AG-81

PROSPECTS FOR THERMAL ENERGY STORAGE

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This paper is concerned with the problem of developing a method of storing thermal energy by the utilization of the heat of fusion of suitable compounds.

The first part of the paper discusses the incentives for the development of this type of energy storage. The second part deals with the problem of synthesising suitable materials. The third part discusses the problem of obtaining the needed heat transfer properties.

The main conclusions of this work are as follows:

1. *A good case can be made for space power systems utilizing thermal energy storage.*
2. *This is predicated on technical developments which appear probable, but which have not yet been accomplished.*
3. *A great deal of work remains to be done in two major research areas. One, the determination of phase diagrams of promising eutectic mixtures, and two, the experimental and theoretical determination of heat transfer properties.*
4. *A carefully planned systematic approach is needed to obtain the information necessary for systems comparisons.*

On considère le problème du développement d'une méthode de stokage d'énergie thermique en se servant de la chaleur de fusion de mélanges appropriés.

Dans la première partie, on discute l'intérêt du développement d'un tel stokage. Dans la seconde, la synthèse des matériaux néccessaires est discutée. La troisième partie a trait aux propritétés de transfert de chaleur requises.

En conclusion il est montré que:

1. *Le stokage d'énergie thermique est une méthode interessante pour les systèmes de propulsion spaciaux.*
2. *Un tel système repose sur des avances techniques probables mais non encore accomplies.*
3. *Un travail de recherche important reste à faire dans deux domaines principaux: les propriétés de fusion des mélanges eutechniques et la détermination théorique et expérimentale des propriétés de transfert de chaleur.*
4. *Un travail systémathique d'information est nécessaire a l'évaluation comparative de systèmes différents.*

INTRODUCTION

A particular class of auxiliary space power systems for orbiting vehicles consists of a combination of a heat engine and solar energy as a heat source. The distinguishing features of such a system are a solar concentrator, a heat receiver, and an energy converter of the static or dynamic type.

In order for the power system to be able to operate while the vehicle is in the dark portion of its orbit, it is necessary to include some form of energy storage. Two possibilities exist. The first method uses an excess capacity of converters. This excess power may then be stored electrically by the use of either batteries or fuel cells. The second method stores thermal energy in the form of heat of fusion of suitable compounds, which makes it unnecessary to provide an excess of converters.

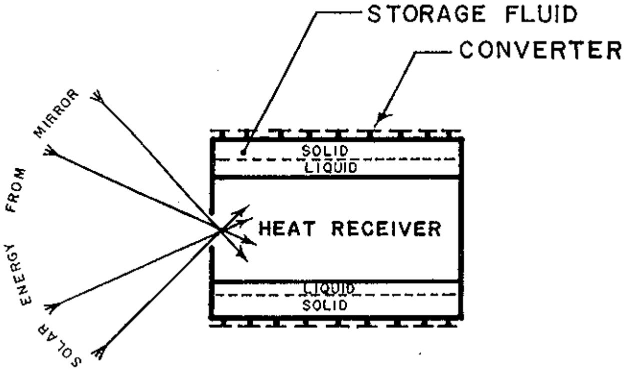

Fig. 1. Heat receiver

The use of thermal energy storage appears to have two major advantages over the use of electrical storage. The first of these is the fact that the use of a thermal energy storage fluid minimizes temperature fluctuations of a system. The advantages of this become more pronounced as the operating temperature of the converter increases. In the case of a thermionic system it is certain that the lifetime of these converters would be greatly increased by the elimination of the severe thermal stresses which would be produced by having a heat receiver be exposed to cold black space from an original temperature of about 2000°K. The second advantage of thermal energy storage over electrical storage appears to be a smaller total systems weight which appears to be the case whenever the efficiency of the energy converter is low.

The general scheme of the use of thermal energy storage is illustrated in Fig. 1. Solar energy is concentrated by the use of a parabolic mirror, and is focused on the opening of a heat receiver. The geometry of the heat receiver will vary greatly with the particular energy converter which is utilized. The simplest type of system is shown in Fig. 1 where an annular space within the heat receiver is filled with a material which has a desired melting point and a high heat of fusion. The energy converter, which may be of the static type, like thermionic or thermo-electric generators, or a dynamic one, such as a turbo-electric generator, would be coupled to this heat receiver.

