation of equipment and processes. A preliminary report reflecting the information obtained in this way was prepared in the summer of 1970 just prior to the International Heat Transfer Conference in Versailles. At that conference an informal "Round Table Session" was arranged for the purpose of discussing the report. The session was attended by representatives of almost all the countries in which extensive heat transfer work is being pursued and the meeting itself was most interesting and stimulating. The report in its present form has been revised to benefit from the comments and suggestions made at that time.

Basically, the report is intended to be useful in three ways:

(a) by serving as a reference to those engaged in research in planning their own programs;
(b) by helping prospective students in orienting themselves when selecting an area of specialization; and
(c) by giving a more complete overview of possible future endeavors to those who may be in a position to sponsor research work.

A survey of this sort, can, of course, never be complete, nor entirely up to date, and it cannot be expected that the opinions expressed will be shared by all of those who participated in the survey, let alone by all of the heat transfer community. Also, none of the material is entirely new or original and some work is certainly being done in all of the areas to be discussed. It is hoped, however, that the report will expose a large number of present and prospective research workers to a great variety of thoughts and points of view. This exposure may stimulate further thoughts and ideas and may be a positive factor in orienting their future work.

The fact that some areas are covered only superficially and others are not represented at all (among them nuclear fusion, magneto hydrodynamics, glass manufacturing, and air conditioning as well as such topics as measuring techniques and instrumentation) is, of course, a shortcoming. It is hoped, however, that this shortcoming will turn into an advantage in that it will instigate those who have extensive experience in these areas to contribute their thoughts and recommendations as to the key problems and pertinent future work. In fact, contributions of this type as well as comments and differing points of view pertaining to the material which is presented in this report *are actively solicited herewith.* Any new information obtained in this way will be used in the preparation of subsequent editions of this report which, hopefully, will be prepared periodically (possibly every two years). Following this approach, it is hoped that the report will remain a "living document" which will become more and more representative of expert opinion and which will continue to serve the purpose for which it was intended.

In the following pages, the information will first be presented according to fields of application, and subsequently the material will be regrouped according to the general type of transfer mechanism involved (forced convection, boiling, etc.). Both groupings are arbitrary and there will be some overlap in the subject matter treated in the several sections. Whenever possible material presented in the portion on "heat transfer by type of mechanism" will be cross-referenced to appropriate applications mentioned in the first section.

There is one general concern which was emphasized by several contributors and which was also raised by participants from various different countries at the "Round Table Session" in Versailles. The concern centers around the fact that applications of heat transfer are given strong emphasis in the present report. This could mislead some readers into concluding that the report favors only short range research projects which are likely to contribute immediately to the solution of some existing practical problem. This, of course, is by no means the intent of the report. On the contrary, it is well realized that research is usually most successful when it is directed toward the understanding of a fundamental phenomenon, the successful interpretation of which is likely to benefit a great number of applications. Support should certainly not be diverted from research on such fundamental phenomena—the study of the turbulent transport mechanism probably being a good example. The discussion of various fields of applications, as given in this report, is in no way intended to detract from the importance of this type of research, but on the contrary it is expected to direct attention to additional important basic phenomena which may then form the subject matter of future research endeavors. The writer is confident that the report will be interpreted in this spirit.

## HEAT TRANSFER BY AREA OF APPLICATION

### A. *Agriculture*

In a broad subject such as agriculture one can only hope to highlight a few areas to illustrate the opportunities which may exist to make a useful contribution by studying the heat and mass transfer aspects.

The first general area concerns comfort and temperature control of animals in hot climates. Questions on which work has been done but which require more attention if quantitative answers are required include radiation coefficients of furs and feathers, analysis of thermal interchange between the animal and the various parts of its surroundings, and methods of of providing desirable temperature time cycles (there seems to be some information on such cycles for maximum growth of swine and cattle, maximum egg production of chickens, etc.).

Secondly, the prediction of temperature-time-depth relationship in soils and an understanding of the factors influencing this relationship could be valuable not only for the purpose of controlling growth rates, water consumption, fertilizer usage, etc., but also for controlling pests and for determining times for the most effective use of insecticides.

Thirdly, there is the area which concerns processing of crops and includes drying of grain, drying of leaf crops and the keeping of fresh fruit and vegetables, and possibly the artificial ripening of fruit. The methods will involve convective heat and mass transfer, possibly in conjunction with flowing granular media such as grain. In certain cases the use of properly filtered radiation may be effective in obtaining the desired drying without spoiling the product in any other way. (It seems that such an approach has been helpful in the drying of sisal fiber.)

The last area to be mentioned is that of micrometeorology, the prediction of atmospheric conditions as they are influenced by local conditions. This investigation involves a study of the boundary layer near the ground, i.e. temperature and velocity distribution, stability criteria (if a cold layer remains stable it may cause freezing), methods to destabilize the layer, effect of roughness (as represented by various crops, bushes, trees), interaction with radiation, radiation and temperature distribution throughout crops, effect on fog formation, the role of evaporation from plants, etc.

The micro-meteorological work has to interface somewhere with meteorology. Questions pertaining to this interface area involve the radiation characteristics of clouds, the effects of aerosols on these radiation characteristics, the effect of city-like areas ("heat islands") on the climate of immediately adjacent agriculture, and vice-versa the effect of parks throughout cities on the city climate.

B. *Biotechnology, ecology*

Only in recent years have engineers started to direct their interests towards problems in medicine, biology, plant physiology and ecology. It is not clear—and no longer relevant—whether the engineers expressed no interest in this field in earlier years, or whether their offers of cooperation were spurned by the other professionals. In any case once collaboration did come about, it was the beginning of a very promising joint effort. This example of collaboration has in fact been a very encouraging factor in promoting interdisciplinary research between other fields also.

One of the first tasks, of course, involves the determination of the basic thermodynamic and transport properties of skin, tissue, bones, blood, etc. Similarly, further information is needed of the thermal interaction—radiation, convection, evaporation—of the body with its surroundings, in and out of doors.

The next group of problems concerns internal exchange mechanisms, such as the heat and mass transfer in kidneys and lungs, and cavitation and bubble generation in blood.

Whereas investigations of the above type are directed towards a better understanding of basic bio-physical processes, the following subjects are directed more towards applications. It may be appropriate to mention first the use of temperature for diagnosis, as the measurement of body temperature for this purpose is certainly an old and familiar one. It now appears that the temperature distribution and the position of temperature contours over various parts of the body may be indicative of the normal or abnormal functioning of various systems, and may also be helpful in locating abnormal growth. In addition to measuring temperature by contact probes, the development of suitable infrared radiation survey techniques seems promising. One may also expect that—in close cooperation with the medical profession—it will be possible to develop more and more sophisticated methods of interpretation of the data and more sensitive methods of exploration, possibly based on the response to transient heat pulses.

The next group of applications is directed towards causing a prescribed temperature–time cycle in a specified area for a definite medical purpose. The new knowledge which is required in most of these instances involves not only the generation and prediction of the cycle, but also the design of the optimum cycle for the desired effect. The applications in this category include the inducement of anaesthesia by modifying the temperature in the brain, procedures for revival from a hypothermic state, specification and control of temperature fields in cryosurgery, and establishing the desirable thermal treatment which will restore damaged cells in frostbites, burns, and inflamed joints, and developing methods to effectively generate the treatment cycles. Heat treatment in metallurgy is specified in great detail, and we could look forward to similar optimized procedures to achieve the desired results for the above applications.

Increased attention is also being given to the possibility of preserving groups of living cells—and eventually entire living beings—in the frozen state. To this end very extensive work will have to be done to determine the required temperature program throughout the sample both for freezing and revival in such a way as to prevent damage.

