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Space Power Systems

PART II

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

SPACE POWER SYSTEMS

Published in Two Parts

P A R T II

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IVB. TURBOMACHINERY FOR SPACE POWER

by

Eugene B. Zwick

8901 Zelzah, Northridge, California,
(213) 345-6078

SUMMARY

Recent advances in turbomachine technology for missile and space power applications have far reaching implications for all power system designs. Low specific machine performance has been greatly improved. In addition, new optimized turbomachinery design data is being derived. Machine performance and design data can now be found on $N_s - D_s$ diagrams. These data are in a form which is immediately usable by systems analysts. No specialized turbomachinery background knowledge is required.

The preliminary design of a 20 kW Biphenyl Rankine cycle power plant was used to illustrate the application of the $N_s - D_s$ concepts and charts.

IVB. TURBOMACHINERY FOR SPACE POWER

Eugene B. Zwick

INTRODUCTION

Dynamic heat engine cycles derive their work output from the difference between the expansion work of a high temperature working fluid and the compression work required by the same fluid at low temperatures. Both reciprocating and turbomachinery can be used in dynamic space power systems to perform the expansion and compression processes required. Turbomachinery is used in most of the systems which are currently under development. Turbomachinery technology has generally been paced by the demands of power generating systems. The early development of efficient turbines was stimulated by the installation of large steam power plants for the generation of electricity. Development in this field reached a plateau which was well described by Stodola in his work on steam and gas turbines.

During the second world war and afterwards the development of turboprop and turbojet engines further stimulated turbomachinery research. Impulse turbine technology was improved and considerable work was done during this period of time on axial flow and radial flow compressors. These machines have high specific speeds. They have relatively small work per stage with large power output and large volume flow of fluid.

The development of missile power systems in the early 1950's led to requirements for efficient turbines in the low specific speed regime. These machines were characterized by low power output with energy being extracted from a gaseous stream with very high specific energy content. The developments which took place under the stimulus of missile power requirements led to two extremely beneficial results. First there was a great increase in the efficiency of low specific speed turbines. Secondly, a generalized approach to optimization and selection of turbines, compressors, and pumps was developed. This generalized approach has had a great influence in the development of space power systems, and I am confident that it will have a considerable impact in many future applications of turbomachinery.

In the present lecture we will examine this generalized approach and see how it is applicable to the design of a typical space power system. In order to make these results significant one must first have a background in the basic concepts of turbomachinery. A preliminary discussion of these concepts is therefore presented below.

I. BASIC TURBINE CONCEPTS AND TERMINOLOGY

Figure 1 shows the typical configuration of an axial flow turbine. The turbine rotor is preceded by a nozzle which draws a supply of gas from an upstream supply line. The gaseous working fluid flows through the nozzles where it is accelerated to high velocity and directed towards the turbine blades. The gas flows through the blade passages, and after emerging from the downstream side of the wheel it passes onto the next stage of the machine or into an exhaust duct. The mechanism by which the turbine provides power to the shaft is the change in momentum of the gas stream as it flows through the turbine blades. In an impulse turbine, see Figure 2, there is no pressure drop across the blading and ideally the gas velocity is constant. In this case the change in momentum of the gas stream is accomplished only by changing the gas flow direction. In a reaction turbine, Figure 3, there is a pressure drop across the blades. This results in acceleration of the gas as it passes through the wheel. The change in momentum which occurs in a reaction machine arises from both the change in flow direction and the acceleration of the flow.

A. Impulse Turbines

To understand the impulse turbine better it is necessary to examine in detail the velocity change which occurs through the wheel. Figure 5 shows the ideal velocity diagram for an impulse machine. The fluid leaves the nozzle and flows towards the blades in a tangential direction with a velocity C imparted by the expansion through the nozzle. The flow enters the turbine blades with a relative velocity W with respect to the turbine blades. This velocity is reduced compared to C by the magnitude of the tangential velocity of the blade system. The relative velocity is thus given by

$$W_1 = C - U .$$

In this ideal case the fluid in the blade passages is turned through an angle of 180° and leaves the wheel flowing tangentially with the same velocity relative to the blade surfaces with which it entered ($W_2 = W_1$). As noted in diagram 5 the absolute velocity of the flow with respect to the stationary nozzle structures is now

$$C_2 = C - 2U .$$

The analysis of this case can be approached from either of two directions. We can examine the fluid velocities before entering and after leaving the wheel, and establish the change in energy which has taken place. This must be reflected in power which has been extracted by the turbine. Alternatively we can examine the forces acting on the turbine blades, caused by the change in flow direction. Since this force acts on a moving surface we can immediately establish the rate of power extraction.

The equations for the external velocity approach are presented below. The inlet energy flow rate, E_1 , is given by

$$E_1 = \frac{1}{2} \dot{m} C^2 .$$

The specific energy flow at the exit is

$$\begin{aligned} E_2 &= \frac{1}{2} \dot{m} C_2^2 \\ &= \frac{1}{2} \dot{m} (C - 2U)^2 . \end{aligned}$$

The decrease in energy of the flow gives the power extracted by the wheel

$$\begin{aligned} P &= E_1 - E_2 \\ &= 2\dot{m}U(C - U) . \end{aligned}$$

The corresponding development for the force on the blades is the following. The change in momentum of the flow gives the force on the blades

$$\begin{aligned} F &= \dot{m}(\bar{W}_2 - \bar{W}_1) \\ &= 2\dot{m}(\bar{C} - \bar{U}) . \end{aligned}$$

The rate of doing work is then

$$\begin{aligned} P &= \bar{F} \cdot \bar{U} \\ &= 2\dot{m}U(C - U) . \end{aligned}$$

We may now form an expression for the efficiency with which the turbine has converted the energy which was available in the nozzle stream into useful work. The total available energy in the stream is given by

$$P_{\max} = \frac{1}{2} \dot{m} C^2 .$$

The power extracted per unit mass flow is given by

$$P = 2\dot{m}U(C - U) .$$

Hence we see that the efficiency of the ideal impulse turbine is given by

$$\begin{aligned} \eta_I &= \frac{P}{P_{\max}} \\ &= 4 \left(\frac{U}{C} \right) \left[1 - \left(\frac{U}{C} \right) \right] . \end{aligned}$$

Figure 6 shows the variation of efficiency with the parameter U/C . It is clear that the maximum achievable efficiency is 100% and that this occurs for a value of U/C equal to 0.5.

Figure 7 shows a real impulse turbine in which the nozzle angle α is no longer zero, and the velocity ratio through the blades is no longer 1.0. The analysis of this case is readily handled by examining the change in momentum of the flow through the blades. The development of the equation yields

$$\eta_I = 2 \frac{U}{C} \left(\cos \alpha - \frac{U}{C} \right) \left(1 + \psi \frac{\cos \beta_2}{\cos \beta_1} \right) ,$$

where

α = nozzle angle

β_1 = blade inlet angle

β_2 = blade exit angle

$\psi = W_2/W_1$.

For a true impulse machine, there is no pressure drop across the wheel to accelerate the flow. If the blade height is constant, then continuity requires that

$$W_1 \sin \beta_1 = W_2 \sin \beta_2 ,$$

so that β_1 cannot equal β_2 unless $\psi = 1.0$. This yields

$$1 + \psi \frac{\cos \beta_2}{\cos \beta_1} = 1 + \frac{[(x^2 - 2xy + 1)^2 - 1 + y^2]^{\frac{1}{2}}}{(y - x)}$$

where

$$x = U/C ; \quad y = \cos \alpha .$$

For $\beta_1 = \beta_2$, the blade height must increase for $\psi < 1$ if there is to be no pressure drop through the wheel. Then the velocity factor in the efficiency equation is

$$1 + \psi \frac{\cos \beta_2}{\cos \beta_1} = 1 + \psi .$$

Figures 8a, 8b, and 8c show the efficiency of impulse turbines. Figure 8a is for the turbine with constant blade height but $\beta_1 \leq \beta_2$. The limiting values of U/C shown correspond to a blade exit angle of 90° . Figure 8b shows the efficiency of a turbine with symmetrical blades but increasing bucket depth in the flow direction. The solid curves are for a nozzle angle of 0° . The dotted curves are for a nozzle angle of 20° . ψ is varied for each case. Figure 8c compares the two types of turbines. It is clear that the symmetrical blade is better. For $\alpha = 20^\circ$ and $\psi = 0.87$, $\eta_{\max} = 0.88$. This occurs at $U/C = 0.47$. These parabolas are typical of the data which one obtains for impulse turbines. In general the efficiency curve is a parabola whose peak occurs at slightly less than $U/C = 0.5$. The reduction in efficiency between the ideal case and the real case illustrated here is due not only to losses in the flow, but also to the fact that a nozzle angle other than zero must be used if there is to be any real flow through the machine.

There are other losses which occur in a real impulse turbine which further reduce the efficiency and shift the optimum point. The wheel usually rotates in a fluid environment, and hence disc friction power must be subtracted from the power extracted by the blades. In addition, there are losses in the nozzle, at the leading edge of the buckets, and at the trailing edge of the buckets. The nozzle losses are generally expressed in terms of the nozzle efficiency which depends on the geometry and Mach number of the nozzle.

If the flow relative to the blades is subsonic, a well rounded airfoil section can be used. This permits uniform flow into the buckets over a range of turbine tip speeds and flow rates. If the flow is supersonic, it is necessary to provide a sharp leading edge to the blades to avoid the formation of a normal shock. Supersonic relative velocities up to Mach 2.0 can be handled with relatively small losses. Above $M = 2.0$, the losses become significant and extreme care must be used in the design of the blades.

As the flow leaves the blades, a wake is formed. Energy lost in this wake can be significant to the performance of the machine. A sharp leading edge and trailing edge are desirable in high energy level impulse turbines.

B. Reaction Turbines

Figure 9 shows the velocity diagrams for a reaction turbine. In this case the so called 50% reaction stage has been shown. The fluid is accelerated through the nozzle and directed toward the blades in the same fashion as in an impulse turbine. Once the fluid enters the blades it is again accelerated by virtue of a pressure drop across the wheel. The high pressure which exists upstream of the wheel and the low pressure which exists downstream of the wheel cause the blades to act as nozzles.

The efficiency analysis for a reaction turbine starts with the delivered power

$$P = mU(W_1 \cos \beta_1 + W_2 \cos \beta_2) .$$

The ideal input energy is the sum of the nozzle and wheel head drops

$$P_{\max} = \frac{1}{2} \dot{m} [C_1^2 + (W_2^2 - W_1^2)] .$$

For 50% reaction, the two head drops are equal, so that ideally for this case

$$P_{\max} = mC_1^2 .$$

In the actual flow, only a fraction, ϵ , of the kinetic head in the gas is recovered in the blades. Therefore the exit velocity from the blades will be reduced to

$$W_2^2 = C_1^2 + \epsilon W_1^2.$$

Noting that

$$\begin{aligned} W_1^2 &= C_{u1}^2 + C_{m1}^2 \\ &= C_1^2 + U^2 - 2UC_1 \cos \alpha, \end{aligned}$$

we can now write for the efficiency of a 50% reaction turbine

$$\eta_{0.5} = \frac{U}{C_1} \left\{ \cos \alpha - \frac{U}{C_1} + \cos \beta_2 \left[1 + \epsilon \left\{ 1 + \left(\frac{U}{C_1} \right)^2 - 2 \left(\frac{U}{C_1} \right) \cos \alpha \right\}^{\frac{1}{2}} \right] \right\}.$$

We define the ideal spouting velocity, C , so that

$$P_{\max} = \frac{1}{2} m C^2.$$

For 50% reaction

$$C = 2C_1.$$

The efficiency is normally plotted in terms of U/C . Since the value of C can be readily obtained from the available head by

$$C = \sqrt{2gH_{ad}}.$$

Figure 10 shows the efficiency of a 50% reaction turbine for $\alpha = \beta_2$. The ideal case of $\alpha = 0$, and $\epsilon = 1$ is seen to yield very high efficiencies over a wide range of values of U/C . When $\epsilon = 0$, the efficiency curve again becomes a parabola as it was for the impulse turbine. It is interesting that the peak efficiency is 100% for this case because at $U/C = 0.707$, the relative velocity is $W_1 = 0$ and there is no kinetic energy to recover. For $\alpha = 20^\circ$ the peak efficiency is now 93% if $\epsilon = 1$ and 88% if $\epsilon = 0$. This efficiency is higher than that obtainable from an impulse machine. Once again we have the question of disc friction losses to contend with. In addition there will be losses in the flow as it passes through the nozzle and blades and as it leaves the blades.

When the fluid leaves the blades, it has kinetic energy. This kinetic energy is represented by a total pressure at the blade exit greater than the local static pressure. The usual procedure in turbine analysis is to assume that all of this kinetic energy in the exhaust is lost. This yields the so called static efficiency of the machine. The curves of Figures 6, 8, and 10 show static efficiency. It is frequently possible, however, to recover part of the exhaust energy carried by the stream after it leaves the blades. In a multistage turbine, this energy can be reclaimed as total head in the flow passing through the next set of vanes. In a single stage machine this kinetic energy may be recovered by means of an exhaust diffuser. This will permit the turbine exit to see a lower pressure than the total pressure at the end of the diffuser. In either case the conversion is not 100% effective.

The performance of the turbine based on the complete recovery of the exhaust energy is called the total efficiency. It is of course always greater than the static efficiency. Optimizing a turbine for total efficiency yields a different design than the optimum static efficiency machine, so it is important to know the characteristics of the application. Total pressure efficiencies are quite often given in literature intended to promote interest in a machine where there is no hope of recovering a substantial portion of the exhaust energy.

The more detailed examination of turbine performance requires a detailed study of the losses. This is obviously beyond the scope of the present lecture.

II. TURBOMACHINERY PERFORMANCE ESTIMATION PROCEDURES

The system designer frequently encounters the problem of estimating the performance that can realistically be expected from turbomachinery components for a specific application. Until recently, there were no techniques available which could supply the necessary information about machine performance to one not skilled in the turbomachinery art. This situation has changed during the last ten years. It is now possible for a preliminary design engineer or a systems analyst with almost no background in the turbomachine field to obtain very accurate estimates of efficiency, size, and feasibility of practical development of turbines, compressor, and other types of prime mover and pumping devices. D.H.Silvern and O.E.Balje under the supervision of E.B.Zwick at the AMF Turbo Division, in 1956, engaged in a program of research in turbines and turbopumps for the Office of Naval Research. During that program, a method of component optimization was developed which involved expressing the characteristics of these devices on a set of coordinates labeled N_s (specific speed), and D_s (specific diameter). The analysis indicated that by proper machine design, efficiencies could be greatly increased in the low specific speed regime, compared to the then current state of the art. These analytical predictions were confirmed experimentally in a parallel program while the original analytical effort was still in progress.

Ten years have elapsed since the publication of the first AMF report, AMF/TD 1196, "A Study of High Energy Level, Low Power Output Turbines". During this period there has been considerable further activity in this field. Sundstrand-Turbo, the successor to AMF, continued to do research for ONR, extending the work to pressure staged single disc turbines, low specific speed pumps, drag pumps and turbines, and later investigating the effects of Mach number and Reynolds number. Balje, who consulted on the original program, extended the work to include the high specific speed range of machines. Benstein and Wood published new data for radial inflow turbines which indicated that the original $N_s - D_s$ diagrams were somewhat conservative in their loss estimates. A re-examination of the analytical optimization was completed by R.Binsley and Balje in December, 1966 under ONR sponsorship. The new results show even higher performance levels achievable than had previously been predicted.

In order to make use of these new developments in turbomachine performance optimization, the systems analyst must have systems requirements expressed in terms of available work or head rise; power or flow data sufficient to permit computation of the volumetric flow rate of the working fluid; and if possible, the desired rotational speed of the machinery. Finally, the systems analyst must understand how to compute a specific speed based on his requirements, and how to use this to obtain the performance and geometrical characteristics of his machinery from the diagrams.

The basic parameter involved in the procedure presented here is called specific speed. It is given by

$$N_s = \frac{NV}{H_{ad}^{3/4}},$$

where

N = rotational speed (rpm)

V = volume flow at the lowest pressure in the machine expressed in cubic feet per second

H = the adiabatic head, either available to a turbine or required by a pump, expressed in feet.

Once this has been determined, the diagrams and reports show the type of machine to use, the efficiency which can be achieved, and some aspects of the geometry of the machine. In particular, the specific diameter, D_s , of the machine can be determined from the $N_s - D_s$ diagram. The specific diameter is given by

$$D_s = \frac{DH^{\frac{1}{4}}}{V^{\frac{1}{2}}}.$$

The diameter of the wheel can be immediately determined from the specific diameter. This in turn allows one to calculate the tip speed of the wheel, which is sometimes an important structural consideration. The diagrams and related curves then show the optimum geometry of the machine.