The heat energy entering the heat receiver will do three things. A portion of it will be reradiated through the opening of the heat receiver, a portion will be transmitted through the storage material to the converters, and a third portion will be used in melting more storage material.

At the end of the heating cycle, i.e., when the space vehicle enters the dark portion of the orbit, the opening of the heat receiver would be closed in order to minimize heat losses from the cavity, and the heat energy liberated by the solidifying storage material would be used to power the converter. A sufficient amount of storage material has to be included such that the space vehicle would face the sun again before all material has been solidified.

This conceptual design of a space power system appears exceedingly simple, but is actually a tremendously difficult technological problem. The main body of this paper is devoted to a discussion of these technical problem areas, but at this point it might be advisable to discuss the possible incentives for developing systems of this type.

It is generally agreed that auxiliary power in the range of less than 1 kilowatt can be provided by the use of photovoltaic cells which utilize either batteries or fuel cells for energy storage. Such power systems have been developed to the point where they can be used reliably and their performance can be accurately predicted. It is expected that photovoltaic power systems in the multi-kilowatt range will become more and more difficult to engineer due to the difficult problem of packaging, deploying, and providing adequate structural support.

In the power range approaching a megawatt it is clear that nuclear powered systems will have major advantages.

It may be anticipated then, that solar-powered systems of the type discussed in this paper would be most competitive in the power range of the order of a few hundred to a few thousand watts.

If one were to attempt to compare a "typical" solar-powered system with thermal energy storage to a photovoltaic system utilizing batteries, one would be forced to commit the grievous error of comparing a tried and true system to a hypothetical "gleam in the eye". In spite of this obvious difficulty it may prove instructive to list the result of one of the many such studies which have been made.

Ker (Ref. 20) reports the following results of a comparison of a solar thermionic system utilizing thermal energy storage with a state of the art photovoltaic system and an advanced photovoltaic system which would depend on the development of rechargeable silver cadmium batteries or secondary fuel cells. The results of this study were as follows:

	Power system specific weight
Solar thermionic system	75 lb/kilowatt
State-of-the-art photovoltaic system	857 lb/kilowatt
Advanced photovoltaic system	256 lb/kilowatt

Admittedly such a comparison must be accepted with a grain of salt. The following point should be kept in mind, however. The specific weight of the solar thermionic system cannot be expected to vary significantly from the figure listed above. In other words, if such a system can be developed, its performance would certainly be within a factor of 2 of that listed, or else technological difficulties will prevent the engineering of such a system altogether.

Needless to say, specific weight is only one of the many factors which must be considered in any such comparison. Other important factors are reliability, cost, volume, etc.

In a comparison to nuclear systems one even has to include such complex considerations as safeguards and the complexity of systems checkout before flight.

At this point it might be well to look at this problem from the point of view of the vehicle systems designer.

SYSTEMS CONSIDERATIONS

1. The vehicle designer who has to select a power plant needs the ability to make trade-off studies between different power systems.
2. In order to accomplish this, he must be able to optimize different systems for his specific applications.
3. This makes it necessary to have a mathematical model of all the components of such a power system.
4. Ideally, a hybrid computer system would be used to provide a realistic analogue of the system.
5. It must be recognized that the eventual design point will be determined by the system transients and not steady-state conditions.
6. This implies that the analogue system must be able to simulate both startup as well as component failure conditions.

It is now appropriate to raise the question as to whether this type of analysis can be performed at this time with solar-powered heat engines including thermal energy storage.

It appears to this writer that our ability to predict the performance of solar collectors and that of either static or dynamic conversion devices has been developed satisfactorily. The big remaining unknowns are the thermal performance of cavity-thermal energy storage combinations.

It must be recognized that the external geometry of the heat receiver will vary greatly depending on the specific system which is used. For instance, in the case of thermionic systems, the heat receiver must have cones projecting into the cavity. The reasons for this are that reliability considerations suggest that separate storage vessels should be used, and the fact that heat transfer considerations place a premium on large surface areas.

It is seen from the above that conflict exists between the design of the cavity to minimize temperature drops through the thermal energy storage fluid on one hand and reradiation losses on the other.