The above requirements also imply the development of new concepts and devices to accomplish the various temperature conditioning tasks. These may include a great variety of systems ranging from special radiation sources to internal or external heat exchangers for blood such as may be needed in connection with artificial kidneys or heart engines.

The transfer processes in plants may also be regarded as part of bio-engineering. There exists, for example, interesting problems concerning the relationship of water needs to heat transfer, and perhaps most importantly, to the total evaporation from plants. In fact a ten per cent reduction in this evaporation could have a significant effect on water supply and on the ability to grow plants in arid zones. It appears that reductions of this magnitude might be achievable with chemical sprays presently available.

As a further area in biotechnology—although more mundane than the previous ones—one may include the design of clothing. It is rather curious to realize that with all the frequent changes in styles and the introduction of new fibers and materials, comfort control has not really progressed. People still seem too often too hot or too cold and there is nothing like a thermostatically controlled garment available, except perhaps for astronauts. One could imagine that even by applying only available information and techniques such a commercially feasible garment could be produced. It seems, however, more likely that an intensive investigation of the interrelationship of physiology and heat transfer may lead to a superior solution. The investigation might include a study of the insulation and radiation characteristics of textiles and a method of controlling it, a study of the heat exchange system of the body with a view toward identifying relatively small body areas (maybe the forearms) which can serve as effective heat exchangers for the body as a whole, and a study of auxiliary cooling or heating sources (heat pumps, resistors, liquefied gas, etc.). In any case engineered clothing may well be an area in which further work could be quite rewarding.

In connection with human comfort the field of air conditioning, heating and ventilating needs to be mentioned. The writer, however, has not obtained sufficient information of problems in this area to supply an overview of the field at this time.

C. *Electronic equipment*

Even in the days of vacuum tube electronics cooling of the tubes and circuits was becoming a problem requiring thoughtful design. Since then the power to operate any given circuit has been decreased spectacularly, but the cooling problem has acutely increased because of the even more spectacular decrease in the size of a given circuit.

So far equipment with significant heat generation has usually been designed so that the heat was removed from the electronic devices by conduction to a base and then removed by convection or—in many space applications—by radiation. As the convective fluid, air has generally been adequate with forced convection becoming more frequent. Also, rather than installing a fan as an afterthought, careful consideration is now given to the layout of the flow passages. Projecting toward the future it appears that liquid cooling will be needed and the investigation of possible candidates for this purpose has already begun. One of the modes of heat transfer that may be most applicable is nucleate boiling, as it provides good heat transfer coefficients and effective temperature control even under conditions of free convection. Faced with the design of a cooling system of this type, however, one comes to the somewhat embarrassing conclusion that despite the intensive effort over the last two decades the heat transfer characteristics in boiling of an arbitrary fluid cannot be predicted with any degree of certainty.

This then will require further experimentation and analysis which is to include the effect of surface material; surface conditions; amount of impurities in the fluid; and in particular the effects of geometrical restraints, for example those imposed by narrow passages and small enclosures. These studies will have the double purpose of providing the necessary information to allow future designs and to eventually bring about a sufficiently complete understanding to allow predictions of heat transfer coefficients and nucleate boiling maxima within possibly 10 or 20 per cent.

In certain applications—as for example the operation of infrared sensors—cooling to cryogenic temperatures will be necessary. As a consequence data for the various modes of heat transfer for cryogenic fluids will be required, including information on helium.

D. *Fire prevention*

Since the starting and spreading of fires is largely determined by the temperature of the combustible mixture heat transfer plays a key role in the analysis of fires and their control.

For outdoor fires (such as forest fires) more quantitative understanding of the motion of the hot plume and the convective and radiative transfer from this plume to combustible material is needed. The study of the effect of different ground geometries and different terrains is a part of such a study as is the prediction of the radiation characteristics of the plumes. For large fires the meteorological effects of a fire have to be considered; "fire storms" have been reported, but their mechanism is not fully understood.

One of the problems concerning indoor fires is the heat transfer mechanism inside a typical room: what is the role of convection and radiation; how is heat transferred from a localized heat source at various points in a room; how can the temperature rise in an adjacent room be predicted; where are the places in which the temperature is likely to reach the ignition limits first, what is the influence of the geometry, the radiation characteristics of the wall, etc. The time required for the heating process is also an important factor as it determines the interval during which preventative action can be taken. Once a fire has started on a large scale, the velocities become very high and the density differences very large. To be able to predict the action of such a fire and to recommend methods of control, it will be necessary to study the free convection of a compressible heat generating fluid in the passages of a building. A further area of study concerns the effect of fires on building materials, the mechanism of failure, the design of fire resistant structures and materials, as well as the development of representative testing methods for materials of all kinds.

Detailed investigations of combustion processes and the role of preheating in this process also remain of importance. A particularly interesting problem concerns the effect of moisture in a porous medium. The moisture ordinarily will be thought of as reducing the tendency of the material to be burned. On the other hand, if the heating rate is sufficiently high so that the vapour instead of coming out of the material toward the heat source is driven into the medium the effect changes. The vapour will then condense far inside the material and heat up the porous structure around it making it more vulnerable to combustion. Similarly, to give a better understanding of burning of solids in general further studies are needed of the process of decomposition of the combustible material, the heat transport by the movement of the resulting gaseous material, and the conduction through the remaining solid. A better understanding of these processes will add to the predictability of fire spreading and will also contribute to the ability of developing fire resistant materials, a subject which was mentioned earlier.

E. *Food processing*

Food processing is one of the areas which may well benefit from increased engineering attention. The scale of these operations is ever increasing and there is, therefore, an ever increasing economic incentive for reducing processing times, and for devising efficient and economical processing equipment.

Among the many areas involved is that of flowing, heating and cooling a variety of ill-behaved liquids euphemistically known as "non-Newtonian". It will be the rewarding task of engineers to discern the key properties of these various fluids and to develop anew the free and forced convection behavior of these fluids. Any successful development along these lines will, of course, have applications outside of food processing, as the transport and treatment of non-Newtonian fluids is becoming more frequent in other industries also.

Other preblems in food processing involve the familiar steps of heating (food in containers, continuous belt cooking of chicken, etc.), freezing, drying (e.g. drying potato chips), freeze drying (vegetables, coffee). In addition there are the familiar problems of cold storage above as well as below freezing temperatures. All of these are being accomplished now and also are being studied and improved continuously. Nevertheless, in the continued rapid development which may be expected more refined understanding of each physical process as well as their interrelationships should be welcome.

An additional process being given consideration is that of reverse osmosis for the purpose of preparing concentrates of juices, milk, cheese, whey, etc. The technical problems which occur in this connection involve mass transfer rather than heat transfer, but they are within the scope of this report.

F. *Some manufacturing processes*

A potentially important area which has received only limited attention from a heat transfer point of view is that of machining and grinding. The essential requirement is, of course, to keep the tool and the work cool. Allowable machining speeds, and tool life, are largely dependent on this factor which in turn influences manufacturing costs significantly. In order to develop improved cooling methods it will be necessary to gain a fundamental understanding of the heat generation process and the distribution of energy. Further diagnostic work is indicated and to give an idea of the magnitude of the problem it is mentioned that an individual grain on a grinding wheel is exposed to a high rate of energy release for perhaps $10^{-6}$s. It is probable that friction, spalling, ablation, and chemical reactions will play a role in the analysis and that a detailed study of the cooling effects of gases, mists and liquids will be required. The coolant frequently will be delivered in the form of jets and sprays, and the study of this mode of convection will be pertinent.

A very large number of metal parts are produced by casting and speed is the key to a successful operation. The factor controlling the speed in this case is heat transfer. In many instances improvements are within the state of present knowledge. However, the process does involve conduction in a solidifying medium as well as conduction through interfaces, and it may benefit from a study of these basic aspects.