A. $N_s - D_s$ Diagram for Partial Admission Axial Impulse Turbine

Figure 11 shows one of the first $N_s - D_s$ diagrams generated by AMF-Turbo for partial admission turbines. The ordinate is D_s and the abscissa is N_s . Lines of constant efficiency (η), blade height to diameter ratio (h/D), arc of admission, and velocity ratio (U/C) are shown. The figure is somewhat confusing at first because it contains so much information. The individual sets of curves are shown separately in Figures 12a, 12b, 12c, and 12d.

It is clear that for a given specific speed, the geometry of the turbine of Figure 11 is completely specified. The efficiency achievable with these partial admission turbines is not high, but in the low specific speed range they are better by far than conventional impulse turbines.

B. Experimental Verification

Prior to 1957, most axial impulse turbines were built with long blades with a small blade number of the type shown in Figure 2. This is customary with high specific speed machines. Operation of these turbines at low specific speed resulted in efficiencies which were so low that other types of machines were preferred.

While the $N_s - D_s$ analysis was being performed, Harold Esten at AMF-Turbo independently designed and built a turbine for a specific speed of about 4. Esten's turbine was based on his own analysis of the low specific speed problem. It was different from the previous axial turbines built by AMF/TD. It had more blades and they were shorter.

Tests of Esten's turbine showed an efficiency of 52% under test conditions where previous designs yielded only 26%! Measurements of Esten's turbine showed that it had exactly the geometry which Silvern and Baljé had predicted to be the optimum! Figure 13 shows how the performance of turbines based on the optimization of Baljé and Silvern compares with the previous state-of-the-art. Note that other turbine types, such as Terry turbine were superior to the axial turbines in 1957 because a greater fraction of their potential was being realized at the time. The marked improvement in turbine performance demonstrated by Esten's turbine is clearly seen in this figure.

C. Effect of N_s on Optimum Turbine Geometry

It is clear from Figures 11 and 12 that the geometry of an optimum low specific speed turbine will be different from that of a high specific speed turbine. Figure 4 shows a comparison of two such axial impulse machines. The low N_s turbine has a lower h/D ratio with more blades.

D. Other $N_s - D_s$ Diagrams

Figures 14, 15 and 16 show other $N_s - D_s$ diagrams which are of interest. Figures 14 and 15 are from a paper by Baljé. They include data over a very wide range of specific speeds

with a wide variety of machine types. Machine size and performance can be readily determined as a function of rpm. These diagrams provide an excellent means of selecting machines for a given application.

The performance indicated in Figures 11, 14, and 15 is conservative compared to recent data for turbines. A more sophisticated analysis of the optimization problem was therefore undertaken by Binsley and Baljé at Rocketdyne (North American Aviation). Their results are shown in part in Figure 16. The peak efficiencies indicated in Figure 16 are 93% compared to 83% in Figure 14. The figure also indicates that some reaction is desirable over very wide range of specific speeds. Figure 14, on the other hand, assumed 0% reaction for axial turbine below $U/C = 0.5$ (about $N_s = 60$). There is still further work to be done to check the assumptions of Figure 16, but the results agree well with recent high performance reaction turbine results.

III. EXAMPLE OF $N_s - D_s$ DIAGRAM USE FOR SPACE POWER PLANT

A 20 kW solar power plant is to be designed using biphenyl as the working fluid. The thermal degradation properties of the working fluid limit the maximum cycle temperature to about 700°F. A minimum cycle pressure of about 1 psia is initially selected based on liquid pumping requirements. The Mollier diagram, Figure 18, and tabulated thermodynamic property data yields the information given in Tables I-IV.

REFERENCES

1. Baljé, O.E. *Performance of Turbomachines in Terms of Similarity Parameters.* October 1962.
2. Benstein, Eli H.
Wood, H.J. *Applications and Performance Levels of Radial Inflow Turbines.* SAE 653 D.
3. Binsley, R.L.
Baljé, O.E. *Turbine Performance Prediction: Optimization Using Fluid Dynamic Criteria.* Rocketdyne Report R-3892, ASTD TDR 63 114, February 1963.
4. Dubey, M. *Study of Turbine and Turbopump Design Parameters - Volume III, Low Specific Speed Turbines Based on Tangential Flow Theory.* Sundstrand-Turbo, S/TD 1735, January 1960.
5. Nichols, K.E.
et al. *A Study of Turbine and Turbopump Design Parameters - Volume IV, Low Specific Speed Turbopump Study.* Sundstrand-Turbo, S/TD 1735, January 1960.
6. Silvern, D.H.
Baljé, O.E. *Study of High Energy Level, Low Power Output Turbines.* Sundstrand-Turbo, AMF/TD 1196.
7. Spies, R. *Study of Turbine and Turbopump Design Parameters - Volume II, A Study of High Pressure Drag Turbines Using Compressible Fluid.* Sundstrand-Turbo, S/TD 1735 Volume II, January 1960.
8. *Study, Design, and Test of Experimental Liquid Hydrogen Pump for Use in Flight Vehicle Systems.* Rocketdyne Report R-3892, AST TDR 63 114, February 1963.

TABLE I

Boiler Exit Conditions		Turbine Exit Conditions	
P_1	- 100 psia	P_2	- 1 psia
T_1	- 688.9°F	H_1	- 315.3 Btu/#
H_{sv}	- 375.4 Btu/#	ΔH_1	- 60.1 Btu/#
		ΔH_{act}	- 48.1 Btu/# (For $\eta_t = 80\%$)
		T_2	- 571°F
		v	- 70.7 ft ³ /#

TABLE II

Powerplant Requirements

Net Power	P_N	= 20 kW of 400 ~ power
Estimated Conversion Efficiency	η_E	= 80%
Estimated Gross Power Required	P_G	= kW 23.8 Btu/sec
Enthalpy Drop	H_{ad}	= 48.1 Btu/#
Flow Rate Required	W	= 0.494 #/sec

TABLE III

Specific Speed Analysis

Ideal Enthalpy Drop	ΔH_1	= 60.1 Btu/#
Adiabatic Head ($H_{ad} = 778 \Delta H_1$)	H_{ad}	= 46,700 ft
	H_1^4	= 14.7
	H_1^3	= 3180
Volume Flow Rate	V	= 34.9 ft ³ /sec
	$V^{\frac{1}{2}}$	= 5.91
Speed (400 ~ Synchronous)	N	= 24,000 rpm
Specific Speed	N_s	= 44.6
Efficiency figure	η	= 88%
D_s optimum	D_s	= 2.4
Diameter	D_{opt}	= 11.6"
Tip Speed	U	= 1210 ft/sec
Blade height ratio	(h/D)	= 0.045
Blade height	h	= 0.521

All of the basic turbine data is thus obtained from the $N_s - D_s$ diagram. It was not necessary to raise the usual question of tip speeds, blade angles, flow factors, and so forth that delight the turbomachinery expert and cause the preliminary designer to shudder.

But the end result is even better than one might suppose. There is something for everyone in the $N_s - D_s$ optimization analysis. Even the turbomachinery expert can find information of value. Additional curves in Binsley and Baljé's report permit one to obtain the detailed design information shown in Table IV.

TABLE IV

Detailed Design Data

Degree of Reaction	ρ	= 56%	Number of rotor blades	Z_R	= 36
Flow factor	C_m/U	= 0.25	Nozzle Blade Angle	α	= 15°
Leaving Velocity Head	$(C_3/C)^2$	= 0.06	Rotor Blade Inlet Angle	β_1	= 83°
Number of Blades Nozzle	Z_N	= 43	Rotor Blade Exit Angle	β_2	= 13°

Fig.1 Axial flow turboalternator

Fig.2 Impulse turbine

Fig.3 Reaction turbine

High specific
speed turbine

Low specific
speed turbine

Fig.4

Fig.5 Velocity diagram for an ideal impulse turbine

Fig.6 Efficiency of an ideal impulse turbine

Fig.7 Impulse turbine velocity diagram

Fig.8a Turbine efficiency for impulse blades of constant height

Fig.8b Turbine efficiency for symmetrical impulse blades

Fig.8c Comparison of impulse turbine types

Fig.9 Reaction turbine velocity diagram

Fig.10 Efficiency analysis of 50% reaction turbines

Fig. 11 $N_s - D_s$ diagram axial turbine large blade numbers

Fig. 13 Turbine efficiencies

Fig. 12a Efficiency curves from Figure 11

Fig. 12b h/D curves from Figure 11

Fig. 12c Arc of admission curves from Figure 11

Fig. 12d U/C curves from Figure 11

Fig.14 Preliminary $N_s - D_s$ diagram for single stage turbines and expanders

Fig.15 Preliminary $N_s - D_s$ diagram for single stage pumps and compressors at low pressure ratios

Fig.16 Specific speed, N_s

Fig.17 Mollier diagram for biphenyl

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IVC. ALTERNATORS FOR SPACE POWER APPLICATIONS

by

Eugene B. Zwick

8901 Zelzah Avenue, Northridge,
California 91324 (213) - 345-6078, USA

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IVC. ALTERNATORS FOR SPACE POWER APPLICATIONS

Eugene B. Zwick

INTRODUCTION

Dynamic space power systems normally use alternators as a means of converting mechanical to electrical energy. Direct current machines are usually unsuitable because of problems with brushes and commutators in a severe environment. Electrostatic machines have been given some attention and will be discussed in another portion of these lecture notes.

Alternators used in missile and space power applications have included many of the types already developed for ground power use. Requirements for very high temperatures, corrosive environments, and extremely high rotative speeds, however, have led to innovations in alternator design. The new machinery which has been developed shows considerable promise for future application in both space and terrestrial use.

REVIEW OF BASIC ALTERNATOR CONCEPTS AND TERMINOLOGY

The conversion of mechanical to electrical energy in a rotating electromagnetic device depends on the interaction between a magnetic field and an electrical conductor which is moving relative to the field. The basic physical principles involved are the laws of electromagnetic induction and the forces acting on current carrying conductors in a magnetic field. Faraday's induction law for a conductor moving through a field as shown in Figure 1a is

$$V = \oint (\vec{v} \times \vec{B}) \cdot d\vec{l} ;$$

V = potential difference along the conductor

$\vec{v}$ = vector velocity of the conductor relative to the field

$\vec{B}$ = magnetic induction vector

$d\vec{l}$ = the vector differential length element of the conductor.

The integral is taken around the closed conductor loop.

Ampère found that a mechanical force is required to move a conductor through the magnetic field when current is flowing as shown in Figure 1b. In differential form this force is given by

$$d\vec{F} = I(d\vec{l} \times \vec{B}) ,$$

where

$d\vec{F}$ = force acting on an element of the conductor

I = current flowing in the conductor.

In electrical machinery, it is useful to consider the total flux of the magnetic field that links the conductors as shown in Figure 2. This allows for an easier physical interpretation of the electromagnetic principles involved. The flux is defined as

$$\phi = \int_S \vec{B} \cdot d\vec{S} ,$$

where ϕ = the flux of the magnetic field passing through the area S . If S is surrounded by a coil of N turns and ϕ varies with time either because B is unsteady or because the coil moves relative to the field, then the voltage output of the coil is given by

$$V = N \frac{d\phi}{dt} .$$

We see that generation of electrical power by magnetic field requires a flux which varies with time, and mechanical energy input.

The simplest type of alternator uses the field of a permanent magnet. Figure 3 shows an alternator with a permanent magnet *rotor* and a stationary *armature* which carries the flux through the conductor coils. In Figure 3a the rotor is oriented so that the flux passes into the top pole of the armature, down through the coils of the armature and out through the bottom pole. In Figure 3b, the rotor has turned through 180° and the flux direction through the armature iron has been reversed. The flux through the coil thus changes continuously as the rotor turns and an alternating voltage is generated in the armature coils.

Figure 4 shows a *permanent magnet alternator* in which the rotating and stationary elements shown in Figure 3 have been reversed. Now the magnet is stationary in the outer frame, while the armature containing the conductors rotates. As the conductors move through the magnetic field, an alternating voltage is generated in the rotating coil. An observer moving with the rotor would find the flux linked by the rotor coils to be continually changing in the same manner as a stationary observer would find in the machine of Figure 3. In order to extract the electrical current from the machine shown in Figure 4, it is necessary to connect the rotating coil to an external load. This would normally be done with *slip rings* and brushes as shown in the Figure.

The rotor poles shown in Figures 3 and 4 are designated *salient poles* because they protrude from the surface of the rotor. Salient poles are used to control the direction and local intensity of the magnetic field. Salient pole rotors have stress problems at high speeds due to stress concentration at the poles. They also have much higher windage losses than a comparable smooth rotor. Figure 5 shows a machine similar to that of Figure 4 in which the poles are not protruding. These *non-salient poles* have more flux fringing in the air gap between the rotor and the stator than would occur if salient poles were used. The choice of non-salient vs. salient poles depends on the relative importance of flux leakage, windage, and stress concentration on the design of the machine. These in turn depend on the power level, speed, and density and viscosity of the medium in the gap.

Figure 6 shows a permanent magnet alternator in which neither the magnets nor the conductors move. In this machine, the flux changes direction through the armature as the rotor changes its position. When the rotor is vertical as shown in Figure 6a, the flux passes from the north pole at the top of the machine into the rotor and into the south pole at the bottom of the machine. The flux passes through the armature and the coils as indicated in the Figure. When the rotor is horizontal, as shown in Figure 6b, the flux passes from the north pole at the right hand side of the frame through the rotor to the south pole at the left hand side of the frame. As the rotor turns through 90° , the direction of the flux through the armature is reversed and an alternating voltage is set up in the conductor coils. Because this reversal of flux is accomplished solely by the motion of the rotor, this type of device is known as a *flux switch alternator*.

Flux switch alternators are part of the general class of alternators in which the rotor is only used as a flux path controlling device. Motion of the rotor changes the distribution of the flux through the armature. Machines of this class are called *inductor alternators*.

Flux switch alternators are of course not restricted to two salient poles on the rotor as shown in Figure 6. Figure 7 shows a flux switch machine with six salient rotor poles, four stator poles and two permanent magnets. Flux reversals occur in the armature each time the rotor turns through 30° .

The direction of the magnetic flux through the rotor of a flux switch alternator changes each time the rotor moves to the next magnetic pole of the stator. Because the polarity of the rotor of a flux switch machine changes as the rotor turns, this machine can be designated a *heteropolar alternator*. This distinguishes it, for example, from the rotating permanent magnet machine where the direction of the flux through the rotor does not change. Alternators in which the polarity of the rotor stays fixed with no internal flux reversals can be called *Uni-polar alternators*.

Rotating permanent magnet alternators are part of that group of machines which do not require brushes. *Brushless alternators* are particularly important in space applications. The long life and freedom from maintenance associated with brushless alternators makes them attractive for many ground applications as well.

When the flux direction reverses in the armature of an alternator, there is an electrical voltage induced not only in the conductors wrapped on the armature, but also in the metal which forms the flux carrying structure of the machinery. This leads to induced currents known as eddy currents, which extract power from the shaft, and dissipate it into heat in the metal structure. Eddy current losses are minimized by two procedures. First the flux carrying structure is made of high resistivity metal. Secondly the flux carrying structure is separated into thin laminae which are bounded together by nonconducting insulation. If the flux direction reverses in the rotor, as it does in a flux switch machine, the alternator must use a *laminated* rotor. Laminated rotors, like salient pole rotors, have stress problems which limit their rotational speeds.

Uni-polar alternators, do not have flux reversal in the rotor. If the flux level stays relatively constant, which it would in a multiple pole machine, rotor lamination is unnecessary. The resulting *solid rotor* configuration can be structurally stronger than a laminated rotor.

The conventional permanent magnet alternator shown in Figure 3 is limited by the structural characteristics of the magnet. Magnetic structures do not lend themselves readily to the complex shapes which might be desirable in a high speed multi-pole alternator. A uni-polar machine which uses strong, high permeability material in the rotor to carry the flux from a geometrically simple magnet through a more desirable path is shown in Figure 8. This is basically a form of the *Lundell alternator*. In the Lundell machine the flux from the north pole of the magnet is carried through a disc out to pole pieces around the circumference of the rotor. A second disc with flux collecting poles is placed at the other end of the rotor. It carries field flux into the south magnetic pole. The flux collecting poles are interdigitated between the flux distributing pole pieces which carry the flux from the north pole. The two-poles Lundell rotor shown in Figure 8a has the armature identical to those found in the permanent magnet machine of Figure 3. The number of poles can be increased as desired by properly shaping the magnetic material as shown in Figure 8b. A Lundell rotor can be made as a solid rotor by embedding the magnet and the two pole pieces in a solid non-magnetic structure.