It is equally clear that it is not possible to separate the solar concentrator from the heat receiver in any optimization scheme, and an optimization procedure will have to include not only the solar collector and heat receiver but the converters as well. The impossibility of optimizing the various components separately is further illustrated by the fact that the reradiation losses are going to be dependent not only on the geometry of the heat receiver but also on the temperature of the inner surface of the heat receiver. The inside wall temperature of the heat receivers is going to depend on the physical, chemical, and transport properties of the thermal energy storage used, as well as on the particular orbit and conversion system which is used. Let us next consider what is known about possible thermal energy storage fluids.

THERMO-PHYSICAL PROPERTIES OF STORAGE FLUIDS

Ideally one would like to have available a variety of thermal energy storage fluids, with melting points covering the temperature range of interest. Systems optimizations could then include a particular thermal energy storage fluid as one of the parameters to be varied. At the present time very little is known about suitable thermal energy storage fluids, and the result of this has been that a particular compound was selected and the system optimized for this particular compound.

At the time of this writing two compounds have received the lion's share of attention, namely, lithium hydride and lithium fluoride. In the case of lithium hydride a major difficulty was encountered in that an irreversible production of hydrogen occurs. This hydrogen gas tends to diffuse towards the coldest part of the system, namely, the radiator, the turbine system under development. The accumulation of this hydrogen degrades the heat transfer performance of the radiator. Because of this it is still not certain that lithium hydride will be a suitable compound, in spite of the fact that it is extremely attractive from the point of view of its high heat of fusion. Work on lithium fluoride has just begun and detailed information has not yet been made available.

Because of the almost complete lack of pertinent information concerning suitable compounds, it appears to this writer that one of the most important things which ought to be done in the immediate future would be to obtain the characteristics of a great many compounds including binary and ternary eutectics which appear to be promising.

To date two major classes of compounds have been scanned for their suitability as thermal energy storage fluids. One group of compounds has melting points compatible with dynamic systems utilizing either the Rankin or Brayton cycle. The other group has melting points suitable for use with high-temperature thermionic systems.

A summary of what is known about the thermo-physical properties of promising storage fluids has been compiled by Sharma and Chang (Ref. 21).

Tables 1, 2, and 3 from this reference are presented below together with excerpts from this reference which are appropriate for our present discussion (with permission of these authors).

Table 1. Thermophysical Properties of Metals

Metals or Compounds	*M.P.°K*	*Heat of Fusion at Melting Point* cals/mol	cals/gm
B[a]	2440(1)	5300	490
Be	1556 ± 2(2,3)	2800(3) ± 500	310
Si	1685 ± 2(4)	12,110(4) ± 100	431
$CoSi_3$	1579(5)	34,000 ± 2500(5)	238
Mg_2Si	1375(2)	20,500 ± 2500(2)	270

[a] Heat of fusion has been calculated on the assumption of entropy of fusion is 2·1 to 2·3 e.u.

Table 2. Thermophysical Properties of Compounds

Compounds	*M.P.°K*	*Heat of Fusion at Melting Point* cals/mol	cals/gm
Li_2O	1700(6)	14·00(6)	470
BeO	2820(6)	17·00(6)	680
		15·10(7) ± 0·4	605
CaO	2860(6,9)	19·00(6,9)	340
MgO	3075(2,6,8)	18·50(2,6,8)	460
Al_2O_3	2318(2)	26·00(2)	260
LiF	1121(6,9)	6·474(6,9)	250
BeF_2	1088(6), 560(20)	12·90(6)	274
MgF_2	1536(2,3)	13·90(2,3)	224

Note. Superior figures in parentheses refer to References.

Table 3. Binary Systems of Oxides or Fluorides

Ref.	*System*	*Eutectic Composition X*	*Eutectic Temp.* T_e0°K	*Estimated Heat of Fusion* cals/gm mole	cals/gm
3, 6	CaO—BeO	0·67 BeO	1738	10,000	283
3, 2	MgO—BeO	0·67 BeO	2143	12,000	400
3, 2	CaO—MgO	0·5 MgO	2573	16,300	340
1, 3	LiF—NaF	0·39 NaF	925	5510	171
1, 2	LiF—MgF_2	0·33 MgF_2	1015	6940	185
2, 3	LiF—BeF_2	0·50 BeF_2	633	5580	153
1, 2, 3	MgF_2—BeF_2	0·90 BeF_2	948	10,900	224

Table 1 indicates the suitability of the materials B, Be, Si, $CoSi_3$, and Mg_2Si for the thermal energy storage insofar as the heat of fusion to weight ratio is concerned. The use of Boron, because of its high melting point of

2440°K, is ruled out while Be, Si, $CoSi_3$ and Mg_2Si may present difficult container problems.