Interestingly enough the same two basic questions arise in the design of ice-cube makers in a refrigerator. The questions to be answered here concern the solidification process of the cubes (effect of shape on rate of freezing), and the contact resistance at various interfaces (e.g. ice to plastic tray, tray to base, fins to tube). In addition in a refrigerator there is the problem of moisture: the effect of moisture on insulation; the deposition of moisture in the form of frost on the evaporator surfaces; and the influence of the surface configurations (e.g. fin spacing) on frost formation. The frost formation process in particular is likely to lend itself to the study of basic mechanisms.

Another basic process in the production of standard supplies involves the forming of sheets between cylindrical rolls. The sheets may be of steel on the one hand and of various plastic materials on the other. In both instances the heat transfer process between sheets and rolls may be a key factor in determining production rates and further analysis of the mechanism involved could result in tangible benefits. In the case of the production of steel sheets it will be particularly important to obtain reliable information on the pertinent properties at the prevailing high temperatures. A lack of understanding of the role of these properties would sharply limit the value of any prediction or design suggestions which might otherwise be based on a sound understanding of the process.

Finally, as a typical operation involving mass transfer, let us mention the finish drying of paper, a process which has to be carried out at high speed and with great uniformity. Rather effective methods have been developed for this purpose and even radiation selectively absorbed by the moisture is sometimes used. Nevertheless there are several processes which are only qualitatively understood, such as the moisture transport within the paper, the transport of heat from the heating surface to the paper, the contact resistance of this surface, and the factors governing the tendency of sticking and adhesion.

*G. Power and process equipment*

(1) *Heat exchange equipment.* Among the many components in power generation and processing plants the heat exchanger is one of the most common ones. The term is used here in a broad sense and includes single phase exchangers, oil coolers, evaporators, condensers, etc. Even though such exchangers have been, and are now being, used so widely it may be surprising to some that there is a lack of understanding of many "details" of the flow and transfer mechanism. In fact, in some fairly common exchangers this lack of understanding often leads to an overdesign of the order of 100 per cent, and if deterioration of the surfaces is involved, this figure may go considerably higher. There is reason to believe that considerably more pertinent information is actually available than is normally used in the design of equipment. The information, however, is often not easily available to the designer nor in a form which would make it easy to apply. One important contribution could probably be made by evaluating and coordinating existing information and presenting the results in the form of recommended design procedures.

The above mentioned "details" on which more information may be needed include flow of single phase and two phase fluids over various arrangements of tubes, flow and heat transfer conditions which lead to instabilities (sometimes involving interaction with the structure), the full appreciation of manufacturing tolerances and geometric perturbations on the performance of an exchanger, the role of contaminants, and—perhaps one of the most important and least predictable factors—fouling (an unappealing word which does not help to attract qualified persons to the study of challenging problems of heat and mass transfer with electrochemical interactions). In fact, fouling is believed by many to be the single most important unknown factor in the design of heat exchangers.

The problem is further complicated by the conditions under which the equipment has to operate. An important one among these concerns the vibrations environment which is hard to predict and to quantify, but which can have important effects on convection in one phase flow and possibly even more in two phase flow. All these uncertainties lead to the design margins mentioned earlier which are of a magnitude which seems incongruous in the cost-conscious power and process industry.

In other cases additional understanding is required to achieve feasibility or practicability. Evaporative desalination units are an example of this kind. The cost of these units is greatly influenced by the extent of the surfaces on which the change of phase takes place and the cost is a key factor in the feasibility of this process on a significant scale. Nevertheless, it appears that the process of evaporation and condensation in industrial equipment is still not fully understood and, for example, the development of effective surfaces (such as fluted tubes) is a very pertinent area of study.

In certain applications—and the recent

interest in steam power plants for automotive use may be one example—there is a special premium on reduction in size, and an interest in surfaces or systems giving increased heat transfer coefficients. A significant amount of work has been done on such surfaces and systems but there appears to be a need for further exploration of the transfer mechanisms and the resulting improvements. Systems and methods of particular interest include roughnesses and other turbulence promoters, swirl flows and an intriguingly different approach, the use of metal powders dispersed in fluids.

(2) *Special processing steps.* A number of chemical processes involve direct contact between a fluid and a solid ingredient with or without chemical activity. The solid may be in granular form and the fluid is made to pass through the solid material. This may be either in a compact stationary but porous form (packed bed) or may be held in suspension by the flowing fluid itself (fluidized beds). In some cases it is also desirable to transfer heat directly between a flowing granular medium and solid exchange surfaces. In all of these cases the transfer mechanism deserves further quantitative study to allow more economical design of the equipment involved. The processes become, of course, particularly complicated when chemical reactions are involved. Problems of this type together with those classified as combustion, ablation, and plasma dynamics may be of increasing importance in the future and point to the importance of chemistry—in particular chemical reactions—in modern heat transfer research.

(3) *Nuclear reactors.* Special mention should next be made of nuclear reactors and the "two phase flow" problems, which under normal operating conditions occur in boiling water reactors, but which also have to be considered in other types of reactors. In the latter this type of flow has to be considered in connection with transients and possible malfunctions, and in exploring the safety limits of the installation. Often free convection effects will then also have to be taken into account. The analyses required will usually ask for a prediction of void fractions in addition to heat transfer information. It may be appropriate to mention here that the heat transfer problems just discussed are not exclusively related to nuclear reactors and that they do, in fact, occur also in fossil fuel heated boilers. However, an understanding of the water-side heat transfer is more important for nuclear applications as the heat transfer coefficient on this side is now controlling, whereas the gas-side coefficient is usually the controlling one for the more conventional power plant. Furthermore, in dealing with nuclear reactors, exact predictions are more crucial, because of the safety aspects.

The problems which have to be solved here are very involved; analytical predictions are very difficult and full scale testing expensive and time consuming. In this kind of situation engineers have often been able to progress by making measurements on small scale models. Although many parameters are involved in the present model, some engineers have high expectations in the successful development of scale models suitable for experimental purposes. Such models would be of great economic benefit in the design of future power plants, and therefore model studies deserve very serious attention.

A further heat transfer problem of interest in the design of nuclear power plants concerns the heat transfer to liquid metals. Liquid metals have and will be used in intermediate exchangers between reactor and boiler and also as a working fluid in the power cycle. For both applications the same general information is needed as in the case of more usual fluids (i.e. forced convection, free convection, boiling, two phase flow, etc.). The design information for liquid metal is, however, in a still much less reliable state and careful further work is needed. Phenomena involving surface characteristics, wetting, nucleation and bubble formation may require special emphasis.

(4) *Power and power transmission.* A thorough understanding of two phase flow, which was mentioned in the previous section in connection

with nuclear reactors, is also required for the successful design of a variety of equipment in other industries. Boiling heat transfer may be considered a part of this complex of problems and although it is qualitatively well understood, numerical predictions are poor. The same may be said about heat transfer near the thermodynamic critical point, a problem which has come to the foreground because power plants are now more frequently operated at supercritical pressures, and because of the wider use of cryogenics. For example, production and handling of liquid natural gas is becoming common and cooling of transmission lines by liquid nitrogen is being actively considered. Even lower temperatures will be required in the future in order to operate a variety of systems, including transmission systems, magnets and possibly rotating electrical machinery in the range of superconductivity. At present cooling with liquid helium seems to be required for this latter purpose and further evaluation of the cooling characteristics of both Helium I and Helium II will be needed. Future advances in the development of superconductors may allow higher temperatures so that liquid hydrogen could be used as a coolant. This underlines the need for continued study of the cooling characteristics of that fluid. It is somewhat more surprising, perhaps, that there is even a lack of information on the cooling of electric motors and generators with ordinary fluids. Some of the important problems for this application involve the heat transfer in gaps formed by one rotating and one stationary surface with a superposed net flow rate.