In all of the alternators discussed so far the necessary field flux for the alternator has been supplied by a permanent magnet. Each of these configurations can be duplicated using an electromagnet. In Figure 9 the rotating magnet illustrated in Figure 3, is replaced by a *wound rotor* field coil which is supplied from an external DC supply through

sliprings. The rotating field coil in Figure 9 has been converted into a rotating armature in Figure 10. This is the electromagnetic field equivalent of the machine shown in Figure 4. The rotating field coil is preferred to a rotating armature because the field current is much less than the output current thus minimizing the brush requirements.

One of the most important innovations in wound rotor machines was the development of the brushless *rotating rectifier* configuration shown in Figure 11. This is really a combination of two machines into one housing. The stationary exciter coil together with the rotating armature at the left end of the shaft constitutes a conventional alternator of the type shown in Figure 10. The output of this *field generator* is then rectified by solid state rectifiers which are mounted on or in the rotor. The main section of the machine is a wound rotor alternator of the type shown in Figure 9. Field excitation current for the wound rotor is drawn from the rectified output of the field generator.

By combining two machines in one housing, the need for brushes and slip rings is eliminated, and the field excitation current required is made very small.

The other alternators discussed previously in which permanent magnets were used can also be supplied with electro magnets. Figure 12 shows a flux switch machine with an electromagnetic field coil. Figure 13 shows the simplest configuration of an electromagnetically excited Lundell machine. Here the field coil is wound on the rotor and supplied through slip rings. The advantage of this type of machine over a conventional wound rotor machine is that the field coil configuration is much simpler and hence stronger and less costly.

Another approach to inducing a field current in a brushless wound rotor machine is the *cascade alternator* shown in Figure 14. This is essentially a three phase rotating armature alternator coupled to a three phase wound rotor machine. Motion of the armature coils in the DC exciter field at the left end of the machine creates a three phase current which is fed to the three phase coils of the wound rotor in the center of the machine. The phase sequence of the wound rotor coils is reversed from that of the generator coils. The wound rotor therefore produces a magnetic field which rotates at twice the rotor speed. (Higher and lower speed ratios can be obtained by varying the number of poles on the two sections of the rotor.) The rotating flux from the rotor induces an alternating voltage in the armature coils. Because the output frequency of a cascade machine can differ from the input rpm, this machine is also known as a *frequency converter*.

SOLID ROTOR BRUSHLESS ALTERNATORS

It is not necessary for the field coils of a Lundell machine to rotate. Figures 15a and b show two versions of a stationary coil uni-polar Lundell inductor alternator. The stationary field pole supplies magnetic flux to the flux distributing disc and through it to the rotating north poles. The flux passes from the rotor into the armature and returns through the rotating flux collectors. These then carry the flux into the collector disc and then back to the stationary pole. The rotor, like other uni-polar machines need not be laminated. The alternator of Figure 15b has electromagnetic field coils, but like a permanent magnet alternator, it is a solid rotor brushless machine.

There are many geometrical configurations possible for a uni-polar inductor alternator utilizing the Lundell concept. By using two coils and placing the pole pieces back to back as shown in Figure 16 a configuration patented by Becky and Robinson is obtained. The *Becky-Robinson* machine has twice the power rating of a single coil machine for a given diameter.

Still another form of solid rotor inductor alternator is the outside coil configuration patented by Rice, shown in Figure 17. Here the field coils are used to induce a magnetic field along the shaft of the rotor. The two ends of the rotor shaft are brought out in the center of the rotor into pole faces which are separated by non-magnetic material.

In the two pole version shown in Figure 17, the rotor presents a north pole and a south pole at 180° in the same fashion as we have in the permanent magnet machine shown in Figure 3. The flux path for the field is completed through the armature between the poles. It flows through the outside frame of the machine at the ends of the shafts. The *Rice alternator* has recently received a great deal of attention for space power applications, and will be discussed in somewhat more detail in a subsequent portion of these lecture notes.

The changing electromagnetic field necessary to generate alternating current can be provided by induced currents in the rotor. Figure 18 shows an *induction generator* which is also called an *asynchronous generator*. This machine is basically an induction motor driven past its synchronous speed. A rotating magnetic field is set up in the stator by virtue of an externally supplied three phase current with suitably disposed windings in the armature. If now the rotor rotates at a speed less than the speed of rotation of the externally supplied field, eddy currents are induced in the squirrel cage conductors. These currents create a magnetic field which interacts with the externally supplied field to provide torque to the rotor and hence the usual action of an induction motor. If the speed of the rotor exceeds the rotational speed of the applied electromagnetic field, the induced currents in the rotor are reversed and torque must be supplied to the rotor. The back e.m.f. becomes greater than the voltage applied to the machine, and it becomes a generator. The frequency of the output of an induction generator is determined by the frequency of the externally supplied source. The power depends on the difference between the rotating speed and the synchronous speed.

Induction generators cannot supply current at lagging power factor. In addition, they require a separate power supply to provide their magnetizing current. A large capacitor bank is used to minimize the current taken from the exciter supply. Because of these special requirements, particularly the large reactive power required by the exciter windings and the normal load, induction generators are not used for large power outputs.

The solid rotor configuration shown in Figure 19 is known as a *homopolar inductor alternator*. This machine is called a homopolar alternator because the flux direction in the stator and rotor do not change with time. An inductor alternator is one in which the field winding is fixed in magnetic position relative to the armature conductors. This is true not only of the homopolar inductor machine but also of the heteropolar inductor machine (the flux switch alternator), the Rice alternator, and the fixed coil Lundell machines. The four pole homopolar inductor alternator shown in Figure 19 has two stator armatures and a double rotor. One end of the rotor acts as a north pole while the other end acts as a south pole. The field coil placed between the armatures creates an axial magnetic flux in the rotor. The flux passes out of the rotor at the north poles, through the left armature into the frame of the machine. It then travels circumferentially to the second armature and returns through the south pole of the rotor. As the rotor turns, the flux in the two armature coils varies with time, but the flux direction never reverses as it does in the Lundell and Rice machines. In a practical homopolar machine, it is sometimes desirable to laminate the rotor poles. Although the flux direction does not vary, there is variation in the flux magnitude which can lead to eddy currents.

It should be noted that any of the machines described thus far can be modified in two obvious ways. First almost all alternators are three phase machines, since this is the most generally useful form of power output. Secondly, the air gap between the rotor and the stator can be an axial gap instead of the radial gap indicated thus far. The axial gap is sometimes considered preferable since it is not effected by thermal expansion and can be carefully controlled by suitable thrust bearing arrangement.

ALTERNATORS IN SPACE POWER SYSTEMS

Many types of alternators have been used in the space power systems which have been studied and/or developed so far. These include permanent magnet machines, wound rotor machines, flux switch machines, induction generators and inductor alternators. A partial list of these alternators is given in Table I. All of the alternators are brushless, and except for the cascade generator and the flux switch machines they have essentially solid rotors. These characteristics are to be expected for space power applications since these machines are generally designed for high temperature, high speed operation. The environment in which the rotor turns is frequently a corrosive vapor. This gives rise to materials problems which are simplified by the use of a solid rotor.

At the present time the principal development activity in space power alternators is directed towards homopolar inductor alternators with laminated salient poles, and solid rotor inductor alternators of the Rice configuration. An interesting variation of the Rice alternator was patented by L. Opel of North American Aviation Company. This so called Nadyne alternator is described briefly in the following section.

CHARACTERISTICS OF A TYPICAL SPACE POWER MACHINE

The Nadyne alternator is a variation on the uni-polar inductor alternator shown in Figure 17. The Nadyne configuration uses two field coils placed against the stator end bells while the Rice configuration uses a field coil which is situated between the armature windings and the outer frame. This changes the leakage flux characteristics of the two machines.

The basic configuration of the Nadyne generator is shown in Figure 20. The solid rotor is a completely smooth cylinder of revolution containing both north and south poles separated by a nonmagnetic material.

The Nadyne generator generates voltage in the same manner as the conventional salient pole-wound field generator. A magnetic field of alternate north and south polarity is rotated mechanically past the generator conductors, generating a voltage in the stator conductors by causing a change in the flux linkages of the conductors as a function of time. The stator of the generator is of conventional design.

The magnetic circuit of the stator section of the generator is identical to that of conventional synchronous generators. The flux path, starting from the concentric gap of the right-hand field pole, is across the gap and then axially towards the center of the rotor. It divides equally between the number of like poles and then travels across the rotor pole gap to the stator iron. In the stator iron, it has two possible return paths, one through the stator yoke to the opposite polarity rotor pole and the other through the magnetic frame. Because the rotor is turning during operation, the least resistant flux path is through the laminated stator yoke iron. The solid frame iron offers higher resistance to a changing flux than the laminated stator iron. The principal flux path is through the stator yoke and across the air gap to the opposite polarity rotor pole. The flux continues axially to the left end of the rotor and returns through the concentric gap to the left field pole and then out to the magnetic frame. In the magnetic frame the flux flows axially to the right field pole and completes its circuit in the pole at the concentric gap.

The rotor flux rotates with the rotor and under steady-state conditions is of constant magnitude. The frame and pole flux under steady-state conditions are also of fixed magnitude. The flux transition from rotating to nonrotating takes place at the pole annular air gaps. As the pole gap is concentric, the flux density is constant around the periphery of the rotor pole, and the rotor pole does not see a varying flux under steady-state conditions; therefore, no power loss is induced in the rotor at the field gap.

The magnetomotive force (MMF) is produced by a direct current flowing in the field coils located on each end as shown in Figure 20. One coil is used for each polarity and a single coil will excite the total number of poles used for each polarity. The field coils are fixed to the stationary parts and do not rotate with the rotor. The poles and frame are made from magnetic material with areas in a plane perpendicular to the flux path sufficient to carry the total flux per magnetic polarity plus all leakage fluxes without saturating the magnetic materials.

The flux distribution is such that the magnetic forces acting on the rotor poles are equal and opposite. Therefore, the magnetic forces cancel and do not impose unbalanced mechanical forces on the generator bearings. This balanced condition exists regardless of the number of poles.

MINIMUM ROTOR DIAMETER

In the solid rotor Nadyne machine, minimum rotor diameter is tied directly to the following two factors: (1) minimum stator gap flux, and (2) highest possible flux density within the machine. The output voltage of the machine is proportional to the product of total gap flux and the number of conductor turns on the stator. Decreasing gap flux requires increased stator turns but permits the rotor diameter to decrease. Gap flux decreases ultimately result in too many stator turns, which result in low efficiency from stator copper loss. Internal machine impedance (leakage reactance) increases also until internal voltage drops become excessive. Application of a digital computer program permits optimization of these parameters to obtain the smallest rotor diameter consistent with reasonable efficiency and internal impedance.

Additional decrease in rotor diameter may be made by maintaining the minimum gap flux above but using materials with very high magnetic flux density capability. Normal silicon-iron magnetic materials have an operating flux density limit of 90 kilolines per square inch. Above this value, magnetic saturation occurs and larger rotor cross-sections and stator stack length are required for a given total flux. Cobalt alloys are available with higher flux capability than iron alloys.

These materials have a flux density capability of approximately 145 kilolines per square inch and can carry a given total flux with a rotor cross-section and stack length which decrease in inverse proportion to the material flux density capability, that is, the cobalt materials allow cross-sectional decreases $= 90/145 = 0.62$. The cross-section decrease translates into minimum rotor diameter.

The combination of gap flux minimization and highest possible magnetic flux density materials permit the Nadyne machine to be specifically tailored to a low-draw, high-r.p.m. configuration

ROTOR DRAG

The drag of the rotor can be a significant factor in the efficiency of a high-speed generator. The drag can be expressed in terms of a friction coefficient as

$$P_D = C_f A_s (\frac{1}{2} \rho U^3) ,$$

where

$$\begin{aligned} P_D &= \text{windage power loss} \sim \text{kW} \\ C_f &= \text{friction coefficient} \\ A_s &= \text{rotor surface area} \sim \text{ft}^2 \\ \rho &= \text{fluid density} \sim \text{slug/ft}^3 \\ U &= \text{surface linear velocity} \sim \text{ft/sec.} \end{aligned}$$

For turbulent flow, which arises in the high density fluid surrounding the present rotor,

$$C_f = \frac{0.078}{Re^{0.43}}.$$

Substituting for the velocity and Reynolds number yields

$$P_D = \frac{0.039\pi}{737.6} \frac{\pi}{60} \frac{2.57\mu^{0.43}\rho^{0.57}D^{3.57}N^{2.57}L}{C^{0.43}},$$

where

μ = fluid viscosity - lb sec/ft²

D = rotor diameter - ft

L = rotor length - ft

C = clearance in the gap - ft

ρ = rotational speed - r.p.m.

To minimize drag loss, the alternator must be configured to reduce rotor diameter as much as possible consistent with high overall alternator efficiency.

10 kW DESIGN STUDY

A computer study was performed to optimize a Nadyne alternator with 10 kW output for use in a high pressure carbon dioxide cycle (Feher cycle). Because of the high density of the gas in the rotor housing, fluid drag was of particular importance in this analysis. The relatively large gap of the Nadyne machine tended to minimize this effect. Figure 21 and 22 show how the characteristics of the alternator vary at 60,000 r.p.m. with the diameter of the rotor. Table II shows the losses as a function of rotor diameter. Figure 23 shows how the weight, efficiency, rotor drag, and size of the optimum alternator are influenced by r.p.m. Table III tabulates the losses of the alternator as a function of speed.

It is clear that the overall system weight and size are not greatly influenced by the r.p.m. of the alternator. The total weight of the alternator is on the order of 10 lbs. Similarly, the size of the alternator is small compared to the other components.

The efficiency of the alternator does vary with the r.p.m. but the dependence is not strong for speeds below 100,000 r.p.m. At higher rotational speeds, the efficiency begins to fall off rather rapidly.

In summary, it seems clear that the alternator is not a major factor in determining cycle operating points. The efficiency is high, the size and weight are small, and the fluxural critical speed is so high that it is not liable to have any influence on system design.

REFERENCES FOR TABLE I

1. Zwick, E.B. Unpublished Data
2. *Design and Development of a 3 kW Stirling Cycle Solar Power Plant.* First Semi-annual Technical Summary Report, Allison Division, General Motors Corporation. 22 January 1966.
3. Wallerstedt, R.L.
Owens, J.J. *Snap Mercury Rankine Program.* I.E.C.E.C., September 1966.
4. Malohn, Donald A. *1.5-kW Solar Dynamic Space Power System.* Space Power Systems Engineering. Progress in Astronautics and Aeronautics, Vol.16, 1966, p.773.
5. Hodgson, J.N.
et al. *Snap-8 - A Technical Assessment.* I.E.C.E.C., August 1967.
6. Pietsch, A.
McCormick, J.E. *Development Status of Closed Brayton-Cycle Systems for Space Power Application.* I.E.C.E.C., September 1966.
7. Hucker, D.J.
et al. *Development of a Family of Light Weight Short Duration Turbo-Alternator Power Supplies.* I.E.C.E.C., August 1967.
8. Linhardt, H.D.
Carver, G.P. *Development Progress of Organic Rankine Cycle Power Systems.* I.E.C.E.C., August 1967.
9. Corcoran, C.S. *Development of Electric Components for a 400 Hertz Brayton Cycle Energy Conversion System.* I.E.C.E.C., August 1967.
10. McGrath, R.E. *Pu-238 Feher Cycle Systems for the Manned Orbiting Research Laboratory.* Douglas Aircraft Company, DAC-57957, December 1966.

ADDITIONAL BIBLIOGRAPHY

- Boretz, J.E., *Isotope Dynamic Space Power Systems*, I.E.C.E.C., 1967.
- Cooper, D.W. and Kuhns, P.W., *Electrical Generator with a Superconducting Magnetic Field for Use in a 1-Megawatt Roating Space Power System*, I.E.C.E.C., 1966.
- Curwen, P.W., *An Investigation of the Effects of Electromagnetic Forces on the Rotor-Dynamic Performance of a 15 KVA Gas-Bearing Brayton Cycle Turboalternator*, I.E.C.E.C., 1967.
- Ellis, J.N. and Collins, F.A., *Brushless Rotating Electrical Generators for Space Auxiliary Power Systems*, Lear Siegler, Inc., NASA CR 54321.
- Opel, L.G., *Design Features of Alternating Current Nadyne Generators*, IEEE paper, April 1964.
- Parker, M.D. and Smith, C.L., *Stirling Engine Development for Space Power*, Energy Conversion for Space Power, Progress in Astronautics and Rocketry, Vol.3.

Pierreo, J.J., *Characteristics of Solid Rotor Synchronous Generators for Space Applications*, IEEE, Paper #31, July, pp.66-512.