Table 2 points out the suitability of the compounds Li_2O, BeO, MgO, CaO, Al_2O_3, LiF, BeF_2, and MgF_2 with heats of fusion per gm of 470, 605, 460, 340, 260, 250, 274, 224, respectively. Pure BeO, MgO, CaO and Al_2O_3 cannot be used, as their melting points are above the temperatures considered. The compounds Li_2O, LiF, and MgF_2, appear to be some of the likely thermal energy storage materials, although the decomposition pressure of Li_2O is high at the melting point (1700°K). They also do not offer a wide range of temperature selection. This may be achieved by utilizing the eutectics of the refractory oxides of fluorides.

Unfortunately, even approximate heat of fusion data are not available for most of these mixtures.

Heat of fusion for 60 BeO–40 MgO 500 cal/gm and for 60 BeO–40 CaO 221 cal/gm reported by Batutis (Ref. 4) and 200 cal/gm for the latter system by Glasscock, Jr. (Ref. 5) may be open to question for the reason that CaO and MgO are chemically similar and the heats of fusion of 60 BeO–40 MgO and 60 BeO–40 CaO, in spite of their different melting points, should not differ more than 100 cals. The present difference is more than double the expected one.

On the assumption that the entropy of fusion of the oxide or fluoride under consideration does not change between the melting point and the eutectic temperature, and that there is no interaction between the components, the heats of fusion of the eutectic compositions have been calculated for the systems whose phase diagrams and necessary thermal data are available. These are presented in Table 3.

This table should also have contained some eutectic mixtures containing Li_2O, but this has not been possible on account of the unavailability of phase diagrams. As may be seen from the table, the eutectic of CaO—BeO, MgO—BeO, CaO—MgO and BeF_2—MgF_2 appear to be suitable. Though the paucity of data does not allow any calculations for prediction, however, some ternary systems such as CaO—MgO—Li_2O, BeO—MgO—Li_2O, BeO═CaO—Li_2O, and CaO—MgO—BeO may cover a wider range, between 1500°–2100°C, while the eutectics of LiF, BeF_2, and MgF_2 may be appropriate for temperatures of about 1000°K. The lowering of the fusion temperature may also overcome the dissociation problem of Li_2O. It might also be possible to use the eutectics, such as $BeF_2 + BeO$, $MgO + MgF_2$ etc., as the strong deviations from ideal behavior typical of such systems may be advantageous. The most disappointing thing about the systems considered above is that neither established phase diagrams nor accurate data on heats of fusion are available.

Basically, the thermo-physical properties and transport properties of the thermal energy storage fluids which are needed are the melting point, heat of fusion, densities, volume changes, conductivities, thermal radiation effects, and container compatibility. It is unfortunately true that for the compounds of interest none of these properties are readily available.

A further difficulty exists in that properties of compounds at very high temperatures are very difficult to obtain. One example of this is the estimation of heats of fusion. One way of estimating heats of fusion is, as has been pointed out before, the use of the entropy of fusion. It is, however, possible to use a much more accurate method for the estimation of the heats of fusion (Ref. 18). If one examines the results of the predictions of these two methods, one finds startling discrepancies in the results of the two. For example, the predicted heats of fusion for the binary eutectic of lithium fluoride and magnesium fluoride are 185 cals/gm using the entropy of fusion method, whereas, the "exact" calculation results in a calculated value of 200 cals/gm. In view of the fact that experimentally measured quantities of heats of mixing and similar measurements were used in the so-called exact method and, further, since the results of the two computations for this particular mixture would be expected to result in very good agreement, one can only conclude that one or several of the measured quantites are in error.