It should be mentioned that the transmission of energy is not limited to electricity but also includes the transport of energy in the form of fuels such as oil and coal slurries. As to the former, the construction of the Alaskan pipeline affords an excellent example of a complicated heat transfer problem involving convection from a hot oil with temperature sensitive properties and conduction to an initially frozen ground. The use of coal slurries may require a clear understanding of the heating, drying, and combustion of the slurry as it is introduced into the furnace.

(5) *Furnaces.* One further major component in both power and processing industries concerns furnaces. The general mechanism of combustion and heat transfer is, of course, rather well understood. However, it appears that there has been relatively few comparisons of the actual characteristics of a prototype furnace to those on which the design was based. To advance the art of furnace design, experimental surveys of temperature velocities and chemical composition may be in order which in turn may make it possible to distinguish the heat transferred by radiation from that transferred by convection. Detailed surveys may also be needed to gain a sufficiently exact picture of the chemical processes to enable the designer to avoid undesirable products in the exhaust as may be required by regulations against air pollution. For example, the elimination of hot spots throughout the furnace volume may significantly reduce the production of NO which is one of the harmful components in the formation of pollutants.

(6) *Environmental factors.* More and more attention is being given these days to the interaction of power plants with the environment, and "heat pollution" has become an item of concern. Many power plants reject heat to rivers, lakes or oceans, as this has been the most convenient "heat sink". As the use of these bodies for such purposes may be restricted in the future, consideration is being given to power plants making use of evaporative cooling towers and condensers which are air cooled. As the plants involved could be very large, very pertinent questions may be asked as to the effect of this rejection of moisture and/or heat on the local climate. This effect could be "good" or "bad", and the beneficial aspects could well be optimized by proper spacing and location of plants. With the large amounts of heat that may become available one may possibly create favorable ocean currents and air movements and bring about improvements of the climate and increase the usefulness of the land. It is also intriguing to speculate that in some cases it may even be possible to bring

about air currents which might help to reduce pollution.

(7) *Fusion, MHD.* So far nothing has been said about power conversion units based on magnetohydrodynamic effects or power plants in which heat is generated by nuclear fusion. It seems clear that in both applications the management of heat transfer will be of crucial importance. At the present time, however, the information collected by the writer has not yet been sufficient to allow a listing of the key problems.

H. *Propulsion—aerospace*

Heat transfer problems in aerospace applications have received the most active attention throughout the last two decades and a very large portion of the research has been oriented towards this field. Information on these problems, methods of attack, and outlines of aspects still unknown are widely available, and for this reason it will be sufficient to enumerate some of the principal areas for future research without attempting to give a detailed description.

One category of problems involves those for which a surface has to be protected under conditions of "very high" heat transfer rates, such as might occur in spacecraft re-entry, rocket nozzles, and in electric propulsion devices. The problem in general involves heat and mass transfer of a chemically active fluid in a boundary layer with temperature dependent properties. In addition, depending on the specific problem, radiation and electromagnetic forces may play a role. Great progress has been made in the understanding of the problems, but because of the very complicated mechanisms and the difficulties in carrying out high temperature experiments highly accurate predictions are not usually possible. A method of cooling surfaces which has proven very powerful is film and transpiration cooling, which can be carried out with gases, liquids, and even foams. The process as such is fairly well understood, but uncertainties as to film stability, shape and spacing of injection slots, etc., still require a large amount of experimentation in arriving at a suitable design in each case.

A problem of a somewhat different kind—but also involving very high heat transfer rates—is that occurring in rocket thrust chambers under conditions of unstable combustion. The problem could be classed as "academic", in that rocket chambers are not supposed to operate in this mode; yet it is rather vexing that the heat transfer mechanism in this phenomenon which has been such a costly one, is not well understood and that there are hardly any measurements of the heat transfer rates which occur under these conditions. In the operation of rocket chambers cooling with fluids of all kinds—gells, cryogenics, fluids near the critical point—remains of interest. To this list of fluids *slushes* (mixtures of solid and liquid phases of a given propellant) should be added, as consideration is being given to loading missile tanks with propellants in the slushy state in order to reduce evaporation losses. A problem of special importance involves the startup of a "warm" engine using cryogenic propellants and the control of the transient heat transfer and two phase flow processes. Furthermore the heat transfer from the exhaust of rockets or jet engines is of importance in the design of adjacent structural members of the craft being propelled, as well as in the design of test stands and launch pads.

Attention is also being given to oscillating flow—and the corresponding heat transfer—in an automobile exhaust pipe. This interest stems from the desire to understand the time dependent pressure and temperature distribution in the pipe and its influence on the chemical reactions. Proper control of these processes may lead to a reduction of the pollutants in the exhaust. Other applications in which flow oscillations and vibrations interact with heat transfer were mentioned in the section on Power and Process Equipment.

A further set of problems concerns the gas turbine. The efficiency of these engines depends critically on the allowable turbine temperature. These temperatures are largely determined by the turbine blades, and further importnant advances may be expected from the continued study of the heat transfer from the gas to the blade and of methods of cooling the blades. The study of the formation of three-dimensional boundary layers in the blade passage on the one hand, and of film cooling on the other, may be particularly pertinent.

Much attention and publicity has been given to the heat pipe. Some of the publicity has been exaggerated and possibly harmful to a clear understanding of the features of this device. The heat pipe does provide a high effective conductivity compared to metals. It is however, limited by the maximum 'nucleate boiling flux and is usually much below this value because of other limitations such as the transfer mechanism at the tube ends. The outstanding feature of the pipe is its convection mechanism which is independent of gravity and does not require a mechanical power source such as a pump. It is this characteristic which makes the heat pipe a most useful design component, and in many instances it is to be preferred over a forced convection system which could well accomplish the heat transfer task, but would be more cumbersome. To extend the range of applicability of the heat pipe, investigations with a large variety of fluids (including liquid metals as well as cryogenics) should be continued. As to the basic mechanism of operation of the pipe, the unknowns do not involve as much the processes of evaporation, condensation and boiling as they do the pumping action of the wick. Further investigations of this latter aspect will be of interest. One may further expect the development of more sophisticated versions of the heat pipes with very special characteristics. Some of these might involve more than one fluid, and may give rise to pertinent studies of the behavior of a multicomponent system in a wick.

Lastly the temperature control of space crafts, propellant tankage, lunar and space instruments, etc., is to be mentioned. In these circumstances heat transfer by radiation and conduction plays the major role. Although the basic processes are well understood, additional information on contact resistance and on the preparation of surfaces with selected radiation characteristics would be welcome.

### I. *Interfaces with meteorology, oceanology, geology and astronomy*

It is, of course, well known that heat transfer is one of the determining factors in some of the central problems in meteorology and oceanology as well as in astronomy and geology. It is, in a way, therefore, somewhat surprising that only relatively few of those who work in heat transfer devote any effort on the heat transfer-related problems in these other disciplines, and that there is relatively little interdisciplinary exchange. One may further point out that for most of these problems the experience of an expert in heat transfer is rather directly applicable. He probably could contribute to the advancement in this field more readily than in such other fields as agriculture or biomedicine where he will have to spend a greater preliminary effort to acquire the prerequisite background information of the special field.