Pierreo, J.J. and Opel, L.G., *Ultrahigh Speed Solid Rotor Generators for Direct Coupling to Turbines*, SAE 867D.

Rackley, R.A. and Mock, E.A., *Potassium Rankine Cycle Power Plant from 10 KW to 1000 KW*, I.E.C.E.C., 1966.

Stancliff, A.C. and Coombs, *Compact Turboalternator Power Systems for Reentry Vehicle Applications*, I.E.C.E.C., 1967.

TABLE I
Alternators in Space Power Systems

<i>Name of Power System</i>	<i>Company Machine (System)</i>	<i>Type of Alternator</i>	<i>Power Level (kW)</i>	<i>Speed (r.p.m.)</i>	<i>Phases Voltage Frequency</i>	<i>Efficiency (%)</i>	<i>Weight (#)</i>	<i>Special Features or Notes</i>	<i>Source</i>
Nike B	AMF-Turbo	PM Flux Switch 4 Pole Stator 6 Pole Stator	0.25	40,000	1 110 4000	55	0.5	Power for Control Operation Built into Turbine Housing	1
Solar 3 kW Stirling	Delco (Allison)	Cascade or Frequency Converter	0.25	3,000	3 220 400	80	Not separated from Engine	Exciter Motors for Start Up	2
SNAP-2 (MRP)	TRW	PM Cylindrical Rotor	0.28	36,000	3 115 1200	85		Armature windings protected from Hg vapor by ceramic bore seal	3
Model 1400 Biphenyl Solar Dynamic	Sundstrand	Homopolar Inductor	1.65	24,000	3 120 3200	88		2 x 8 salient poles	4
SNAP-8	General Electric (Aerojet)	Homopolar Inductor	60	12,000	3 120/208 400	88 at 0.75 PF		Efficiency over 90% at 1.0 PF	5
Brayton Cycle	AiResearch	Rice	5.4 kVA	85,000	3 112/194 1067	88			6
Brayton Cycle	AiResearch	Axial Gap Homopolar Inductor	20 kVA	48,000	3 — 3200	89			6
Short Duration Power System	Sundstrand	Homopolar Inductor	1.3 & 5	120,000	— — 4000			Laminated Pole Faces welded onto Solid Shaft	7
Silent Low Power Unit MIPB	Aeroneutronic	Induction Generator	65 watts	30,000	3 — —		L 2#	Entire power plant weight 16 lb	8
Brayton Cycle	General Electric (Pratt & Whitney)	Homopolar Inductor	12	12,000	3 120/208 400	92	82	94% eff. at 1.0 PF	9
Feher Cycle	North American (Douglas)	Nadyne	10	60,000 100,000 120,000	3 110 —	90 @ 60,000 89 @ 100,000 88 @ 120,000	11.5 @ 60,000 7.6 @ 100,000 6.8 @ 120,000	Operates in 2000 psia Carbon dioxide. Low drag due to large gap	10

TABLE II

Nadyne Alternator Losses at 60,000 r.p.m.

Losses (kW)	Diameter of Rotor			
	1.822	2.02	2.22	2.42
Iron	0.3537	0.402	0.445	0.541
Drag*	0.263	0.443	0.714	1.106
Stray load	0.1000	0.100	0.100	0.100
Rotor pole face	0.0273	0.051	0.089	0.153
Copper	0.365	0.316	0.285	0.252
Total	1.109	1.312	1.633	2.152
Efficiency	90%	88.3%	86%	82.5%

TABLE III

Losses at 400°F in a 10 kW Nadyne Alternator

Type of Loss (kW)	r.p.m.		
	40,000	80,000	120,000
Iron	0.2598	0.3752	0.5180
Drag	0.1311	0.2190	0.3240
Stray load	0.1000	0.1000	0.1000
Rotor pole face	0.0217	0.0141	0.0126
Field copper	0.1434	0.1045	0.0852
Stator copper	0.4696	0.3562	0.2953
Total losses	1.1256	1.1690	1.3351
Efficiency	90.0%	89.6%	88.0%

* Rotor turns in CO₂ at 2000 psia and 400°F.

Fig. 1a Generation of induced voltage by motion of a conductor in a magnetic field

Fig. 1b Force on a current carrying conductor in a magnetic field

Fig. 2 Electrical induction by variation of flux linkage

Fig.3 Permanent magnet alternator

Fig.4 Permanent magnet alternator with a rotating armature

Fig. 5 Rotating armature permanent magnet alternator with non-salient poles

Fig. 6 Permanent magnet flux switch alternator

Fig. 7 6 pole flux switch machine

FIG. 8A

EXPLODED VIEW OF
SIMPLE PERMANENT
MAGNET - TWO POLE
LUNDELL ROTOR

FIG. 8B

MULTIPLE POLE END
PIECE FOR LUNDELL
ROTOR

Fig. 8 Permanent magnet Lundell type alternator

Fig.9 Wound rotor alternator (rotating field)

Fig.10 Alternator with stationary electromagnetic field

Fig. 11 Rotating rectifier alternator. A brushless wound rotor machine

Fig. 12 Flux switch alternator (with wound field coils)

Fig. 13 Wound rotor Lundell alternator

Fig. 14 Frequency converter or cascade alternator

Fig. 15a Stationary coil cantilevered Lundell induction alternator

Fig. 15b Solid rotor Lundell inductor alternator

Fig. 16 Becky Robinson alternator

FIGURES ADAPTED FROM
PIETCH & McCORMIC (1966)

Fig. 17 Rice alternator

Fig. 18 Induction generator

Fig. 19 Homopolar inductor alternator

Fig. 20 Nadyne generator configuration

Fig. 21 Effect of rotor diameter on weight. Efficiency and size at 60,000 r.p.m.

Fig.22 Effect of rotor diameter on rotor stress, critical speed and rotor drag at 60,000 r.p.m.

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VA. TECHNOLOGY OF THERMOELECTRIC
AND THERMIONIC ENERGY CONVERSION

by

Ned S. Rasor

200 Tait Road, Dayton, Ohio, USA

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INTRODUCTION

A general definition of thermoelectricity includes all effects which produce electric currents as a result of a temperature difference, excluding those employing the motion of mechanical or fluid components. Although a large number of such effects exist, only two approaches have been demonstrated to be significant for practical power generation. These two approaches, semiconductor thermocouple and thermionic energy conversion, will be discussed in detail.

Both thermoelectric (thermocouple) and thermionic energy converters are heat engines which use an electron gas as their working fluid. Therefore, it is worthwhile first to review briefly the elementary nature of this fluid and the associated properties which are important in thermoelectricity.

ELECTRONS IN SEMICONDUCTORS¹

For present purposes a solid should be considered as a regular array of atoms forming the crystal lattice. In an electrical insulator at zero absolute temperature, all the electrons are strongly bound to the atoms and therefore are not free to migrate through the lattice as an electric current. Figure 1 is a diagram showing the electron potential energy in the solid as a function of distance.

The electrons most tightly bound to the atoms lie in energy states or levels at the bottom of the diagram. The less strongly bound electrons are represented by a succession or band of energy states extending up to those for the most weakly bound electrons at the upper edge of the band. These weakly bound electrons are those which determine the valence of free atoms, and so this energy band is called the valence election band. At higher temperatures, some of the electrons are excited to higher energies, such that they occupy energy states above the valence band. Those which receive sufficient energy to become detached from the atoms and migrate through the lattice as an electric current are called conduction electrons, and their energies lie in what is called the conduction band. The energy gap between the valence and conduction bands therefore may be considered, for present purposes, as the minimum energy required to detach the electrons from the lattice atoms. This energy gap sometimes is called the forbidden band, since a current cannot be conducted by electrons having these energies.

When an electron is detached from a lattice atom, it leaves behind a positive hole, i.e. an atom with an electron deficiency in its vicinity. In addition to the current carried by the detached conduction electrons, electrons in the valence band can shift successively into the electron deficient region and also give rise to a current. It is more convenient to regard this latter current as being carried by the migration of the positive holes than to consider the detailed electron motion.

For present purposes it is instructive to consider the conduction electrons as a negatively charged vapor, and the holes as a positively charged vapor, which permeates the lattice. As in other gases, the density of particles dn having energies in a given energy interval dE

has an exponential (Maxwellian) energy dependence, which in this case (and for $|E - E_f| > 2kT$) takes the form

$$dn \propto \exp(-|E - E_f|/kT) dE \quad (1)$$

for an energy E and temperature T , where k is the Boltzmann constant. The quantity E_f , known as the Fermi energy, is determined by the requirement that there must be equal numbers of positive and negative particles to maintain electric neutrality in the crystal. In the case of the electric insulator described above, this means that there must be equal numbers of electrons and holes, so that the symmetry of the energy diagram in Figure 1 requires that the Fermi energy be located at a level halfway between the valence and conduction bands in the energy gap.

In an insulator, therefore, $|E - E_f| > E_g/2$, where E_g is the energy gap. For a typical insulator $E_g \simeq 1$ electron volt (eV), and kT is only about 0.03 eV at room temperature. Equation (1) thus shows that the density of conduction electrons and holes is quite low in insulators, which results in a very low electrical conductivity. If impurity atoms with a higher valence than the lattice atoms are introduced into the insulator, their extra valence electrons are much more easy to detach, so that they appear on the energy diagram at a level just below the conduction band, as in Figure 2. Then, even at room temperature the electrons from these impurity atoms are excited into the conduction band. One important result is that the electrical conductivity of the crystal can now be adjusted over a wide range of values by "doping" the crystal with sufficient impurity atoms; i.e., it becomes a semiconductor. Another result is that only one type of current carrier is introduced, since the electron deficient region in this case is immobilized in the vicinity of the impurity atom, and therefore cannot lead to hole conduction. Atoms which donate electrons to the conduction band are called donors, and the resulting crystal is called an n-type semiconductor, since current is conducted by negative particles. When a lower valence impurity is introduced, it captures (accepts) valence electrons and creates holes in the valence band. The situation then is analogous to the previous case, except that the introduction of acceptor impurities produces a p-type semiconductor, in which current is conducted primarily by positive holes.

In effect, the donor levels replace the valence band as an adjustable and temperature-independent source of conduction electrons, and the acceptor levels replace the conduction band as a similar source of holes. By analogy, it can be seen that the Fermi level must be located about halfway in the narrow gap between the impurity levels and the nearest band edge for a purely n- or p-type semiconductor.

ELECTRONS IN METALS

A metal is made up of atoms whose valence electrons are so loosely bound that, when assembled into a closely packed crystal lattice, these electrons freely move from one atom to another through the crystal. There is, therefore, no energy gap between the conduction and valence electron bands. Since again equal numbers of holes and conduction electrons must exist for neutrality, symmetry in this case requires that the Fermi energy be located at the top of the valence band, as shown in Figure 3.

THERMOELECTRIC ENERGY CONVERSION

Basic Thermoelectric Effects¹

A thermocouple consists of two different materials a and b connected to form a loop, as in Figure 4. It is found experimentally that when a current I is passed through the loop, heat is released at one junction and absorbed at the other at a rate proportional to the current, i.e.

$$q_1 = \Pi_{ab} I. \quad (2)$$

This is called the Peltier effect and Π_{ab} is the Peltier coefficient for the couple composed of materials a and b . If the temperature difference between the junctions is increased, the open-circuit emf V in the loop increases in direct proportion to the temperature difference, i.e.

$$\frac{dV}{dT} = S_{ab} . \quad (3)$$

This is the Seebeck effect, and S_{ab} is called the Seebeck coefficient for the couple.

It can be shown that these effects are closely related. Suppose that one junction is at temperature T and the other junction is slightly hotter at temperature $T + dT$, and that the corresponding Peltier coefficients at the two temperatures are Π and $\Pi + d\Pi$ respectively. Suppose also that the circuit is broken at one point and a potential difference dV applied such as to reduce the current in the loop to nearly zero. If the current is small enough, the process is thermodynamically reversible, and the net rate of heat produced at the junctions must equal the electrical power input. Therefore, from Equation (2), passage of one coulomb around the circuit gives a net heat release

$$(\Pi + d\Pi) - \Pi = dV . \quad (4)$$

For a reversible process the net entropy production ds is zero, so that

$$ds = d(\Pi/T) = 0 . \quad (5)$$

Equations (3)-(5) combine to give

$$S_{ab} = \frac{\Pi_{ab}}{T} . \quad (6)$$

Thermoelectric Generator Optimization

The efficiency of conversion of the heat q supplied to the hot junction into electrical power P in a load resistance R_L is

$$\eta = \frac{P}{q} = \frac{I^2 R_L}{q_1 + q_2 - q_3} , \quad (7)$$

where q_1 is the Peltier heat (Eqn.(1)), $q_2 = (K_a A_a + K_b A_b)(T_h - T_c)/L$ is the heat conducted down the two legs of area A_a and A_b and length L between junctions at hot and cold temperatures T_h and T_c respectively. The heat

$$q_3 = \frac{1}{2} I^2 \left(\frac{\rho_a}{A_a} + \frac{\rho_b}{A_b} \right) L ,$$

half of the total Joule heat which is dissipated in legs of electrical resistivity ρ_a and ρ_b , in effect flows back to the hot junction. Maximization of Equation (7) with respect to R_L and A_a/A_b gives

$$\eta = \frac{T_h - T_c}{T_h} \frac{(1 + Z_{ab} \bar{T})^{\frac{1}{2}} - 1}{(1 + Z_{ab} \bar{T})^{\frac{1}{2}} + T_c/T_h} , \quad (8)$$

where

$$Z_{ab} = \left[\frac{S_{ab}}{(\rho_a K_a)^{\frac{1}{2}} + (\rho_b K_b)^{\frac{1}{2}}} \right]^2 \quad (9)$$

and $\bar{T} = (T_h + T_c)/2$. This optimization also prescribes optimum values¹ for R_L and A_a/A_b . It may be seen therefore that the efficiency is entirely dependent on the

operating temperatures and the materials properties contained in the single parameter Z_{ab} . Efficiency increases as either Z or the temperature difference increases. It is convenient to compare individual materials against a hypothetical reference material having a Seebeck coefficient and resistivity equal to zero (e.g. $S_b = \rho_b = 0$), whereupon Equation (9) gives

$$Z = \frac{S^2}{\rho K} \quad (10)$$

as the figure of merit for any material with properties S , ρ and K . Most pure metals are suitable as the hypothetical reference material for comparison of semiconductors, since their S and ρ are relatively very small.

Material Optimization

In Figure 5 the energy level diagram for an n-type semiconductor-metal thermocouple is shown. The Fermi levels of the metal and semiconductor must match at the junction to preserve the charge neutrality of the vapor of electrons and holes in the vicinity of the junction. Because of their higher average velocities, conduction electrons at the hot end of the semiconductor diffuse more rapidly toward the cold end than the reverse diffusion of cold electrons to the hot end. A net electron current therefore flows to the cold end and through the external circuit, causing a potential drop V across the load.

Consider the situation at the cold junction in Figure 5. From the kinetic theory of gases it can be shown that each electron which migrates across a plane carries a kinetic energy $2kT$ across the plane. Furthermore, the potential energy of each electron changes by an amount E_0 as it moves across the junction, where E_0 is the energy difference between the Fermi level and the bottom of the conduction band. This total energy change must be equal to the Peltier heat released at the junction, i.e., from Equation (2),

$$E_0 + 2kT = e\Pi, \quad (11)$$

where e is the charge of the electron. The Seebeck coefficient of an n-type semiconductor therefore is given by Equations (6) and (11) as

$$S = 2 \frac{k}{e} \left(1 + \frac{E_0}{2kT} \right). \quad (12)$$

Similarly, it can be shown that the value of S for a p-type semiconductor is the negative of the value given in Equation (12).

The thermal conductivity $K = K_a + K_e$ is the sum of the thermal conductivity of the atomic lattice K_a and that of the electron gas K_e . From kinetic theory it can be shown that K_e is directly related to the electrical resistivity ρ , by what is known as the Lorentz or Wiedemann-Franz relation,

$$\frac{\rho K_e}{T} = \frac{\pi^2}{3} (k/e)^2 \quad (\text{here } \pi = 3.14) \quad (13)$$

Combining Equations (10), (12) and (13) gives

$$ZT = \frac{12}{\pi^2} \left[\frac{K_e}{K_e + K_a} \right] \left[1 + \frac{E_0}{2kT} \right]^2 \quad (\pi = 3.14) \quad (14)$$

If lattice conduction were negligible, then a material with $E_0 \gg kT$, and a large value of S , would give a high figure of merit Z . In reality however, K_a is not negligible. Since K_e is proportional to the density of the electron gas, the semiconductor must be doped with a high density of impurities to make K_e comparable to K_a and thus improve

the first bracketed factor in Equation (14). This high concentration of impurities causes E_0 to decrease to the order of kT since, as discussed previously, the Fermi level is located near the impurity energy levels, which themselves must be near the conduction band to be effective. It is found that the maximum value of Z is obtained when the conduction electron or hole density is about 10^{19} cm^{-3} , which is intermediate to that of insulators ($< 10^{15}$) and that of metals ($> 10^{23}$). Corresponding optimum properties are: $E_0 \simeq kT$, $S \simeq 3k/e \simeq 200 \mu\text{V}/^\circ\text{C}$, and $K_a/K_e \simeq 2$. The best existing materials, when given the optimum donor or acceptor density, have $ZT \simeq 1$. Other densities could make S , ρ or K_e much larger or smaller, but would lead to a lower value of Z , and therefore to a less efficient thermoelectric generator.