Another difficulty which must be watched out for is illustrated by the two compounds calcium fluoride and magnesium fluoride. Because of the similarity in structure of these two compounds one would expect that the heats of fusion ought to be very close to one another. It turns out, however, that the experimentally determined heats of fusion are 91 cals/gm for calcium fluoride vs 224 cals/gm for magnesium fluoride. This would indicate that in all likelihood calcium fluoride exhibits a metastable state. Clearly, then, one has to be on guard as far as other compounds are concerned to make sure that such metastable states do not exist. One way to determine definitely whether such a state does indeed exist would be to determine the heat of fusion of a mixture of calcium fluoride and magnesium fluoride. In such a mixture it is not likely that calcium fluoride would exhibit such a metastable state, and therefore, one should expect to find a combined heat of fusion of the mixture to be closer to the high value corresponding to magnesium fluoride.

An examination of various available compounds tends to indicate that the binary eutectics of lithium oxide with beryllium oxide, magnesium oxide, and calcium oxide, ought to be very good from the point of view of high heats of fusion over a considerable temperature range. Yet, no data on these compounds are available.

HEAT TRANSFER PROPERTIES OF THERMAL ENERGY STORAGE FLUIDS

The general problem is illustrated by Fig. 1. Solar energy is concentrated by the use of a parabolic mirror, and is focused on the opening of a heat receiver. An annular space within the heat receiver is filled with a material which has a desired melting point, and a high heat of fusion. Mounted on the outer surface of the heat receiver are the energy converters which produce electric power. These concerters might be the "Direct" type, like thermionic or thermoelectric generators, or else the working fluid or turboelectric generators could be heated in this fashion. The heat energy entering the heat receiver will do three things. A portion of it will be reradiated through the opening of the heat receiver. A portion of it will be transported through the storage material to the converters, and a third portion will be used in melting more storage material.

At the end of the heating cycle, i.e. when the sun goes down, the opening of the heat receiver would be closed to prevent further reradiation and the heat energy liberated by the solidifying storage material would be used to power the converters. Enough storage material would be used, so that before all the material was solidified the mirror would face the sun again, and the cycle would be repeated.

This simple concept leads to an exceedingly complex heat transfer problem, as illustrated by the following figures.

For a typical space power application, a duty cycle might consist of 60 minutes of sunlight and 40 minutes of shade. A thermionic converter may need heat fluxes of the order of magnitude of 100,000 Btu/hr-ft^2 of active emitter area. A representative thermal storage material might have a heat of fusion of 300 to 400 Btu/lb, a density of 200 lbs/ft^3, and a thermal conductivity of the order of 1 Btu/hr-ft-°F. A simple calculation shows that if the cross-sectional area of the container is equal to that of the converter, then its depth would have to be about 0·8 ft to contain enough storage material to allow operation for 40 minutes. In order to transfer 100,000 Btu/hr through 0·8 ft. of storage material would require a temperature difference of about 80,000°F, an obvious impossibility. This explains why the cross-sectional area of the thermal storage container shown in Fig. 2 is so much larger than that of the converter. However, even if the area ratio is as large as 10, and the depth is only one tenth of that in the above example, temperature drops will still be about 800°F, which is still too large for practical purposes. The next step would be to resort to internal finning, which would, however, result in increased weight.

Figure 2 shows the conceptual design of a thermionic converter with attached thermal storage and internal finning. The fins are shown as concentric cylinders, and are attached alternately to the top and bottom surfaces for reasons to be discussed later.

Let us now consider the region between such concentric fins. Neglecting the effects of curvature, it is possible to consider heat transfer between the fins as a one-dimensional problem.

Figure 3 shows an anticipated temperature history for an enlarged section of the space between two fins. Figure 3a shows the temperature distribution to an arbitrary scale at a time which would correspond to the end of the sunlit portion of the cycle. Almost all the material has been melted. Figure 3b shows the temperature distribution about halfway into the dark cycle. Note that a great deal of solidification has taken place on the side connected to the converters. Because of heat leakage through the heat receiver, some solidification has taken place at the opposite end also.

Figure 3c shows the temperature profile some time after the mirror is exposed to the sun again. Note that four regions exist in the storage fluid.

Figure 3d shows the profile after the solid region near the heated end has disappeared again.