The problems in the areas under discussion in this section all essentially involve free convection arising from a variety of heating conditions and force fields. The answers sought usually include stability limits, velocities and heat transport. The classical problem of this type is that named after Bénard in which a fluid between two plates is heated from below. Depending on the conditions, a cellular or similar flow pattern develops. It is easily imagined that somewhat analogous conditions can arise in the atmosphere or in the ocean albeit complicated by the rotation of the earth. The resulting motion of the fluid is of course a central feature in meteorology and oceanology and the scope of interest now also includes the behavior of atmospheres on other planets. A considerable amount of experimental and theoretical work on these subjects has been performed, but they certainly represent active areas of investigation, and considerable interest is focused on a more quantitative understanding which would allow accurate predictions which would eventually lead to economic benefits. Further research, both experimental and theoretical, may well be rewarding; for example, skillful modelling may yield further insight into some of the mechanisms. A person with a background in the more industrially oriented phases of heat transfer, just because of his different experiences and different point of view, may very likely contribute significantly to the progress in these areas.

Very similar free convection phenomena seem to occur in geology and astronomy, areas usually thought of as being even more remote from traditional heat transfer. In the former, Bénard-type motions are believed to exist in the earth mantle and are thought by some to be responsible for the drift of the continents. The fluid involved here is one of high Prandtl number. These ideas have been recently very much expanded through theories of sea-floor spreading and plate tectonics. A corresponding problem in astronomy concerns the motion within stars. In that case the exchange (by radiation) throughout the fluid is very rapid compared to the motions and the effective Prandtl number is, therefore, very low. Other problems in astronomy have to do with the oscillations of a star, a heat generating mass of gas with the radiation heat transfer strongly dependent on the gas density.

## HEAT TRANSFER BY TYPE OF MECHANISM

In the following pages the heat transfer problems which have been suggested by the respondents for further study are grouped according to the type of transfer mechanism. The subdivisions which have been selected are fairly arbitrary and there is overlap between them. The arrangement does allow a more concise description of each possible research task and some readers may prefer to survey the problems in this manner. Whenever possible the pertinent areas of application corresponding to each research task are pointed out by means of letters placed in parentheses following the statement of each task. These letters refer to the sections in the first part of the report in which the applications are discussed. The grouping by heat transfer type as given in the following pages has the undesirable feature that it might create the impression that the various modes always occur separately, whereas the interaction of the several mechanisms is often the essential aspect of an application. It is hoped that this portion of the report will not be misleading in this respect.

The topics are given in alphabetical order and no priorities are implied by the sequence.

### I. *Conduction*

*General comments.* The conduction process as such is quite well understood and powerful mathematical and computational tools are available to solve the governing equations. The new challenge involves unusual situations in which a special insight into the problem is required in order to specify a model with realistic physical properties and appropriate boundary conditions. Information on thermal properties and interface resistances will often limit the obtainable accuracy. Typical problems include the following:

*Suggested areas of investigation.*

1. Conduction with change in phase, with emphasis on realistic boundary conditions. *Related applications.* Frost formation and freezing of ice cubes in refrigerators (F); solidification of cast metal parts in molds (F); freezing and subsequent thawing of living cells without damage (B).
2. Non-steady conduction in special media. In certain cases the change in density with temperature may have to be included. *Related applications.* Temperature distribution in the brain caused by cryosurgical instruments (B); temperature distribution and changes on the body surfaces as a a diagnostic tool (B); temperature cycles in soil and its relation to biologic processes in the soil (B); temperature distribution in tools used in machining or grinding (F).
3. Contact resistance at various interfaces. *Related applications.* Thermal distribution

in space craft (considerable attention has been devoted to this problem but greater accuracy may be required for future prediction) (H); distribution of heat between a tool and the part being machined (F); heat transfer between drum and wet paper in drying process (F); contact resistance between parts of fuel elements in nuclear reactors (G).

II. *Cryogenic fluids*

*General comments.* Cryogenic fluids are listed under a separate heading as the experimental conditions are sufficiently different—and in the case of Helium II the behavior is so different—that the study of heat transfer in cryogenic fluids has become a separate specialty. It may, therefore, be convenient for some readers to find problems in this field grouped together. Nevertheless, in any study of cryogenics full use should, of course, be made of the information already obtained in the study of more usual fluids.

*Suggested areas of investigation.*

1. Reliable data on free and forced convection, with and without change of phase; peak transfer rate in nucleate boiling; film boiling; heat transfer near the thermodynamic critical point. Data on Helium I and Helium II may be of particular interest.
2. Transfer characteristics of "slushy" (liquid-solid phase mixtures) fluids.
3. Thermal contact resistance at cryogenic temperatures.

*Related applications.* Manufacture, storage and transformation of liquid natural gas (G); cooling of electric transmission cables (G); rocket chamber cooling (H); handling of slushy propellants (H); maintaining electronic elements at desired cryogenic temperature (C); producing superconductivity in electronic components and electric generating equipment (C, G); design of cryogenic surgical probes (B); design of superinsulation. In addition, heat transfer experiments in Helium II may well add to the fundamental understanding of transport mechanisms.

III. *Liquid metals*

*General comments.* The interest in liquid metals stems largely from the fact that they represent one of the very suitable coolants for nuclear reactors. In addition certain other applications, such as liquid metal quenching baths, and liquid metal heat pipes, have been suggested. The heat transfer problems are much the same as those which are encountered with other fluids, and some of these have been discussed in the sections on free and forced convection, boiling, and two phase flow. Liquid metals are listed under a separate heading, as the properties of these metals are so different from other fluids that the investigations into their behavior often require quite a separate approach and very special experimental techniques. It is particularly difficult to obtain accurate and repeatable data and reliable design information is sparse.

*Suggested areas of investigation.*

1. Basic free and forced convection data. With presently available information even turbulent forced convection results under well specified conditions can generally not be predicted within 50 per cent.
2. Nucleate boiling, critical heat flux in nucleate boiling for free and forced convection.
3. Film boiling—effect of surface on wetting and the promotion of film vs. nucleate boiling.
4. Nucleation, bubble formation and growth.
5. Effect of impurities, fouling and surface interaction.
6. Transient response.
7. Mechanism of evaporation and condensation.

*Related applications.* Reactor cooling, space power plants using metal working fluids, reactor safety analysis (I); space radiators (H); heat pipes (H).

IV. *Evaporation, condensation, sublimation*

*General comments.* Evaporation and condensation are processes of major importance in industry. A large amount of practical experience has been accumulated and a very significant number of experimental and analytical studies have been performed which pertain to this type of application. Yet when predictions are to be made for specific designs the limits of uncertainty are still surprisingly high. One also finds that, although the mechanism of the processes are generally well understood, there are still open questions regarding such effects as wetting, surface waves, film stability, accommodation coefficients and surface tension. A recently much discussed improvement in condensation offered by fluted tubes, for example, seems to depend on the adaptation of the surface tension effect.

In some recent problems such as those involving ablation or the pyrolysis of combustible matter the dynamics of the fluids is becoming an increasingly important factor. Further interpretation of the mechanism may serve to elucidate the processes and additional rather basic work could well be fruitful.

*Suggested areas of investigation.*

1. Heat and mass transfer from evaporating or condensing films; stability of the film for free and forced convection; effect of surface shape and surface tension on the behavior of the film; processes in multicomponent mixtures including noncondensible gases.
   *Related applications.* Boilers and condensers (particularly "high performance" units for limited space) (G); desalination equipment (e.g. improvement of coefficients in such units by corrugated surfaces) (G); certain types of ablation cooling (F,H); protection of rocket chambers by film or transpiration cooling (I); chemical distillation.
2. Convection and conduction within porous media and from the surfaces of such media. Transfer mechanism and motion of vapor during evaporation, sublimation or condensation. Effect of passage size on the above processes.
   *Related applications.* Drying of paper (F); drying of certain agricultural crops (tobacco, pyrethrum) (A); freeze drying (coffee) (E); evaporation from leaves (B); combustion of wood and similar solids (D); transfer mechanisms in wet soil.
3. Transfer mechanism to subliming solids with or without chemical reaction.
   *Related applications.* Cooling of re-entry vehicles (H); cooling of machining and grinding tools (F); cooling of electrodes in plasma arcs.
4. Factors affecting dropwise and film condensation; "wetting" of liquids being boiled (film boiling vs. "nucleate" boiling).
   *Related applications.* Design of evaporators as in desalination units (G); boiling of "non-wetting" fluids, as in power plants with liquid metal working fluids (G); cooling of electronic components with cryogenic fluids (C).