Materials Research and Development

During the period 1949-1956, most of the basic principles of semiconductor thermoelectricity became defined, primarily by the pioneering work of A.F. Ioffe² and his co-workers in the USSR. The best materials they found were lead and bismuth tellurides.

Following this, a sizeable effort was launched in the U.S. seeking materials with substantially higher figures of merit. Over 800 companies in the United States have been engaged in some type of research or development related to thermoelectric devices³⁻⁵. About 50% of the cost of these programs has been financed by government agencies. Not all of this work was specifically for power generation; a considerable fraction of it was for refrigeration, i.e. for the utilization of Peltier cooling. Major attention was received by inter-metallic compounds or alloys of high atomic weight elements. Those that attracted major attention were lead, mercury, bismuth, thallium and antimony in combination with tellurium, selenium and sulfur. Hundreds of compounds were investigated including: nickel oxides doped with lithium; titanium oxides with varying stoichiometric ratios of oxygen and titanium; polycrystalline carbon with a variety of dopants; rare earth sulfides, selenides and tellurides; cerium sulfide; gallium arsenide; zinc antimonide, etc. Although the number of basic elements and compounds considered is in itself impressive, the additional number of variations in stoichiometric ratios and dopant concentrations investigated is larger by at least an order of magnitude.

Figures 6 and 7 summarize the figures of merit for the best materials on which data have been published to date⁶. It can be seen that there have been only relatively minor improvements made over lead and bismuth telluride, primarily through various alloys of these materials. The only really different materials to make their appearance within the last 5 years, and which have promising performance, are the silicon-germanium alloys⁶. These are not compounds, and the ratio of silicon in the alloys varies between 60 and 90 percent depending on the desired properties. These materials are doped with boron to produce the p-type semiconductor and with phosphorous to produce the n-type.

Inspection of Figures 6 and 7 reveals some of the fundamental limitations encountered in trying to increase the figure of merit. First it should be noticed that the figure of merit is strongly dependent on temperature for a given amount of impurity doping. It initially rises with increasing temperature primarily because the lattice thermal conductivity K_a in Equation (14) is about inversely proportional to temperature. Since, as previously discussed, the optimum doping depends on the magnitude of K_a , a different doping is required for optimization at each temperature. This is difficult to achieve in practice, so that a single doping is chosen which gives the best Z over the temperature interval of interest in the application. The curves for two degrees of doping of PbTe in Figure 7 illustrate this point.

The fall in Z at high temperatures is primarily due to the excitation of electrons into the conduction band for the p-type materials, and positive holes into the valence band for the n-type, cancelling out the desired current carrier obtained by doping. This "intrinsic" type of carrier excitation can be suppressed, and efficient operation extended to higher temperatures, by choosing materials with a large energy gap E_g . Unfortunately a

large gap implies strongly bound valence electrons, which in turn implies a strong coupling between atoms, and therefore a high lattice thermal conductivity K_a . The net result is a lower value of Z , but somewhat more efficient operation is made possible because of the increased temperature drop available.

The quantity ZT is actually more significant than Z alone in determining the efficiency (Eqn. (8)), and in relation to the basic properties (Eqn. (14)). Included in Figures 6 and 7 is a curve for $ZT = 1$. It may be seen that $ZT \simeq 1$ represents an approximate limit to what has been achievable by extensive materials exploration. The only significant exceptions to this statement are of less practical significance, since it has not been possible to achieve long time operation of the tellurides much above 500°C due to their vaporization. Detailed basic exploration of the bracketed quantities in Equation (14) has led to the conclusion that the present electronic limitation on ZT is fundamental, and that the development of materials with $ZT > 2$ is quite unlikely⁷. The most substantial improvement could arise by obtaining a much lower value of K_a , but it seems likely that this would be accompanied by mechanical and thermal instability.

Thermoelectric Material Selection

In the process of engineering a thermoelectric converter, a number of considerations affecting the selection of the thermoelectric materials must be evaluated. The figure of merit alone is not a sufficient criterion.

Operating Temperature - For maximum converter efficiency, it is necessary to maximize the temperature difference $T_h - T_c$ between the hot and cold junctions of the thermocouple. The actual junction temperatures available, however, are strongly dependent on the final use of the converter. If it is to be used for a terrestrial application (ground or sea), then a low value of T_c may be employed because of the availability of a low temperature heat sink. For application on a space vehicle, the waste heat must be radiated. Since radiator size and weight are highly sensitive to temperature, it becomes necessary to operate at a high T_c , which in turn requires a high T_h to obtain an acceptable efficiency. The value of T_h , however, is limited by the available heat source. It may be concluded that for terrestrial uses, materials based on Bi_2Te_3 and PbTe are still the best available. For space application, PbTe and Si-Ge alloys are the only materials that should receive serious consideration at present. Figure 8 is a diagram permitting the efficiency of a Si-Ge converter to be determined for given junction temperatures³.

Structural Properties - The importance of the structural properties of a thermo-electric material depends on the design and intended use of the converter. The tellurides have notoriously poor structural properties and must be held in compression since their compressive strength is much higher than their tensile strength. The Si-Ge materials have much better mechanical properties. For this reason they are being considered for uses even at temperatures where the tellurides are much more efficient. Typical values are:

	PbTe (3M)	Si-Ge (500°C) (RCA)
Tensile strength (lb/in^2)	1000	4000
Compressive strength (lb/in^2)	10,000	150,000
Expansion Coefficient ($^\circ\text{C}^{-1}$)	18×10^{-6}	5×10^{-6}

Lead telluride based materials exhibit some plastic flow at the higher operating temperatures, and have a significant tendency to sublime tellurium above 500°C and thereby degrade electrically, particularly at the hot junction contact. Silicon-germanium does not encounter these difficulties up to at least 1050°C .

Reliability and Life - These two considerations are strongly related, since reliability becomes a more important consideration as the expected converter life increases. The basic reliability of thermoelectric materials of the telluride type is relatively low. Their

weak structural characteristics, brittleness, tendency to oxidize and vaporize impose stringent design criteria if a reliable device is required. Spring-loaded cold shoes, pressurized sealed compartments and other components that must be added to make the PbTe thermoelements work, have a tendency to decrease the basic reliability of a device by providing additional failure possibilities. In fact, some of the early failures on PbTe thermoelectric converters were spring failures. Reliable spring assemblies now have rather sophisticated designs. Another common failure in the early SNAP programs was in the seals, with subsequent leak of the inert gas and sublimation of the lead telluride.

Lead telluride, especially the p-type which is doped with sodium, is only compatible with iron at the hot shoe end. Other materials have a tendency to react with the sodium and deprive the PbTe of dopant, greatly altering its thermoelectric properties. The magnetic field of the iron can be objectionable in some space missions. Si-Ge converters need not be protected against sublimation or oxidation. With structural characteristics superior to the PbTe materials, highly reliable chemical bonds have been obtained using tungsten shoes.

As a general rule, if the desired power supply life ranges from a few days to about 6 months, PbTe converters can be quite adequate for space use from a durability standpoint. If longer life (on the order of years) is desired, Si-Ge converters have an advantage.

To enhance the reliability of the converter, a network of series-parallel connected couples can be used. To minimize the effect of single couple failures, a large number of parallel connections is desirable, but output voltage of the converter is proportionately lowered. Since a low output voltage reduces both the efficiency and reliability of other power subsystem components, there is a compromise necessary between reliability and efficiency. Studies have shown that for relatively low power output sources (10 to 100W), two parallel strings, cross connected at each couple, is near-optimum.

Module Configurations

An ideal thermocouple would have its composition and doping continuously change along the legs so that the Z obtained at each temperature would fall on the maximum Z envelope in Figures 6 and 7. Furthermore, the cross section of the legs would have to vary to maintain the optimum area ratio. From a practical standpoint, such refinements would be very difficult to achieve. However, two more practical alternatives toward the same objective, segmenting and cascading, are under development.

In the segmenting method⁸, two or more different materials are joined, thermally and electrically in series, to form each leg, as in Figure 9. The length and position of each segment is chosen so that it spans its most effective temperature range. For example, the materials discussed above, and appearing in Figures 6 and 7, might be used as follows in a three-stage couple operating between 25 and 1000°C: Bi_2Te_3 between 25 and 200°C; PbTe between 200 and 500°C; and Si-Ge between 500 and 1000°C. The different materials must be joined by a diffusion barrier which is compatible with both segments joined, from both the chemical and thermal expansion standpoints. Such a barrier would be easier to find for joining the two tellurides, since they have similar properties, than for joining the PbTe to the Si-Ge, which has substantially different properties. The large difference in the optimum area ratios further complicates the joining problem if the full potential advantage of the arrangement is to be realized. Figure 11 shows experimental results⁶ for a two-stage segmented couple compared with the computed performance for both single and two-stage devices. The couple consisted of segments of $(\text{Bi,Sb})_2(\text{Te,Se})_3$ operating between 25 and 200°C (max), and Si-Ge hot segments.

In the cascading method⁹, shown in Figure 10, each material is assembled into a separate converter optimized to perform over a specific temperature interval. The converters are then stacked in thermal series, separated by electrical insulation, but with their outputs electrically in series or parallel. This arrangement removes the geometrical and segment-joining constraints encountered in the segmenting method, but it is more complex, and introduces new problems of electrical and thermal insulation and contacts. Figure 12 shows

the ideal improvement in performance possible over the segmenting method, but considers no non-essential heat losses or temperature drops which must occur in practice.

Both segmented and cascaded approaches are under active development, but progress has not been rapid, probably due to the modest funding level of the work. Also, from a general viewpoint, it should be realized that these multiple-material devices must contend with the worst characteristics of all the materials employed, and multiply the number of electrical connections and mechanical components which have been a major source of difficulty in the past.

Conclusion

The basic understanding and materials technology of thermoelectric conversion are well-developed. However, an intensive application of this knowledge over the past decade has resulted in only modest improvements in the performance of practical generators. The only major improvement has occurred through the development of the Si-Ge thermoelements, but their advantages outweigh their disadvantages only at the higher temperatures. The single stage approach, using older telluride-based materials, continues to be the choice for most new generator development. Apparently it is still felt that the higher performance potentially available does not justify the cost and uncertainties associated with the development of higher temperature heat sources, or with other new technology substantially different from that of the well-proven generators in present use.

THERMIONIC ENERGY CONVERSION

Basic Thermionic Effects¹⁰

It was shown in the section on thermoelectric conversion that heat conducted by the atomic lattice of a semiconductor is the principal factor which limits the efficiency of a semiconductor thermocouple. An obvious approach to overcome this limitation is to remove the atomic lattice, i.e. to completely remove the semiconductor from region *a* in Figures 4 and 5. The electron gas then must evaporate from the hot junction, be transported across region *a* and condense at the cold junction. Such a device is known as a thermionic energy converter. When the junctions are at nearly the same temperature, such as to approach thermodynamic reversibility, the operation of the device is very similar to that of a "vacuum thermocouple", as it was called by Ioffe². In practical use, the operation of the device is highly irreversible, and the analogy fails to have analytical significance. However, the reversible case gives insight into the basic nature of both devices and their relative advantages.

Before proceeding further, the brief review of the elementary properties of an electron gas should be extended to include its passage into and through the space between two electrodes. As an electron leaves a metal, its lines of force must intersect the equipotential surface normally. The force on an electron at a distance *x* from the surface therefore is the same as that between the electron and its mirror image in the surface, $F = e^2/(2x)^2$. The energy required to completely remove the electron from the surface against this force is, therefore,

$$\phi_1 = \int_{x_0}^{\infty} F \, dx = e^2/4x_0 = 3.6/x_0 \text{ eV} , \quad (15)$$

where x_0 (in angstrom units) is the distance where the approximation of a plane surface fails, which is on the order of atomic dimensions. If a surface charge is present, an additional energy ϕ_2 is required for the electron to pass through the surface. The total energy barrier which an electron must overcome to become completely detached from the surface is $\phi = \phi_1 + \phi_2$, a quantity known as the work function. Only electrons with energies greater than ϕ can enter and conduct current across the region between the electrodes. These energies therefore constitute a "conduction band" for this region, and

ϕ is analogous to the energy gap in a semiconductor. As was discussed previously (Fig. 3), the Fermi energy E_F lies at the top of the valence band in a metal, so that Equation (1) can be integrated for $E > \phi$ to obtain the number of electrons capable of leaving the metal. This results in the Richardson equation for the electron emission current from a surface,

$$J_s = AT^2 \exp(-\phi/kT), \quad (16)$$

where $A = 120 \text{ amp/cm}^2 (\text{°K})^2$ is the Richardson constant.

Since x_0 is about one angstrom unit and $\phi_1 \gg \phi_2 > 0$ for clean metal surfaces, $\phi \gtrsim 4\text{eV}$ for most refractory metals. Equation (16) therefore indicates that very high temperatures ($> 2500^\circ\text{C}$) would be required to obtain currents in the ampere/cm² range with such pure surfaces. Fortunately, the addition of only a small amount of cesium vapor to the interelectrode region "dopes" the surface with positive adsorbed cesium ions. Their surface charge gives rise to a large negative ϕ_2 , which can decrease ϕ to as low as 1.5 eV, depending on the pressure of the cesium vapor and the temperature of the surface. The cesium therefore plays the same role as the donor impurities used to dope a semiconductor, by moving the Fermi energy much closer to the conduction band, and thereby greatly increasing the current flow at lower temperatures.

COMPARISON OF THERMOELECTRIC AND REVERSIBLE THERMIONIC CONVERSION

The energy diagram for an ideal thermionic converter in Figure 13 shows that it is very similar to that for the thermoelectric case in Figure 5, and that ϕ is analogous to E_0 . The hot electrode is called the emitter, the cold electrode is called the collector, and their respective work functions are ϕ_e and ϕ_c .

When the temperature difference between the two electrodes is small compared with their absolute temperature, and the output voltage V is adjusted so that net current is small compared with J_s , the electron vapor between the electrodes is near equilibrium, as in a semiconductor thermoelement. The net current density is

$$J = J_e - J_c = AT_e^2 \exp\left(-\frac{V + \phi_c}{kT_e}\right) - AT_c^2 \exp\left(-\frac{\phi_c}{kT_c}\right), \quad (17)$$

where J_e , J_c , T_e and T_c are the respective currents from the emitter and collector and their temperatures. Note that $V + \phi_e$ is the energy barrier presented to electrons from the emitter, and ϕ_c is that for those from the collector. By setting $J = 0$ in Equation (17), Equation (12) is obtained for the Seebeck coefficient S with $E_0 = \phi_c$. Since, as before, the kinetic energy carried across the gap by each electron is $2kT$, the net heat transferred by the electron gas for $J_e = J_c$ is $q_e = 2kJ_e(T_e - T_c)$, so that $K_e = 2kJ_eL$, where L is the width of the gap. Similarly, the radiant heat transfer which replaces lattice heat conduction, $q_a = \sigma\epsilon(T_e^4 - T_c^4) \simeq 4\sigma\epsilon T^3 (T_e - T_c)$ corresponding to $K_a = 4\sigma\epsilon T^3 L$, for small $T_e - T_c$, where σ is the Stefan-Boltzmann constant and ϵ is the net radiant emissivity of the surfaces. Furthermore, the effective electrical resistivity for small J and $T_e - T_c$, found by differentiating Equation (17) with respect to V , is $\rho = kT/J_eL$. Combining these quantities in Equation (10) gives Equation (14), except that the $12/\pi^2$ is replaced by 2, and

$$\frac{K_a}{K_e} = 4 \frac{\sigma\epsilon T^4}{2kJ_e} = 2 \frac{\sigma}{k} \frac{\epsilon T^3}{J}. \quad (18)$$

Therefore, there is a conflicting desirability of lowering ϕ_c , to increase the first bracketed quantity in Equation (14), and raising it to increase the second. An analogous conflict for E_0 was described in the thermoelectric case. In the present case, however, Equation (14) is readily maximized with respect to ϕ_c , giving

$$(ZT)_{\max} = \frac{\phi_{\text{copt}}}{kT} \left(1 + \frac{\phi_{\text{copt}}}{2kT} \right), \quad (19)$$

provided that,

$$\frac{\phi_{\text{copt}}}{kT} = \log_e(k^2 A / \sigma \epsilon \phi_c) (J/J_c) \simeq 13, \quad \text{and} \quad \phi_e < \phi_{\text{copt}} + V. \quad (20)$$

Although the logarithmic term is quite insensitive to the values of ϵ and ϕ_c , the quantity $1/\epsilon\phi_c$ is the ultimate property figure of merit for the thermionic converter operating reversibly.