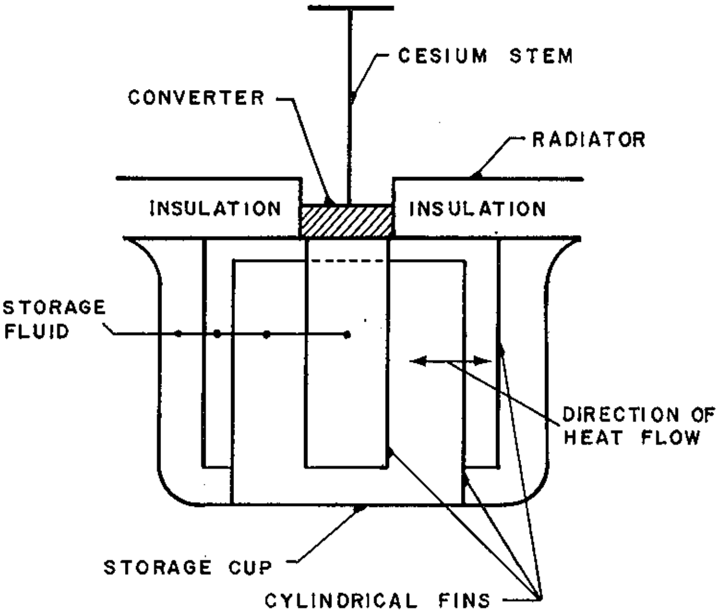

Fig. 2. Conceptual cup design

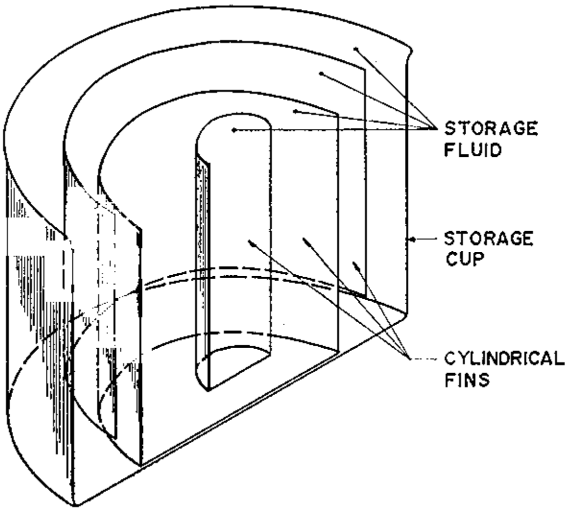

Fig. 2A. Isometric conceptual cup design

From the above description of the physical process it is clear that the heat transfer problem is one which involves six regions, i.e. the walls and the four regions within the storage fluid, and two moving boundaries. The problem is further complicated by the fact that one of these moving boundaries, namely that separating the melted and solid regions near the hot end, appears only during part of the cycle.

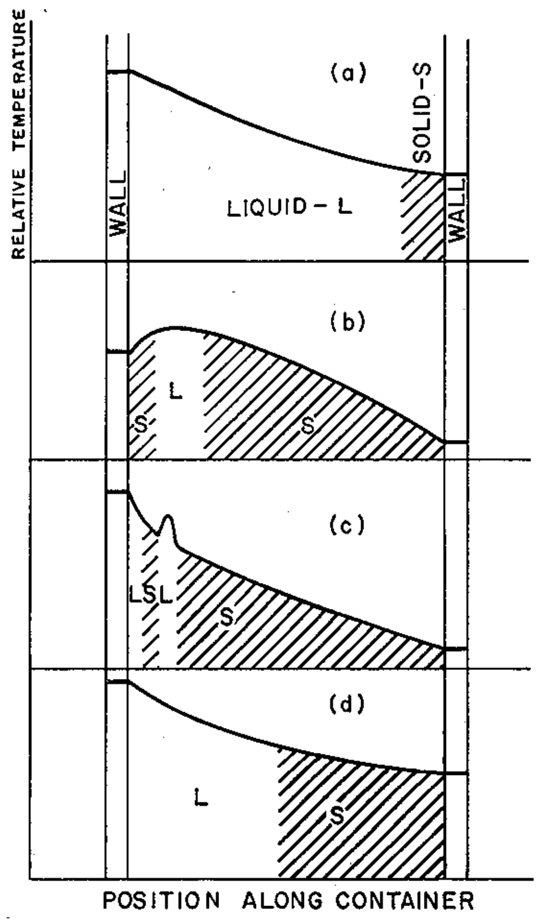

Fig. 3. Temperature profiles

The above problem, even the one-dimensional one, is complicated enough. There is a further complication, however. At temperatures in the neighborhood of 1500°C or higher, some of the materials of interest become partially translucent. Some of the heat transfer will then occur as radiation heat transfer superimposed on the conduction (Ref. 15).