V. *Forced convection* (*single phase flow*)

*General comments.* When looking towards further research in single phase-forced convection, it has to be realized that an enormous amount of work has been done on forced convection problems. Extended analytical as well as experimental studies have been performed for a great variety of fluids and flow conditions. Further pertinent research will most likely center around (a) very basic aspects which are still not well understood (such as turbulence), (b) problems with very special boundary conditions or applications which have not so far been explored, and (c) well known and commonly occurring heat transfer conditions which, however, need to be predicted with much greater accuracy in the future in order to meet the demands of modern technology. In view of the large body of knowledge available in forced convection successful research programs in this field will have to be planned with particular care and sophistication. The suggestions listed subsequently should be interpreted with this thought in mind.

*Suggested areas of investigation.*

1. Effect of more complicated, but realistic, geometries. Among these, arrangements of tube banks or tube bundles (mutual influence of tubes, optimum spacings for various purposes); interaction of "channels" in nuclear reactors; influence of entrance conditions such as determined by manifolds and headers.
   *Related applications.* Power plant heat exchangers (G); nuclear reactors (G); heat exchangers in processing and refining equipment (G).
2. Unsteady flows (either imposed or self-induced), effect of vibrations and flow oscillations, instabilities caused by influence of heat transfer on the flow field, and change in fluid properties.
   *Related applications.* Process equipment (G): heat exchangers in stationary and mobile power plants (G); oscillatory flow in automobile exhaust pipes and its relation to heat transfer and chemical reactions (H), heat transfer in rocket motors under conditions of combustion instability (H).
3. Fluids near the thermodynamic critical point and other fluids with properties which strongly depend on temperature and pressure. Possible flow instabilities with such fluids. Analytical models accounting realistically for the property variations.
   *Related applications.* Power plant boilers (G); nuclear reactors (G); cooling of rockets (H); heat transfer to cryogenic fluid (H).
4. Fluids with contaminants (such as oil) or additives (such as drag reducing polymers). Study of the effect of such impurities and mechanism by which the effect is brought about.
   *Related applications.* Coolants in industrial and power plant heat exchangers (G); cooling with fluids containing drag reducing substances.
5. "Fouling" of surfaces. The interaction of flow, heat transfer, temperature distribution and solubility on the tendency to form deposits on surfaces, prediction of fouling rates.
   *Related applications.* Although only indirectly connected with forced convection, the fouling of surfaces is one of the most crucial factors which limits precise design and performance predictability of heat exchangers (G).
6. Jets (single phase or sprays) impinging on surfaces of various types; also transfer between adjacent jets in direct contact.
   *Related applications.* Spot cooling in machining and for electronic components (C,F); heating of neighboring structural surfaces by exhaust jets (H).
7. Role of surface roughness, fins, and other surface modifications in augmenting heat transfer; the development of optimum surfaces for a balance of friction and heat transfer for a given application; additional detailed studies of the flow between fin configurations, the flow in annular geometries, and of swirling flows in tubes may be in order. An effective interpretation and coordination of existing data, however, may well lead to important contributions.
   *Related applications.* Basic information for the design of heat exchangers of all types, including nuclear reactors.
8. Laminar and transition flow in tubes. Despite the classic nature of the problem specific information on heat transfer in these areas is not plentiful. The difficulties in laminar flow are associated with the importance of "entrance effects" and the fact that fluids which in practice are in this flow regime often have properties which are highly dependent on temperature. Because of this dependence, it is even possible that temperature perturbations may lead to large operating excursions, and rather precise understanding of the processes is required for reliable prediction.
   *Related applications.* Transporting, heating

and cooling of viscous fluids, design of oil heat exchangers (G).

9. Laminar and turbulent flow in the presence of rotating surfaces; for example, heat transfer to a fluid flowing axially through an annulus with one rotating surface.
   *Related applications.* Cooling of electric motors.
10. Effect of external vibrations on the performance of heat exchange equipment; instabilities caused by interactions of the flow and heat transfer with the mechanical structure.
   *Related applications.* Heat exchange equipment in general, in particular nuclear reactors, refinery equipment (G).
11. Continued basic investigations such as: heat and mass exchange mechanism in turbulent flow particularly at very high (viscous fluids) and very low (liquid metals) Prandtl and Schmidt numbers; boundary layer heat transfer especially in corners and general three-dimensional configurations.

VI. *Free convection (single phase)*

*General comments.* Free convection is perhaps the most universal type of heat transfer. It occurs over an extremely wide range of scale involving such diverse problems as the processing of food cans to the motion of the earth's atmosphere or the gases in stars. For this reason many investigators in diverse scientific and technical areas have concerned themselves with free convection problems for a long time. There is, consequently, a large amount of information available in the literature. In attacking new problems it may be particularly fruitful to examine the findings and techniques of earlier workers in the diverse fields and to bring this knowledge to bear on the solutions of the new challenges. Nevertheless, there are problems which in the past have received very little attention (like free convection involving large density changes) and among those that have been studied extensively the amount of reliable experimental data is often surprisingly small. In future experiments it will be most important to carefully control all initial and boundary conditions as these have a particularly strong influence on free convection heat transfer. For this reason an especially careful description of these conditions should be included when reporting experimental results. Despite the long history of the field, there still is a great need for further very fundamental work on problems such as the stability of laminar boundary layers, the onset of turbulence, and the development of convection patterns and cellular structures.

*Suggested areas of investigation.*

1. Steady and non-steady heating of horizontal or inclined surfaces. The onset of various types of flow patterns as well as the onset of turbulence under these conditions. Effect of surface roughness on the transition points. Free convection with large differences in density and other properties as may occur in gases with large temperature differences or with fluids near their critical point.
   *Related applications.* Temperature and moisture distribution over agricultural fields and groves of fruit trees, its effect on crop damage by freezing, fog formation, etc.; effect of surface vegetation (roughness) on these phenomena (A). Spreading of forest fires on plain or hilly terrain and inside of buildings (D).
2. Free convection in enclosures with uniform as well as concentrated heat sources; also heat transfer to partially filled containers.
   *Related applications.* Processing of canned foods (E). Heating caused by concentrated fire in a room and its effect on the spreading of fire (D); the removal of heat and pollutants from city streets particularly when bounded by high buildings.
3. Effect of vibration on heat transfer to fluids in containers.

*Related applications.* Processing of canned foods (E).

4. Free convection from external surfaces and in combination with other modes of heat transfer.
*Related applications.* Heating and air conditioning; factors affecting human comfort, clothing design, plant ecology (B).
5. Free convection in the presence of centrifugal and/or electromagnetic fields.
*Related applications.* Meteorology, oceanology. Cooling of rotating structures such as turbine blades.
6. Heat release from one or more concentrated sources into a semi-infinite medium.
*Related applications.* Effect of heat rejection from power plants on local climate (G), as well as on air and ocean currents in general.

VII. *Non-Newtonian fluids*

*General comments.* The description "non-Newtonian" is not only a negative one but also a very imprecise one. There are many ways in which a fluid can be "non-Newtonian", and one generally includes under this heading such diverse substances as gells, slurries, slushes, heavy oils, polymer solutions, tomato puree, and even granular media such as powders and sands. The reason for the present way of classification is, of course, the fact that water and air are "Newtonian" and for very valid reasons most of the past experimental and analytical work has been for those liquids. More and more frequently, however, fluids of the kind mentioned above are being transported, heated and cooled on a commercial scale and accurate design information is becoming necessary.