Equations (19) and (20) show that ZT can exceed 100, and thereby closely approach the limiting Carnot efficiency $(T_h - T_c)/T_h$ in Equation (8), if the optimum collector work function can be achieved. At present, only work functions greater than about 1.4 eV are practically available, so that Equation (20) limits highly efficient operation to temperatures greater than about 1200°K, below which the figure of merit falls exponentially to small values. This illustrates an inherent distinction that should be made between thermoelectric and thermionic conversion. The thermoelectric case is limited to $E_0 \ll E_g$ to avoid intrinsic conduction (e.g. hole conduction in the n-type semiconductor). Hole conduction, of course, cannot occur in the thermionic case, so that ϕ_c can be made large enough to achieve much higher efficiencies. However, it is inherent to this advantage that it is obtainable only at much higher temperatures. Therefore, if the application inherently requires high temperature operation, such as in large space-power systems, the thermionic converter is inherently capable of operating efficiently there, whereas the thermoelectric system is not. On the other hand, where low temperature operation is feasible and desirable, the thermoelectric system has an inherent capability, and the thermionic system does not.

Practical Thermionic Converter Operation

In reality, it is not necessary to restrict operation of the thermionic converter to small temperature differences where the limiting Carnot efficiency is very low. However, at large temperature differences the operation becomes highly irreversible, since the electron temperature can change by a large factor within only a few electron free paths. Thermoelectric quantities, such as the Seebeck and Peltier coefficients, no longer have analytical significance or usefulness in their previous sense. The formulation of the performance of an ideal thermionic converter operating over a large temperature difference is straight-forward, but cumbersome. Since it is available elsewhere¹¹, it will not be repeated here.

Non-ideal aspects of thermionic conversion are those introduced by the effects of the space charge and scattering of the electrons as they are transported across the gap. These are not essential to the operation of a thermionic converter, but constraints associated with practical electrode spacings and emission properties cause them to be significant in practical devices. These will be only mentioned briefly here, since they have been reviewed elsewhere^{12, 13}, and will be discussed further in the following section.

Since approximate neutrality is maintained throughout a semiconductor by the presence of the lattice ions, a simple linear potential gradient exists across the thermoelement. However, the potential distribution between the electrodes of a thermionic converter, as in Figure 14, reflects the existence of local net electron or positive ion space charge (negative or positive curvature respectively). In the vacuum diode, the space charge of electrons in transit can give rise to an intolerably large emission barrier, unless the spacing is impractically small ($\ll 0.001$ inch). If cesium vapor is introduced, positive ions from the emitter can neutralize the electron charge to form a neutral, low resistivity plasma, separated from the electrodes by very narrow "sheaths" where neutrality cannot exist. This is known as the extinguished or unignited mode of operation of the cesium discharge. Other means for generating the ions have been tried (triodes), but have not

been successful practically. In another mode of the discharge the neutralizing ions are formed within the cesium vapor itself by impact of energetic electrons which fall through the sheath drop at the emitter. This ion production process requires a potential drop V_d across the gap, which otherwise would appear across the load, as shown in Figure 14. Nevertheless, this latter mode of operation is the most practical to date, as is shown in the next section on Engineering Aspects.

REFERENCES

1. For a more detailed and rigorous treatment, see:
R. Heikes and R. Ure, *Thermoelectricity: Science and Engineering*, Interscience, N.Y. 1961. (Detailed technical reference.)
S. W. Angrist, *Direct Energy Conversion*, Allyn-Bacon, Boston, 1965 (Pedagogical).
2. Ioffe, A. F. *Semiconductor Thermoelements*, Infosearch Ltd., London, 1957.
3. Leventhal, E. L. *Thermoelectricity: Introductory Notes*, TRW 4713-67 1-1 (January 1967). The writer gratefully acknowledges liberal use of material contained in these informal but informative recent notes.
4. *Status Reports on Thermoelectricity*, Naval Research Laboratory, 1959-1963.
5. Proceedings of the Thermoelectric Specialists Conferences, 1961-1966, IEEE. Inc., 345 E. 47th St., N.Y.
6. Dismukes, J.
Rosi, F, *Ge-Si Alloys for Thermoelectric Power Generation-A Review*, AIChE-ICHEME Symp Series #5, 1965 (London: Instn Chem Engrs). Good bibliography.
7. Ure, R. W. Jr Ref. 5; May, 1966, paper 11.
8. Freas, D.
Mueller, J.
also
Bates, H.
Weinstein, M. *ibid*, papers 12 and 14.
9. Rocklin, S. R. *Adv. in Energy Conv. Engr.*, ASME, 345 E. 47th St., N.Y., p. 207.
10. For a more detailed and rigorous treatment, see:
C. Herring and M. Nichols, *Thermionic Emission*, Rev. Mod. Phys. Vol. 21 (1949). (Detailed technical reference on thermionic emission.)
J. Millman and S. Seely, *Electronics*, McGraw-Hill, N.Y. (Pedagogical treatment of emission and gaseous discharge.)
11. Houston, J.
Webster, H. *Advances in Electronics*, pp. 125-206, Academic Press, N.Y., 1962 (Early comprehensive review of thermionic conversion.)
12. Bullis,
et al. *J. Appl. Phys.* Vol. 38 (Aug. 1967). Recent summary of converter transport physics.)
13. Rasor, N. *Proc. IEEE* Vol. 51, 733 (1963). (Early review of converter emission physics.)

Fig. 1 Electron energy diagram for insulator

Fig. 2 Electron energy diagram for n-type semiconductor

Fig. 3 Electron energy diagram for metal

Fig. 4 Thermocouple of materials a and b

Fig. 5 Energy diagram for thermocouple with n-type semiconductor as material a

Fig.6 Temperature dependence of the figure of merit Z for p-type semiconductors. Dashed line is ZT =1

Fig.7 Same as Figure 6, but for n-type semiconductors

Fig.8 Efficiency of Si-Ge thermoelectric converters

Fig.9 Segmented thermo-electric module

Fig.10 Cascaded thermo-electric module

Fig.11 Experimental and theoretical performance of a two-stage segmented thermo-couple constructed from Ge-Si and $(\text{Bi}, \text{Sb})_2(\text{Te}, \text{Se})_3$ alloys

Fig.12 Theoretical efficiency of thermo-electric modules using Si-Ge and PbTe thermoelements

Fig.13 Energy diagram for ideal thermionic converter

Fig.14 Effects of space charge in actual thermionic converters

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VB. ENGINEERING ASPECTS OF THERMIONIC ENERGY CONVERSION

by

Ned S. Rasor

200 Tait Road, Dayton, Ohio, USA

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ENGINEERING ASPECTS OF THERMIONIC ENERGY CONVERSION

Ned S. Rasor

INTRODUCTION

Less than a decade ago, the conversion of heat to electrical power by thermionic emission was little more than an interesting effect. Since then, the thermionic energy converter has been developed to the point that it now can be considered to be a respectable member of the family of ceramic-metal electronic power tubes. Basic investigations have removed much of the mystery which formerly set its operation apart from that of other thermionic devices, and the art of handling the new materials involved has been absorbed into the large body of skills and equipment which constitute the electron tube industry. In fact, this development has been so intensive that the basic and applied technology of the thermionic converter is now more sophisticated than that of other gaseous discharge devices which have been in practical use for half a century.

As is often the case, increased familiarity has exposed a basic simplicity of the device and its operation. Formerly, it was necessary to cite a large amount of experimental data to illustrate the interaction of the many variables, and to catalogue a variety of suspected physical mechanisms. There now exist physical models of converter operation which correlate the variables and permit comprehension of the process as a whole. This simplicity is deceptive since exposing it has been a major task, involving systematic testing of many theoretically plausible basic models, and rejecting those which were inconsistent with observed data in the regions of engineering significance. The existing description is adequate for most engineering purposes, and identifies the most significant parameters and dominant physical processes in existing devices. The description of the details of these basic processes is still unsatisfactory, however, and their resolution is the key to the improvements which will take place in the next decade.

Great evolutionary changes in the anticipated practical applications of thermionic conversion, and in competing energy conversion devices, also have occurred during the past decade. Therefore, unlike the objective of basic truth in converter research, the objective of practical application in thermionic conversion engineering has been a moving target. The failure of some important missions to materialize, the unexpected failure of competing devices to dominate some areas of application, and their unexpected domination of others has resulted in a re-examination of the engineering development goals. The previous tendency of the engineering work to converge on a few approaches has been reversed, i.e., new approaches are emerging which are responsive to existing conditions.

This section outlines the status of thermionic converter development from the viewpoint of prospective engineering use. The research upon which the description is based is reviewed elsewhere¹⁻³³. Also, a perspective of recent trends is taken in describing progress toward practical application, rather than a review of past work. Special attention is given the broadening spectrum of new approaches which have arisen in response to changes in requirements, especially when viewed on an international scale. The engineering utility of the present understanding, and the potential impact of research in progress, is illustrated by specific examples of their application in these new approaches.

SYNOPSIS OF CONVERTER TECHNOLOGY

Physical Description

A cesium vapor thermionic converter is similar to a hot-cathode mercury vapor rectifier (phanotron) in many respects, consisting of a cold and a hot electrode immersed in a metal vapor contained in a vacuum envelope, as shown in Figure 1. In both devices, the metal vapor is maintained in equilibrium with a droplet of liquid metal condensed in the coldest region of the envelope, and the temperature of this "reservoir" determines the pressure of the vapor. In both devices current flows between the electrodes by an electrical discharge through the vapor.

In the thermionic converter, however, the thermal energy given to the electrons emitted from the hot electrode is alone sufficient to maintain the discharge between the electrodes, and to drive the current through the external circuit without an external electrical power source. As shown in Figure 1, the only energy input to the device is the heat required to maintain the temperature of the hot electrode. Although the hot and cold electrodes are called the cathode and anode respectively in a rectifier, they are called the emitter and collector in a thermionic converter to avoid confusion with the cathode and anode of a chemical battery, which have just the opposite polarity.

For electrodes immersed in cesium vapor, the efficiency of the electron emission and gaseous discharge processes is so high that most of the heat supplied to the emitter is carried away by the emitted electrons, and typically 10 to 20% of it appears as electrical power in an external load. To obtain such high efficiency, there are optimum values for the cesium vapor pressure and the spacing between the electrodes which depend on the temperatures and composition of the electrodes. While these temperatures, pressures and materials are not greatly different than those encountered in mercury vapor rectifiers, the spacing between the electrodes in a converter is much smaller, being typically 0.001 to 0.020 inch instead of an inch or two as in the rectifier. This is a direct consequence of the much larger electron scattering cross section of the cesium atom, rather than being an inherent consequence of the thermionic energy conversion process.

Electrical Description³

*Ignited Mode*⁴⁻⁶. As shown in Figure 2, the electrical output (current-voltage) characteristic of a cesium vapor converter shows two modes of operation. The vapor between the electrodes glows brightly in one of these modes, which therefore is called the ignited mode of the discharge. In this mode, the electrons in the interelectrode region are maintained at about twice the temperature of the emitter by a potential drop across this region, known as the arc drop V_d . This high electron temperature in the glowing region is sufficient to excite and ionize the cesium vapor and thereby maintain the high density plasma necessary for the flow of a large electron current between the electrodes. The potential difference between the electrodes therefore is

$$V = (\phi_e - \phi_c) - V_d, \quad (1)$$

where $\phi_e - \phi_c$ is the contact potential difference, and ϕ_e and ϕ_c are the effective work functions of the emitter and collector respectively.

In most applications it is desired to obtain the required electrical power output of the converter at the highest potential difference consistent with adequate power density, since this generally corresponds to maximum efficiency for the converter and minimum losses in the external circuit. In the ignited mode it has been found that the output current falls rapidly when V_d becomes less than the minimum value V_d required to maintain the plasma, i.e., for V greater than $V_0 = (\phi_e - \phi_c) - V_d$, identified as the transition point in Figure 2. Maximum power output typically occurs near this point. It has been found that V_d has a minimum value of about 0.4 volt, and therefore V is maximized, when the electrodes are spaced about 5 to 20 electron free paths apart, which occurs for

$$10 < (pd)_{\text{opt}} < 40 \text{ torr-mils}, \quad (2)$$

where d is the electrode spacing in mils (1 mil = 0.001 inch), and the cesium pressure p is related to the cesium reservoir temperature T_R in $^{\circ}\text{K}$ by

$$p = (7.4 \times 10^6) \exp(-8702/T_R) \text{ torr} . \quad (3)$$

The optimum potential difference between the electrodes therefore is about

$$V_0 \simeq \phi_e - \phi_c - 0.4 \text{ volts} . \quad (4)$$

It has been found that at the optimum condition corresponding to Equation (2), the output current per unit electrode area J_0 is equal to about 0.4 of the saturation electron emission current density J_s from the emitter, i.e.

$$J_0 \simeq 0.4 J_s \quad (5)$$

with

$$J_s = AT_e^2 \exp(-\phi_e/kT_e) , \quad (6)$$

where $A = 120 \text{ amp/cm}^2 - ^{\circ}\text{K}^2$ is the Richardson constant, $k = 8.6 \times 10^{-5} \text{ volt}/^{\circ}\text{K}$ is the Boltzmann constant, and T_e is the emitter temperature. Optimum output power density therefore is

$$P_0 = J_0 V_0 . \quad (7)$$

The optimum electrical output for given values of the emitter temperature and electrode work functions is readily computed from Equations (4)-(7), especially since Equations (3) and (6) are generally available in charts. The dependence of maximum output power on ϕ_e and T_e for $\phi_c = 1.6 \text{ eV}$, a typical value, is illustrated in Figure 3. These results represent the experimental data to the accuracy needed in most engineering estimates. More general expressions exist⁵⁻⁶, but such precision is inconsistent with the predictability of engineering device performance. Actual experimental performance data should be used to establish an exact design point for a given system once the region of interest is identified by the foregoing expressions.

*Extinguished Mode*⁷. In the other mode of the discharge, the interelectrode space is dark, i.e., the arc is extinguished. The positive ions required to maintain the plasma are thermionically emitted from the hot electrode. If precisely enough ions are emitted to neutralize the electron emission from the emitter, no significant space charge exists. Therefore, since electrical energy is not required to produce the ions, the arc drop V_d can be zero, and Equation (4) becomes, for the extinguished mode,

$$V_{0x} \simeq \phi_e - \phi_c , \quad (8)$$

provided that ϕ_e is chosen to give neutral emission, i.e., if⁸

$$\phi_e = \phi_n \equiv \frac{V_i}{2} + \frac{kT_e}{2} \log_e \left(\frac{P}{p} \right) ,$$

where

$$P = \frac{2AT_e^2}{e} (2\pi mkT_R)^{\frac{1}{2}} \simeq 10^5 \text{ torr} , \quad (9)$$

$V_i = 3.9 \text{ volt}$ is the ionization potential of cesium, and e and m are the electronic charge and mass. The dependence of ϕ_n on emitter and cesium reservoir temperature is included in Figure 5. Equation (9) combines with the Richardson equation (Eqn (6)) to give

the saturation neutral emission current

$$J_{sn} = \left(\frac{p}{P}\right)^{\frac{1}{2}} AT_e^2 \exp\left(-\frac{V_1}{2kT_e}\right). \quad (10)$$

The emission current which diffuses to the collector in the extinguished mode is

$$J_{0x} = \frac{J_{sn}}{1 + 0.8 \text{ pd}} \quad (11)$$

for pd in torr-mils. Differentiation of Equation (11) with respect to p , using Equation (10) shows that the maximum current obtained for a given spacing d is

$$J_{0x} = J_{sn}/2 \quad (12)$$

and occurs for

$$(\text{pd})_{0x} \simeq 1.3 \text{ torr-mils} . \quad (13)$$

Maximum power $P_{0x} = J_{0x} V_{0x}$ computed from Equations (3), (8), (9), (10) and (12), for $\phi_c = 1.6$ volt, is given in Figure 4 for comparison with ignited mode operation. It should be noted that at high temperatures and small spacings, power output in the extinguished mode can exceed that in the ignited mode for the same conditions. In fact, the current in the extinguished mode can exceed J_0 , whereupon the obstructed region (Fig.2) ceases to exist.