The interface resistance between the container wall and the liquid will depend strongly on the wetting properties. To really appreciate this problem, it must be remembered that operation in a zero gravity field must be considered. The container will have to be bigger than the volume of the storage fluid to allow for expansion due to phase transformation. If the liquid does not wet the container, then it might collect in the form of a bubble, and heat might actually have to be transferred by radiation across any resulting gap between fluid and wall. Even if it does wet the container, it is difficult to predict what the interfacial resistance will be.

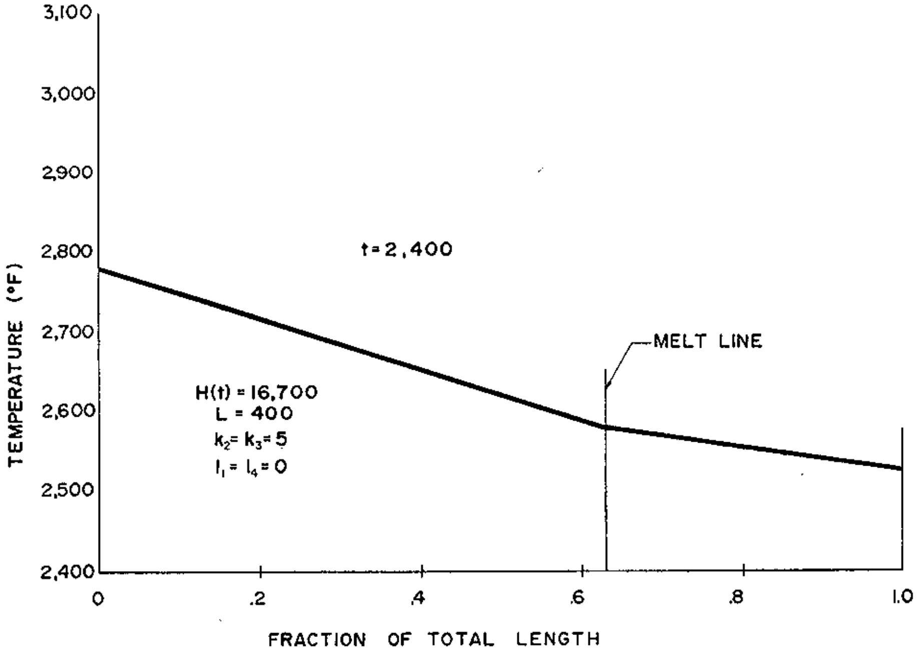

Fig. 4. Computed temperatures

The interface resistance between the wall and solid is another important unknown.

The total heat transfer problem, then, can be conveniently divided into two main problem areas. One, the determination of effective diffusivities, and two, the analysis of the multiregion-multiple moving boundary problem.

The different modes by which heat may be conducted through solids and liquids at temperatures greater than about 1500°K is discussed in detail in Refs. 15 and 16. It is known that photon conduction as well as the electronic thermal-conductivity may approach the order of magnitude of lattice thermal-conductivities. The consequence of having an appreciable fraction of the heat transported by photon or electron conduction is the fact that the heat transfer problem becomes a strongly nonlinear one. At the present time analytical techniques for treating this type of heat transfer problem do not exist. The crux of the problem is that if an effective conductivity is determined for a specific set of conditions it may not be possible to extrapolate readily to other conditions which might involve different geometries or temperature distributions. The strong variation in heat transfer due to combined phonon and photon conduction is illustrated in Table 4 which has been calculated by Ross (Ref. 17). For a detailed study of the problem of predicting heat transfer by simultaneous conduction and radiation through absorbing media the reader is referred to Refs. 22, 23, 24, and 25.