Even though the field has not received the attention that has been given to Newtonian fluids, a considerable amount of work has been done including some very sophisticated analytical studies. Those who plan to contribute to this field will find a good base on which to build. Many of the basic tasks, however, such as the definition and determination of the governing properties and the measurement of heat transfer and friction for simple flows, remain to be done. It could well be that research on non-Newtonian fluids will be fruitful and rewarding. It is clearly an area in which many fundamental aspects need to be examined and clarified.

*Suggested areas of investigation.*

1. Systematic collection of basic information, such as:
(a) Characterization of fluids—what are the pertinent properties (such as viscosity in a Newtonian fluid) which describe the fluid. How can they be measured; what basic experiments can be devised to reveal the special behavior of each fluid.
(b) Development of analytical formulations which describe the behavior and which are useful in predicting performance. Identification of analytical models with specific fluids.
(c) Collection and classification of basic data on forced convection, free convection, boiling, etc.
*Related applications.* Preparation of foods in the form of purees, gells, pastes, etc. (E); cooling of soap powders, cement and other chemicals in powdered form; behavior of drag reducing fluids in heat exchangers; heating or cooling of blood such as in an artificial kidney (B); oxygenation of blood (B); heating of slurries in chemical processing (G); heat and mass transfer in fluidized beds; fluids containing solid particles ("dusty" fluids) as improved heat transfer agents (for example the propellant in gas-core nuclear reactors) (G).

VIII. *Nucleate and film boiling*

*General comments.* There is some overlap between this section and the ones on "Two Phase Flow" and "Evaporation and Condensation" and some of the suggested subjects are listed under both headings.

Intensive work on boiling has been carried out during the last twenty-five years. An enormous amount of information has been accumulated and the physical processes are generally quite well understood. Yet, as is apparent from some of the discussion in the first part of the report, it is often quite difficult if not impossible to make predictions which are sufficiently reliable for design purposes. This indicates the need for additional reliable and repeatable data obtained under well controlled and specified conditions. Further insight into the problem developed from analytical studies could yield the key to the coordination and presentation of the needed design information. Aside from the steady state problem an understanding of transient boiling and void formation is of major importance in the analysis of the safety of nuclear reactors. Ingenious approaches to estimating these transient phenomena are certainly needed.

*Suggested areas of investigation.*

1. Critical heat flux in free and forced convection, including zero gravity conditions.
2. Effect of surface condition on boiling rates and critical heat flux; the role of nucleation sites; effect of aging and flow history.
3. Fouling of surfaces (a particularly important and rapid process in the presence of boiling). Effect of initial surface conditions; effect of chemical composition of fluid.

   *Related applications* (*Items* 1–3). Nuclear reactors, rocket chamber cooling, flow of cryogenic fluids in pipes, low temperature electronic components, start-up in space power plants (G,H,C).
4. Boiling in complex geometries. (The effect of geometry can be of major importance and this aspect of a "real" problem should not be ignored by investigators; for example, the geometrical arrangement can have a definite influence on the "critical" flux.)

   *Related applications.* Same as for Items 1–3 with emphasis on restricted passages in heat exchangers, interaction of adjacent tubes, and annular spaces.

## IX. *Properties*

It is certainly in order to devote one section to properties of substances. In all predictions for heat transfer designs we depend heavily on the availability of the material properties, both thermodynamic and transport properties. The ones most frequently needed for conduction and convection include density, specific heat, conductivity, viscosity, and enthalpy differences for phase changes. For radiation, surface emissivities, reflectivities, etc., are often needed as a function of wave length, surface temperature and direction and information on the radiation characteristics of gas masses, aerosols, clouds, etc., is still often lacking. With growing interest in very high temperatures (hypersonic flow, plasmas) and very low temperatures (cryogenic fluids including helium) and with the simultaneous interest in a greater variety of solids and fluids the task is becoming increasingly demanding. It takes on even greater proportions as heat transfer work is being conducted with biological materials, with substances used in the food and chemical industry and with "non-Newtonian" fluids in general. In these latter it will usually be necessary to first define the properties to be measured before the task of obtaining the numerical values can be started.

The determination of properties is a very exacting and tedious procedure. Unfortunately most people consider it unglamorous and it generally is not accorded the recognition it deserves. Yet, it is quite obvious that reliable predictions for a heat or mass transfer system cannot be achieved unless the pertinent physical properties are known with the required accuracy. In planning for any future research, therefore, attention should be given to the availability of property data and if necessary appropriate concurrent efforts should be initiated to procure the missing information.

## X. *Radiation*

*General comments.* The basic theory of radiation is thoroughly understood and elaborate techniques have been developed for certain categories of problems. Some of these have been obtained as a result of studies of nuclear processes. Accurate solutions of problems are, however, often restricted by a lack of information about the radiation characteristics of the material involved. These characteristics include absorption, transmission, reflection, and scattering coefficients of solids, liquids, and gaseous mixtures of various kinds. The coefficients may depend on temperature and pressure and may depend on the direction of the incident and leaving radiation. In short the task of obtaining the needed information may be a very demanding one, yet it may be a prerequisite to the successful treatment of many future problems. In some ways the task of collecting radiation coefficients may be likened to that of collecting nuclear cross-sections and a very significant effort was expended for that purpose. Among other important advances one may expect further understanding of phenomena in which radiation is combined with convection and possibly conduction. A few of these are mentioned below.

*Suggested areas of investigation*

1. Radiation properties of vapors, aerosols, liquid–vapor mixtures and gas–solid suspensions.
   *Related applications.* Heat exchange from clouds and aerosols and its influence on smog formation, micrometeorology and human comfort (B); heat transfer from furnace gases to boiler tubes (G); protection of aircraft or spacecraft from radiation from exhaust plumes (H); absorption characteristics of propellant gas in gas-core nuclear reactors (G).
2. Emissivity of solid surfaces; sensitivity to corrosion and contamination; role of roughness; design of surfaces for special emissivity characteristics.
   *Related applications.* Temperature control of spacecraft, space radiators, solar heat collectors (H); superinsulation for cryogenic applications (H); relation of animal fur or plumage to acclimatization of species (B); design of "temperature controlled" clothing (B).
3. Heating by means of radiation at special ranges of wave lengths to obtain selected heating and controlled depth effects.
   *Related applications.* Food preparation by penetrating radiation ("radar ranges") (E); heat supply for freeze drying (E); evaporating "wet spots" in paper drying (F); diathermy controlled to specified time-temperature sequence at given locations inside body (B).
4. Absorption–emission in transparent media and combined heat transfer modes.
   *Related applications*: Micro-meteorology stability of air and vapor over fields (B); local climate control in city design (B); manufacture of glass (F).

XI. *Two phase flow*

*General comments.* Heavy emphasis is presently being placed on two phase flow of a single component largely because of its importance in power generation and chemical processing. A vast number of papers has been written on this subject and it is one of the areas which would greatly benefit from an authoritative summary of the state of the art, even though new information is being gained continuously. A considerable amount of planning has been—and is being—done, however, some of which is presented at national and international meetings devoted solely to this subject. For this reason only a very few relevant problems need be mentioned here. Two phase flow of multi-component systems (oil–water, air–water, two component substances in two phases, solid–gas, etc.) is also a problem of engineering importance and represent a field for fruitful study.

*Suggested areas of investigation*

1. Prediction of void fractions as well as droplet and bubble distributions under various steady and nonsteady flow conditions, including fast transients. The geometrical constraints may be an important factor.