Electrode Technology

*Emitter*⁸⁻⁹. As can be seen in Figures 3 and 4, emitters with work functions between about 2.2 and 3.2 electron volts are necessary to obtain useful power densities between 1600 and 2100°K. A few emitter materials are known which have elementary vacuum work functions in this range, but they all evaporate too rapidly at the corresponding temperatures in Figures 3 and 4 to achieve stable operation over a useful lifetime. An exhaustive search has failed to uncover any satisfactory materials. It appears that there is a fundamental correlation between the rate of evaporation and electron emission which makes the use of this class of elementary emitters impractical.

Fortunately, when immersed in cesium vapor at reasonable pressures, materials with vacuum work functions greater than 4.0 eV, such as most of the refractory metals, adsorb enough cesium on their surfaces to lower their work functions into the range of required values. Since the surface is in equilibrium with the vapor, problems of emitter stability and lifetime are virtually eliminated. It has been found that the cesium pressure required to maintain a given work function is closely related to the vacuum work function of a surface; i.e., the higher the vacuum work function ϕ_0 , the lower the required cesium pressure. The vacuum work functions of some typical refractory metals are Nb(4.0 eV), Mo(4.4 eV), Ta(4.2 eV), W(4.5 eV), Re(4.9 eV), and Ir(5.5 eV).

Because of its stability and relatively high ϕ_0 , rhenium has become a popular emitter material. The cesium pressure which is necessary for a rhenium emitter to achieve the work function required at each emitter temperature is included in Figure 3 for that example. It can be seen that even for a favorable material such as Re, Equations (2) and (13) require the interelectrode spacing to be less than 5 mils in the ignited mode, and less than 0.5 mil in the extinguished mode, to obtain power densities greater than 10 watts/cm². The situation is worse in applications where rhenium cannot be used, e.g., in some nuclear reactor application.

The interplay among electrode materials, temperatures, and spacings is summarized in Figure 5. A plot of work function ϕ against the ratio of surface temperature T to cesium reservoir temperature T_R is a convenient tool for mapping the emission-dependent

properties of the thermionic converter. The family of curves shown in Figure 5 is based on a particular theoretical model¹⁰ which identifies the parameter ϕ_0 with the bare or vacuum work function of the surface, and virtually all experimental data for surfaces in pure cesium vapor fall within the envelope defined by this family. The principal exception is in the region below 2.5 eV where data frequently extend the lower envelope down to the dashed curve, although such behavior is often known to be associated with contamination. Therefore, for many purposes it is convenient to identify data which fall within the envelope, and exhibit the characteristic slope, with an effective value of ϕ_0 as a correlating parameter.

Only a relatively small part of this plot is important to thermionic conversion. The upper heavy trapezoid is the region of greatest importance to emitters operating in the ignited mode. The upper and lower boundaries correspond to work functions for sufficient electron emission at 1600 and 2100°K respectively and the left and right boundaries correspond to optimum spacings for the ignited mode of about two and twenty mils respectively (10 mfp). For the extinguished mode, emitters are restricted to operation on the heavy line segment labeled ϕ_n , which represents the neutral emission condition for maximum spacings between 2 and 20 mils (1mfp) at its left and right ends respectively.

In recent years, substantial progress has been made in moving to the right in the emitter region of the diagram, i.e., toward large spacings. This has been accomplished by selecting the highest ϕ_0 materials which are compatible with the other restrictions, and by treating them to uniformly expose the highest ϕ_0 crystal planes. Emitters with ϕ_0 up to about 5.0 eV have been successfully developed by this approach, but further progress is likely to occur only through the use of additives to the cesium vapor.

The additive studies which are being actively pursued take two different approaches which can be discerned by confining attention to a single operating point, e.g., the left (small spacing) terminus of the extinguished mode line segment, labeled point A in Figure 5. It should be noted that this point can be reached by either a bare surface having $\phi_0 = 2.9$ eV, or by a surface with absorbed cesium having $\phi_0 = 5.5$ eV. As far as the converter is concerned, both methods give the same output, since the ion and electron emission currents and the cesium pressure are the same for both. However, these work functions represent the extremes for known materials (e.g., 2.9 eV for La B₆ and 5.5 eV for Ir), and such materials often are unattractive for other reasons, primarily vaporization. There are two alternate ways of reaching this operating point by adding other vapors to the cesium vapor. The effective ϕ_0 of an otherwise attractive material such as tungsten ($\phi_0 \simeq 4.6$ eV) could be lowered to 2.9 eV by the addition of electro-positive elements (e.g. barium) to the cesium vapor or it could be raised to 5.5 eV by the addition of electronegative elements (e.g. oxygen). The principle of both approaches has been verified in laboratory tests, but has not been applied yet to engineering hardware. Initial indications are that the electronegative additives are preferable since only very small amounts are required (e.g. 10^{-7} torr of oxygen), and due to the inherent difficulty of maintaining a low collector work function in the presence of electropositive additives.

In summary, although virtually all significant engineering tests and designs to date have utilized operation in the ignited mode, it should be anticipated that practical use of the extinguished mode should become possible in the near future, making available the substantially higher output voltage and efficiencies inherent to this mode. Reference to Figures 3 and 4 shows, however, that relatively higher temperatures and closer spacings are inherent to extinguished mode operation, regardless of emitter improvements, so that the ignited mode continues to be the most practical for many, if not most, purposes.

*Collector*⁴⁻¹¹. It has been found that as the collector temperature is increased above the optimum value T_{c0} , the collector work function ϕ_c effective in Equations (4) and (8) increases so as to limit the collector emission current to about 5% of that which it is collecting, i.e.

$$\left. \begin{aligned} \phi_c &= \phi'_c \quad \text{for} \quad T_c \leq T_{c0} \\ \phi_c &\simeq kT_c \log_e \left[\frac{AT_c^2}{0.05J} \right] \simeq \frac{T_c}{600^\circ\text{K}} \quad \text{for} \quad T_c \geq T_{c0} \end{aligned} \right\} \quad (14)$$

where ϕ'_c is the true collector work function. For the example in Figure 3, if $\phi_c = 1.6$ eV, then Equations (14) give the optimum collector temperature T_{c0} as about 1000°K . The effective collector work function ϕ_c is independent of ϕ'_c above this temperature, and increases about 0.17 volt for each 100°K increase in T_c , with a corresponding decrease in output voltage and power.

The true collector work function ϕ'_c is apparently dominated by a layer of condensed impurities, and therefore is found to be relatively insensitive to the bulk composition of the collector. It usually stabilizes after a few hours of converter operation in cesium vapor and approaches the dashed curve in Figure 5, which fortunately falls within the region of greatest importance to the collector shown as the heavy triangle. The right boundary of this region is imposed by collector emission at the lowest cesium pressure given for the emitter region, and the upper boundary corresponds to a collector temperature of 1000°K , which is high enough for most applications. Substantial improvement in converter output could be obtained if lower work functions in this region could be employed, particularly at the lower emitter temperature. However, little progress has been made in obtaining anything better than that which occurs spontaneously when the temperature is optimized in engineering tests. The basic technology of the collector is poorly understood compared with that of the emitter.

It should be pointed out that a collector work function of 1.6 eV or slightly lower is typical only for converters using pure cesium or electronegative additives. The use of electropositive additives (e.g. barium or Philips cathodes) results in collector work functions which stabilize at about 2.1 eV, and thus reduces the converter output by about 0.5 volt at collector temperatures below 1000°K .

Thermal Description¹²

The heat balance for a thermionic generator is summarized by

$$\alpha_s \alpha_L Q = P_e + P_r \quad (15)$$

where Q is the total heat input to the emitter, $P_e = J(\phi_e + 2kT_e - 0.4)S$ is the heat removed from it by electron vaporization and $P_r = \sigma \epsilon S(T_e^4 - T_c^4)$ is the heat removed by thermal radiation. S is the area of the emitter, $\sigma = 5.6 \times 10^{-12}$ watts/cm² - ⁰K⁴ is the Stefan-Boltzmann constant, and ϵ is the thermal emissivity of the electrode system.

A fraction $1 - \alpha_s$ of Q bypasses the converter by stray heat losses. For converters with cylindrical electrodes, α_s is near unity. Careful design is required to achieve an α_s of 0.8 to 0.9 with planar electrodes, however. A fraction $1 - \alpha_L$ of the heat which passes through the converter is conducted from the emitter through the lead which connects the emitter to the load. This lead cannot be too thin since it must also conduct the emitter current. Optimization of the size of this lead shows that maximum converter efficiency is obtained when α_L is about 0.9.

The electrical potential drop across this optimum lead equals $1 - \alpha_L$ of the electrode potential difference, so the optimized potential difference V_t between the output terminals of the converter is

$$V_t = \alpha_L V_0 \quad (16)$$

and the total power available at the load is

$$P_t = J_0 V_t S. \quad (17)$$

The overall energy conversion efficiency of the converter therefore is

$$\eta = \frac{P_t}{Q}. \quad (18)$$

Lines of constant efficiency, using the typical values $\alpha_L = \alpha_S = 0.9$ and $\epsilon = 0.2$, are included for the examples in Figures 3 and 4. Inspection shows that the efficiency is about 35% of Carnot efficiency (the thermodynamic limit of heat engine efficiency, $1 - T_{C0}/T_e$) for converters operating in the ignited mode, and about 55% of Carnot efficiency for the extinguished mode.

Materials, and Lifetime¹³

Most of the materials and construction techniques for thermionic converters are also employed in other types of ceramic-metal electron tubes. However, due to the somewhat higher envelope temperatures and compatibility considerations, associated with the maintenance of the required cesium vapor atmosphere, the class of materials used in thermionic converters is somewhat more restricted. In particular, the metalized, copper-brazed, pure alumina-niobium sandwich is almost a universal choice for the ceramic-metal envelope seal. Envelope and collector materials are typically molybdenum, nickel, niobium, or copper. Stainless steel and tantalum have been used, but have fallen into disfavor due to their undesirable gas absorption properties. Emitter materials are typically tungsten, rhenium, molybdenum, or less typically tantalum. Rhenium is usually only used as a thin cladding on the emitter electrode due to its cost and limited availability in desired shapes.

As is typical for electron tubes, each new converter design must go through a development period in which the factors which initially limit its lifetime and reliability are detected and removed; e.g. electrode distortion and envelope failure resulting from the cracking of joints or insulators, through thermal stresses, interdiffusion of components and impurity evolution. A significant lifetime for a design can only be established if the design is fixed and an iterative series of life tests is undertaken under realistic practical operating conditions. In the few cases where such hardware development has been carried through, lifetimes of the order of a year have been demonstrated for groups of converters, with individual cases exceeding two years. This present limit is set more by the unavailability of funds to carry out longer tests, than by any known inherent lifetime limiting factors. Demonstration of longer lifetimes and detailed failure statistics must await the initiation of full-scale engineering development of a complete system.

Auxiliary Innovations

Methods have been developed recently to assist in the coupling of the converter to the heat source and heat sink. While these do not change the performance of the converter itself, they provide increased flexibility for its integration into a system.

Integral Reservoirs. Methods have been developed by which the cesium reservoir temperature can be made to coincide with the temperature of another region of the converter proper, such as that of the collector, thus eliminating the need for independent control of the reservoir temperature. In one of these, the cesium reservoir is a small crystal of graphite which reversibly absorbs cesium to form a series of lamellar compounds¹⁴. In another method, the graphite is replaced by a porous metal sponge which has a very large surface area for cesium adsorption¹⁵. The converter is placed in operation at the desired operating point using an external liquid cesium reservoir and with the graphite crystal or sponge located inside the envelope. Once equilibrium is obtained, the liquid

cesium reservoir can be removed since cesium adsorption or desorption on the sponge buffers any changes in pressure which might otherwise occur. By perspicacious thermal coupling of such an "integral reservoir" to an electrode, the cesium pressure can be automatically maintained near the optimum value when electrode temperatures change.

*Heat Pipes*¹⁶. The heat pipe is a refluxing vapor chamber which can be used to transfer a large heat flux with a relatively small temperature drop. Its principle of operation is identical with that of the steam heating system for a building, except that the condensate is returned to the boiling region through a wick, by capillary action, instead of by gravity. Figure 6 illustrates the operation of a typical heat pipe. The wick is usually a wire mesh or grooves on the inner surface of the pipe wall. Heat pipes have been demonstrated repeatedly to have long life at collector temperatures. However, the severe conditions encountered at emitter temperatures, such as clogging of the wick by mass transport, indicate that a substantial development period may be necessary before the heat pipe approaches the reliability and lifetime of the converter itself.

NUCLEAR REACTOR APPLICATION

General Situation

The relative importance of thermionic conversion for nuclear space power systems has increased rapidly over the past few years due to the rapid maturing of thermionic technology, and due to the failure of the Rankine cycle systems to achieve their development goals. The reduction of dynamic system development to a component technology improvement level means that the thermionic system can be in a much stronger competitive position when the first firm requirements emerge. Thus, in this case the thermionic system might not be forced to compete against an accumulation of engineering experience with earlier systems, as has occurred in the isotope and solar generator areas.

Work in the thermionic reactor field has been exploiting this "reprieve" to good advantage. A number of successful life tests on nuclear fuels at thermionic temperatures have done much to remove the stigma of unreality formerly assigned to the field due to the absence of such technology. Also, the present lack of a system which fulfills the evolving needs in the 5 - 100 Kwe intermediate power region has encouraged the design of evolutionary thermionic systems. Such designs depend more on the use of existing technology, whereas advances well beyond the present state of art are required for the more revolutionary concepts appropriate to the high power region, to which thermionic reactors were confined previously. Many of these evolutionary designs have originated in Europe, where the thermionic conversion field developed more recently and therefore is relatively less influenced by these previous constraints.

In anticipation of the forthcoming competition with dynamic systems, the thermionic systems being designed for the intermediate power region are putting emphasis on a potentially decisive factor which they can uniquely possess in this power region i.e., high redundancy. Such redundant systems consist of dozens or even hundreds of independent modules of which many can fail without catastrophic loss or even serious degradation of the system¹⁷. The failure of a single bearing, winding or coolant loop can lead to the complete loss of a dynamic system, and even a two-fold redundancy is obtained at great expense in complexity and weight. Good failure statistics can be established experimentally for thermionic modules at a relatively modest cost and reasonable time, whereas it is virtually unfeasible to do so for a dynamic system with a mission duration of a year or two.

The less conservative thermionic concepts, which have a great potential for superior performance at high powers, are continuing to receive the most attention, particularly in the United States. Whether these concepts are ever employed, however, may depend to a great extent on whether thermionic systems gain acceptance through their successful use in the initial and formative stages of nuclear space-power plants.

In-Core Concepts

Fast Reactor. Historically, and at present in the United States, this concept has dominated work aimed toward practical application of thermionic conversion. This has occurred because it appears to result in the lightest and most compact space-power system at the higher power levels, but also because its complexity places the greatest demands on all the technologies involved. Figure 7 illustrates schematically the most popular version of this concept, frequently called the TFE (thermionic fuel element) version¹⁸. In this version, the fuel is contained entirely within cylindrical emitters which are surrounded by cylindrical collectors, and a number of such cells are assembled into a series-connected column, like cells in a flashlight. A large number of such columns are then assembled to form a core similar to that in conventional reactors, and a liquid metal coolant removes the waste heat from the collectors.

Many detailed studies and discussions of the problems and characteristics of this version are available, so it is neither appropriate nor necessary to repeat them all here. However, because of this backlog of discussion and experience, this concept will be used as a standard for comparison of the other concepts. Table I lists the principal considerations for such a comparison, and cites the relative difficulty associated with the different concepts in each consideration.

Among the difficulties associated with the TFE in a fast reactor, several stand out as being crucial to its feasibility. The stringent requirements for high fuel stability were formerly thought to be the most severe problem¹⁹. Recent tests have shown that simple cermet fuels can probably meet these requirements, at least under the well-controlled conditions of the tests. Whether these conditions can be maintained within the uncertainties and over the full lifetime of a practical system, especially with regard to the venting of fission products at high fuel burn-up, is still a moot point.

The requirement for insulating the collector of each cell from the coolant might now be considered as a problem nearly as crucial to the feasibility of the TFE as that of the fuel. The thin insulating sandwich required must pass a large heat flow with little temperature drop. Also, it must maintain a relatively high electrical resistance in the presence of intense high energy nuclear radiation at collector temperatures ($\sim 1000^\circ\text{K}$), and possibly in contact with cesium vapor and fission products. In large systems, it is required that the output voltage be at least 100 volts and preferably several hundred or higher. Any electrical breakdown across or puncture of the several square meters of thin insulating sandwich, operating under the severe conditions described, will result in the short circuit and subsequent loss of a large part of the system output. This possibility greatly reduces the redundant reliability which is a decisive factor in the competition between thermionic and dynamic systems. Dependence on a single coolant loop similarly degrades the inherent redundancy of a thermionic system.