Table 4. ½-inch Sample Thickness ($\varepsilon = 1$)

T_2 (°K)	T_1 (°K)	K_{-1} (in.)	k (Btu/hr-ft°F)	$q_{r/A}$	$q_{c/A}$	qA (Btu/hr-sq ft)
2000	1900	21	5	5400	21,600	27,000
1800	1700	21	5	3900	21,600	25,500
2000	1900	5·9	2	17,200	8700	25,900
1800	1700	5·9	2	12,400	8700	21,100
2000	1900	—	0·5	5400	2160	7560
2000	1700	21	5	14,000	65,000	79,000
2000	1700	5·9	2	45,000	26,000	71,000
2000	1700	—	0·5	140,000	6500	146,500
2000	1700	5·9	0·5	45,000	6500	51,500
2000	1700	21	0·5	14,000	6500	20,500
			one-inch sample			
2000	1700	21	5	7500	32,500	40,000
2000	1700	5·9	2	25,200	13,000	38,200
2000	1700	—	0·5	140,000	3250	143,250
2000	1700	5·9	0·5	25,200	3250	28,450
2000	1700	21	0·5	7500	3250	10,750

The problem of predicting the transient heat transfer performance of thermal energy storage fluids with moving boundaries is discussed by Altman *et al.* (Ref. 14) and by Springer and Olson (Ref. 19) among others.

Reference 14 includes an analysis of a typical solar thermionic system. Results of a mathematical solution of a two-region problem with one moving boundary are presented. Figure 4 shows the results of a typical calculation giving the temperature profile throughout the two regions of the thermal storage fluid at a specific instant of time. It can be seen from this curve that the temperature profiles are linear, which suggests that for this particular class of problems it is possible to simplify the analysis greatly by the utilization of quasi steady-state techniques, i.e., the heat stored as sensible heat in the solid and liquid may be neglected, compared to the heat throughout and the heat stored at the moving interface. At higher heat flux rates, such simplification may not be possible, and the method of Ref. 14 is recommended as a good approximation.

SUMMARY AND CONCLUSIONS

The development of heat receivers utilizing thermal energy storage is at a stage of development where feasibility has not yet been established, nor has it been ruled out. The development program involves the generation of a high-temperature technology which currently is in an "infant" stage.

It is essential that a systematic effort be made to generate phase diagrams for promising eutectic mixtures.

The problem of superimposed phonon and photon conduction is well understood qualitatively but extensive experimental measurements must be made before data can be extrapolated with confidence.

The analytical techniques for utilizing effective average diffusivities have been developed but further study is necessary to justify the use of these average diffusivities or conductivities.

Past work has shown that the containment of high-temperature thermal energy storage materials presents a major problem and suitable heat receiver fabrication techniques will have to be developed.

*This work was supported by the National Aeronautics and Space Administration under contract NsG-*316 *to the Institute for Direct Energy Conversion of the Towne School of Civil and Mechanical Engineering of the University of Pennsylvania.*

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DISCUSSION

E. M. Cohn:

Dr. Altman has pointed out the great lack of detailed and basic information regarding the physico-chemical properties of potential candidates for thermal energy storage. To this I might add that some of the substances investigated thus far have proven to be thermally unstable or corrosive in the presence of traces of water and are extremely difficult to contain at their operating temperatures. A more empirical approach to a quick solution of these problems, now being studied at GE under a NASA contract, is to fabricate CERAMETS. In effect, the idea is to enclose the ceramic in a metal "sponge", the pores of which are closed during fabrication. Film deposition of metal on ceramic, followed by hot pressing or machining, is being studied, with the objectives of (a) solving fabrication problems now experienced with welded containers, (b) minimizing troubles due to volume changes, and (c) improving thermal conductivity over that possible with finned containers. Needless to say, having the missing thermodynamic data, which Dr. Altman's group is in the process of obtaining, would greatly simplify this more empirical approach.

As the author has already said, Kerr's comparison, made in 1961, between thermionic and photovoltaic systems is a bit outdated. Later data indicate more nearly equal power densities for the two kinds of systems. Nevertheless, spacecraft with heat engines and thermal energy storage are of interest. The storage feature would be useful for satellites or perhaps for long mid-course maneuvers when altitude control is impossible. Dynamic engines, particularly, promise large weight savings if and when tens of kilowatts may be needed. Since this is still some time in the future, a crash program, fortunately, is not needed. We hope that, meanwhile, much of this gap in our knowledge can be filled—not only to assist in solving space power problems but also to advance high-temperature science and technology generally.

SECTION C

ENERGY CONVERTERS