*Related applications.* Nuclear reactor heat transfer prediction and safety analysis (G). A thorough understanding of the transient response is particularly important for the latter.

2. Determination of critical heat flux ("burn out point", "DNB") for various geometries and flow conditions.
   *Related applications.* Reactor cooling (G); also cooling of transmission lines or electronic components with cryogenics (C, G).
3. Interaction of parallel flow paths; prediction of flow and heat transfer in an array of channels from data on a single channel.
   *Related applications.* Design of cooling systems for power or propulsion reactors (G, H).
4. Modelling to two phase flows: development of modelling parameters and techniques which allow the prediction of heat transfer and flow in a prototype from small scale experiments. Modelling of transients will be of particular interest.
   *Related applications.* Design of nuclear reactor and assessment of safety margins (G).
5. Behavior of flow over tube bundles and mutual influence of tubes on each other.
   *Related applications.* Process heat exchangers, evaporators (G).
6. Interaction of flow, heat transfer and structure and the tendency to cause structural vibrations.
   *Related applications.* Heat exchangers and in particular reactor vessels (G).
7. Transfer mechanisms in sprays.
   *Related applications.* Spot cooling of surfaces.
8. Direct transfer between fluids, such as between jets, between droplets and the surrounding gas, bubbles and surrounding liquids, etc.
   *Related applications.* Food processing, chemical processing, combustion of liquid fuels, spray condensers, atmospheric processes.

## CONCLUDING COMMENTS

In reviewing the wealth of material obtained from the many experts in the field of heat transfer a few general observations seem to emerge on which it may be worthwhile to comment.

1. There are two areas—those of aerospace and nuclear power—for which a precise understanding of fluid mechanics and heat transfer is essential for any kind of satisfactory operation. It is quite understandable, therefore, that an extensive amount of research has been conducted in these two areas in universities, in industry, and in government laboratories. The work was aided by the fact that the aerospace and nuclear power development were recognized as national needs and supported to a significant degree by government sources. As can be seen from the comments in the main part of the report, many research problems remain to be solved but one would expect that these problems are well known to many of the research workers and that solutions are continually being sought.
2. The history and the present status are different for such equipment as heat exchangers, condensers, evaporators, etc., as used in the power and process industry. For these applications very satisfactory equipment was devised several decades ago. The improvements since then have been gradual but at no time was the need sufficiently urgent to require a massive research effort or a major involvement of the academic community. Over the years the manufacturers of this type of equipment and the research workers grew more and more apart, and as so often happens, each group became convinced of the other's inferiority. With the continuing demands for more efficient and more economic operations, the time for closer future cooperation may be at hand and it would not be surprising if those charged with the manufacture of equipment would find

some of the research work to be useful, and if the research minded individuals would be intrigued and challenged by some of the fundamental problems in the so-called conventional heat exchange equipment. To make a contribution in this area the research worker may find that he has to include in his investigations more realism than has been done in the past. By this is meant that fluid properties, geometrical boundary conditions, initial conditions, characteristics of approaching flows, surface conditions, environmental vibrations, etc., will have to be taken into account. In addition it has to be realized that the designer of this kind of equipment demands accurate predictions, accurate enough, say, to predict the size of the equipment within 10 per cent. It will take a great insight into the problems and real ingenuity to accomplish this and at the same time produce information which has some general applicability.

3. Whereas the above areas have formed the main core of heat transfer information, there are several others to which heat transfer engineers have paid only relatively little attention but which may well stimulate some of the most exciting and rewarding research and development. These areas include biotechnology, agriculture, food processing, fire prevention, as well as certain manufacturing processes. Although great opportunities for fruitful work exist in these fields of application a word of caution may also be in order. These disciplines have existed in the past without the help of any heat transfer experts, and sobering as the thought may be, significant progress has been made in spite of this. It therefore behoves those who wish to work in these fields to acquaint themselves thoroughly with all aspects of the problem to be solved before formulating their own research plans. Otherwise the efforts of the heat transfer engineer may add to the confusion rather than to the solution.
4. A field of study which relates to several applications and which will be of increasing importance is that concerning non-Newtonian fluids. Because of technological trends, interest in the study of a variety of such fluids may develop, including such diverse ones as slurries, polymer solutions, pastes, process foods, and granular media. In order to advance in this field there seems to be a special need for well planned experiments to elucidate the essential characteristics of the flow and the pertinent properties of the fluid. Eventually the role of non-Newtonian fluids in fluid mechanics may well be analogous to that of non-linear systems in solid mechanics.
5. A further point which has been emphasized by several contributors is actually non-technical in nature. An enormous amount of research and development has been conducted over the past years and the work is continuing at a rapid pace. A large portion of it has been conducted with aerospace or nuclear applications in mind but the results could well be relevant to problems in other fields. The amount of information that has been published is very large; the quality varies; some results are contradictory; some of it is difficult to interpret; experimental conditions are not always clearly pointed out—as a result much potentially useful information is lost and unavailable to the designer. For this reason there is a great need for careful and critical evaluation of results in the several fields and the periodic publication of authoritative surveys presenting the current state of knowledge and art in as clear a form as possible. Forty or fifty years ago textbooks often fulfilled this need—Stodola's work on "Steam and Gas Turbines" probably being one of the outstanding examples. For several reasons, textbooks only very rarely fulfil this role at present. Some books usually designated by such titles as

"Advances in ..." come the closest to rendering this service but usually are meant for the information of other research workers rather than for the designer. Just how the proposed evaluation and survey is to be done is not clear—but the need certainly exists and the service of making the best research information available to our technology in an efficient way should be rated highly.

A somewhat related point bears on the format of published papers. In order to make the information in the papers more easily accessible, publishers and societies might agree on a suggested format which may urge authors to include whenever applicable statements on the purpose of the work, the exact boundary conditions, accuracy of any measurements, comparison with previous results, etc. A certain standardization of this type will in turn make it easier to review and assess the work and to abstract any pertinent results for the types of surveys recommended above.

In closing it may be in order to comment again on the purpose of the report and to repeat some of the thoughts presented in the introductory remarks. Accordingly it is hoped that the material collected will be stimulating to the reader; that it will succeed in pointing out the very wide variety of subject matter in which heat transfer plays a major role; that it will encourage those presently engaged in a particular area of research to examine a wider range of needs in formulating his future plans; that it will give the prospective graduate students a feel for the rich possibilities of selecting a scientifically challenging and socially relevant area of investigation; and that it will give to the sponsors of research a broad spectrum of areas of interest against which proposed future work may be evaluated. Again, the most important contributions are likely to come from programs directed towards the understanding of fundamental aspects and mechanisms and any current projects directed towards this goal should enjoy continued support.

The report certainly does not pursue any one field or any one subject in depth and the information in the report is to be regarded as a "first lead" only. If a reader becomes interested in a particular subject he will have to consult persons directly concerned with the subject and familiarize himself with the pertinent literature. The present report lists no references largely because most of the information was derived on the basis of discussions, meetings and personal communications rather than from the literature. If, therefore, a prospective investigator should have difficulty in finding further discussion on a subject of potential interest, he should communicate with the writer who will then attempt to refer him to appropriate publications or to establish contact for him with an expert in the field who may be willing to give further information and advice.

In its present form the report does not establish any priorities and it is believed that such a listing is not appropriate at this time. One may expect, however, that with a fuller appreciation of the wide scope of heat transfer, both the investigators and sponsors will be open to opportunities in areas which have hitherto received relatively little attention.

As stated in the introduction the writer hopes to be able to keep this report current and pertinent by periodically preparing revised editions. In order to do so he is dependent on the active support of the *readers of this report who are again urged to communicate their thoughts, comments and suggestions as to pertinent future research in the field of heat and mass transfer.*