Another type of failure which can propagate to catastrophic loss of a TFE system is the open-circuit condition which results from the loss of the cesium vapor. This occurrence, which is responsible for most of the failures in test models, terminates electron cooling in all the cells of an element, and results in the fuel temperature rising by several hundred degrees. Since presently it is necessary to operate existing fuels near their maximum safe temperature, to achieve the power densities which make the TFE attractive, such a further temperature increase would so drastically shorten their life as to be equivalent to immediate failure of the element. This failure can propagate to other elements when the decomposing fuel short circuits the sandwich insulator or disrupts coolant flow.

An inherent property of the TFE which intensifies these crucial problems is the difficulty in testing the complex TFE element before it is required to perform in the reactor in space. Indirect tests of a quality control nature, performed at the output terminals of the element, cannot ensure that the performance and integrity of individual cells in the element will be within the acceptable limits for system performance and reliability, even at beginning of life.

Alternate versions of the in-pile concept can overcome some of the problems of the TFE version. It is obvious, for instance, that if the core is an assembly of completely independent cells, each with its own output terminals and cesium reservoir, the redundancy can be increased over that of the TFE, especially if they are connected in a series-parallel network. Also, it would be possible to pre-test the individual cells. However, it is questionable whether these advantages offset the penalty in reactor size required to provide the complex network of electrical and reservoir connections to each cell. Furthermore, the other problems of the TFE remain, and the much larger number of ceramic-metal seals which must operate in the core amplifies this problem. In another approach, the fueled emitter is placed outside the collector and coolant channel, as shown in Figure 8, and such elements are assembled without touching in an array to form the core²⁰. Accordingly, the element is easily tested, offers potential reductions in ohmic losses in its electrodes, and a relatively small increase in temperature is required to transfer the excess heat from an open-circuit element to its neighbours. However, this concept introduces some unique problems, such as potential contact between the closely spaced hot emitters, assembly of the elements to a coolant manifold, and the support, electrical insulation, and thermal insulation at the external surface of the core, which is even hotter than the emitters.

Since the major interest in the in-core thermionic reactor arises from its elegance and high performance, and since the less elegant alternate versions do not greatly reduce the most crucial problems, it seems likely that the TFE version will continue to prevail. The argument that the TFE module is too complex to be successful has tended to lose force, since a module was built and successfully tested in a reactor for 1000 hours²¹. A single cell unit of similar design has exceeded 6000 hours of in-core testing without degradation of output²².

Thermal Reactor. For output powers of about 100 kWe or less, the size of the thermionic reactor becomes limited by heat transfer and thermionic conversion considerations, rather than by the amount of fuel required to maintain criticality for one to two years operation. The total quantity of fuel required occupies only a small fraction of the volume inside the reactor, so that space is available for introduction of moderator and other materials which allow the existence of a thermal neutron energy spectrum. For example, the critical mass of U^{235} in a fast-spectrum 100 kWe reactor is about 100 kilograms, whereas it is only 10 kilograms for a thermal reactor of this power. In addition to reducing fuel cost and weight, removal of this large amount of uranium from the core provides space for more flexible design of the fuel and the thermionic converter components.

Figure 9 shows²² a 50 kWe version of a type of thermal reactor which is being studied in detail by several groups in Germany²²⁻²⁴. It is similar to the TFE fast reactor, except that each element is surrounded by a can of zirconium hydride moderator ($\sim 6 \times 10^{22}$ hydrogen atoms/cm³). The coolant flows between the element and the moderator can, so that the moderator is maintained at slightly less than collector temperature, or about the same temperature as in SNAP-8. The fueled emitter, shown in Figure 10, consists of a molybdenum cylinder with an array of axial holes containing UO_2 powder. The large central hole is for venting of fission products, and can be used for testing each cell by insertion of an electric heater. Several emitters of this type have been operated to high fuel burn-up at thermionic temperatures in a reactor for more than 1000 hours with no observable deterioration, and one was used to successfully operate a converter in a reactor²³. It has been found that the fuel automatically distributes itself to give a uniform temperature over the length of this type of fuel element during operation in a reactor. This is important in that a non-uniform emitter temperature can greatly reduce converter performance.

Figure 11 shows²⁴ how the total unshield-weight of this type of system (in kilograms), varies with electrical power output (in kilowatts). The curve labeled A is for a system in which the core is composed of 75 fuel elements (and moderator cans) of the type shown in Figure 9, which is optimum at about 75 kWe for niobium as the collector and cladding structure. The curve labeled B is for 37 fuel elements, which is optimum for a

beryllium structure. This illustrates the much greater importance of the nuclear properties of materials in the thermal reactor, which greatly limits the choice for otherwise superior properties. Curve C shows that for the niobium structure, it is profitable to replace some of the thermionic fuel elements with fueled moderator elements, of the SNAP-8 reactor type, as the required electric power output decreases. The optimum number of fuel elements is about 19 between 3 and 20 kWe power output. The attractiveness of this approach is that a single reactor and TFE design can be utilized over a wide range of power levels.

Curve D shows that the weight of an advanced thermoelectric system, of the improved SNAP-10A type, is much greater than that of the thermionic system for powers greater than a few electrical kilowatts. Furthermore, it can be seen that the optimized thermionic system is also much lighter than the Rankine cycle SNAP-8 (~ 1500 kg at 20 kWe), and is comparable to the Brayton cycle SNAP-8 (> 330 kg at 10 kWe).

The TFE thermal reactor retains almost all the crucial problems described above for the TFE fast reactor. A modification of the TFE has been proposed²⁵ which can overcome most of these problems if extinguished mode operation can be achieved, particularly for power levels of 50 kWe or less in thermal reactors. In analytical studies of the TFE for ignited mode operation, it is found necessary to have the order of ten series-connected cells in each element to avoid substantial ohmic losses in the cell electrodes. Since these losses are inversely proportional to the square of the cell output voltage, and since the output voltage in the extinguished mode is about twice that in the ignited mode for the same power density, the optimum number of cells is reduced to three or four. If the height-to-diameter ratio of the core is reduced to slightly less than that optimum for criticality, and if the electrical conductance of the electrodes is increased to the full extent possible in the thermal reactor, it is possible to employ only two cells in each element, with only a slight increase in system weight over the multiple cell TFE version. As can be seen in Figure 12, this arrangement permits the terminals of all cells to be outside the core, and thus to be cross-connected for maximum redundant reliability. Similarly each cell can have an independent fission product vent and cesium reservoir, and can be pre-tested independently by insertion of an electrical heater into its emitter. The collector insulator problem is virtually eliminated by providing an independent collector coolant loop and radiator segment for each element, and insulating the complete module from the moderator by thick ceramic spacers located outside the core. The coolant loops can be either heat pipes or small thermoelectric pumps similar to that employed with SNAP-10A. Since even the coolant loops are independent, the failure of one element cannot propagate to the others, and the redundancy of the system is equal to the number of elements.

A logical sequence of development for in-core TFE reactor systems might include the "double-diode" thermal reactor version of Figure 12, the multiple-diode thermal reactor version of Figure 9, and the multiple diode fast reactor version of Figure 7, in that chronological order. They evolve naturally from one another as power output requirements and component reliability increase.

Out-of-Core Concepts

Fluid Convection. The system in which heat is transported by fluid convection from a reactor to an external thermionic generator has not received significant attention in recent years. The generally greater weight of this system compared with the in-core systems, the severe high temperature electrical insulation problem, and the generally severe problems of a large coolant loop and pump operating for long periods at emitter temperatures have tended to suppress interest in this approach.

Heat Pipes. The concept shown in Figure 13 has been under study by the Euratom laboratory at Ispra, Italy²⁶. Heat is transported by heat pipes from fuel elements suspended inside a thermal core to the emitters of thermionic converters located just outside the reactor. Another set of heat pipes removes the waste heat from the collectors,

and a third set of heat pipes cools the hydride moderator. The system has an advantage of high redundancy since each converter, together with its emitter and collector heat pipes, constitute a completely independent module, electrically insulated from the core. It also has a much higher tolerance for fuel distortion than the in-core concepts. Complete modules, such as that shown in Figure 14, have been constructed and tested with electrical heating.

The principal difficulty with this concept is that, like the fluid convection out-of-core system, it is completely dependent on overcoming the problems of corrosion, leakage and mass transport in a liquid metal system operating at emitter temperatures. While such developments are not highly improbable, it is likely that serious attention to this concept will have to wait until as much confidence has been gained in the reliability of the heat pipe as in the thermionic converter.

Core Surface Concept. In this concept, heat is conducted from the interior of a solid core reactor to heat the emitters of converters which are mounted on the outer surface of the reactor, and which reject waste heat by conduction to a radiator. The extreme simplicity and potential high reliability inherent to this concept attracted most of the early investigators. However, previous studies of this concept employed very high temperatures, new materials and complex reactor designs which were far beyond experience²²⁻²⁷. Even so, the weight and power level of the resulting system were only marginally competitive with those of the SNAP-8 Rankine system which was then thought to be in an advanced stage of availability. The general impression was obtained that any unique advantages this system might offer were greatly outweighed by the high development cost required to bring the new technologies into being, and the uncertainty of eventual success.

In recent years much has happened to reverse this conclusion. First, the SNAP-8 system has failed to become available, and its projected weight is now much larger than before. Second, a reactor has been demonstrated in the USSR ("Romashka")²⁸ which operated at thermionic temperatures for two years, and which appears to be compatible with thermionic converters in the core-surface concept. Third, planar diodes of a type compatible with the thermionic version of Romashka have reached a high degree of development in the thermionic solar generator (SET) program¹³, and have been operated for over two years under the conditions required in the thermionic Romashka. Finally, the development of heat pipes has offered increased design flexibility, even though they are not essential to the concept.

Figure 15 is a diagram of the thermionic version of Romashka, which is only a slight perturbation of the demonstrated Romashka design²⁹. The length of the reactor is the same as that of Romashka, but the core length has been increased by about seven inches. All other dimensions, compositions and controls are the same as in Romashka. Thermionic converters of the SET type* are mounted in cavities bored into the inner surface of the monolithic beryllium reflector casting. The molybdenum emitter shoes are spaced without touching, in a close-fit hexagonal array, forming a cylindrical surface separated by a 2 to 3 mm annular gap from the surface of the core. The emitters are radiant-heated by the core, and the surfaces facing the gap are darkened and deeply grooved to approach black-body radiant heat transfer conditions.

The plane working surfaces of the emitter shoes, inside the converter, are clad with a metal which optimizes their electronic properties. The collector structure of each converter extends through a hole in the reflector to the external surface of the reactor, and can contain a heat pipe. It is thermally bonded to and electrically insulated from the reflector, using the same material and method employed to insulate the hot-straps from the contact shoes in Romashka. The external cylindrical surface of the reflector forms the radiator for reject heat, and is also blackened. Straps connect the emitters and collectors of adjacent converters in series-parallel arrangements for maximum reliability consistent with load voltage requirements.

*See Figure 19.

By using the reported heat release distribution and thermal conductivity of the fuel²⁸, it is possible to compute the temperatures in the system for various total thermal input powers Q , with the maximum core temperature T_m held constant at the reported value, as shown in Figure 16. The net thermal emissivity of the gap was taken to be 0.8. The effect of using a highly oriented graphite in the core, and of using various materials for the collector structure is shown at 40 kWt. The values for copper are about equivalent to the use of a collector heat pipe. It should be noted that only about 50°C temperature difference between the core surface temperature T_s and the emitter temperature T_e is required to transfer 40 kWt across the gap. Figure 17 shows how the maximum electrical power output, and associated variables computed from the equations presented above, depend on input power for converters with rhenium emitters ($\phi_e = 1.3 [(T_e/T_R)-1]$ eV). The optimum ratio of the core surface area A_s to the total emitter area A_e is found by differentiation of Equation 7 with respect to A_e , and occurs when $\alpha_s \alpha_L Q/A_e P_r = (V/\alpha_L k T_e) + 1$. The values $\alpha_s = \alpha_L = 0.9$ were used since these are consistent with what was achieved in solar (SET) generators. The design employed here is similar in concept to several such generators which were constructed and extensively tested (including vibration)¹³, except that the cavity is filled with radiation from the incandescent core in this enlarged version, instead of concentrated solar flux.

Table II contains a summary of the system characteristics at a reference design point of 40 kWt, and for the reference system when the central core temperature is increased to 2200°C, which is still well below the melting temperature of the fuel (2500°C). The shield weight corresponds to that for a non-radiation-hardened payload of the SNAP-SHOT type. Table III summarizes the growth in power output which can occur by perturbation of the basic Romashka design. Further increases in output would require extensive modification of the core to reduce temperature drops, and would require extending the radiator axially beyond the reactor proper by heat pipes or convective loops.

Since all the major components of this system have actually been operated for two years under approximately the conditions specified, there appears to be considerable reality and inherent reliability associated with the concept. This reality, the much smaller weight, and the much greater simplicity of the thermionic Romashka indicate that the potential usefulness of the core-surface concept should be re-examined for missions in the 5-50 kWe range, and especially for those in which compactness or completely static operation would be important.

RADIOISOTOPE GENERATOR

In recent years, progress toward the use of thermionic converters in radioisotope generators has been impeded by the lack of a suitable fuel. Therefore, the detailed discussions of their characteristics and problems in the literature³⁰ are adequate to describe the present status of those aspects related to the converter. However, certain new approaches are beginning to take form which represent a distinct departure from the constraints previously placed on the fuel, and are worth brief mention.

The desirable qualities of the high power density and long half-life, which tend to match the requirements of the thermionic converter, seem to be mutually exclusive properties. One exception to this rule is found in actinium-227, which has a half-life of 22 years and a power density of 120/watts/cm³ in the refractory oxide form (Ac_2O_3). Since this is prepared by neutron irradiation of radium-226, its relative expense has been considered to be too great for use as a heat source in the US. However, the more limited availability of other isotopes in Europe has led to the consideration of the use of actinium-227 there³¹. As can be seen in Figure 18, a 50 watt electrical thermionic generator, using Ac-227 as a fuel and a heat pipe as a radiator, is an exceedingly simple and compact system, weighing only about one pound. However, the heavy shielding required by this isotope is not shown.

At the other end of the power density spectrum, there are isotopes which require little or no shielding, which require no helium venting, which are relatively inexpensive, and which have compounds with desirable high temperature properties. Unfortunately, these either have half-lives which are too short and/or power densities which have been considered to be too small for thermionic conversion. A particular example in these respects is promethium-147, with a half-life of 2.6 years and an oxide with a power density of 1.8 watts/cm³. It is interesting to note that this is about the same power density as in the core of Romashka at a power of 40 kWt. Therefore, a 6-8 kWe isotope generator (at beginning of life), using Pm-147 in the thermionic Romashka configuration, would be about the same size as that shown in Figure 15. The size and weight of the isotope version³² could be somewhat less, since the thick neutron reflector could be replaced by a thinner and lighter shell. Little or no shielding would be required for most applications.

Because of the experience and acceptance being gained by the thermoelectric isotope generators now in regular use, it will be necessary for thermionic generators to achieve efficiencies and specific powers several times greater than the thermoelectric to justify the expense and uncertainties of developing a new system. Thermionic generators seem to offer such improvements based on present technology, and the projected improvements in thermionic performance should allow this superiority to be maintained.

SOLAR GENERATOR

The solar thermionic generator was brought to the highest state of development of any potential application thus far. These generators and their testing are described in detail elsewhere¹³. The thermionic system was developed to weigh less than half that of the solar cell panels in existence at the outset of the work. Although this goal was nearly achieved, solar cell panels also improved to about the same extent. In view of the extensive experience with solar cells, and the erosion uncertainties and precise orientation associated with the solar concentrator, there is little if any incentive to use the thermionic system in most applications. The thermionic system is being considered now only for missions where the radiation or thermal environment cannot be accommodated by existing solar cell technology, such as for a solar probe. However, even in this case the solar cell technology is improving rapidly, and it is likely that the thermionic system again will be unable to compete with the confidence arising from the prior use of solar cells, even if the thermionic system is somewhat superior in weight and cost. Therefore, it is unlikely that the status of development in this area of thermionic conversion will change in the foreseeable future. The most recent model developed, shown in Figure 19, will probably serve mainly as a monument of achievement in the field, and as a point of departure for other applications, e.g. the thermionic Romashka.

FLAME-HEATED GENERATORS

For more than four years, burners, heat exchangers and thermionic converters have been available which could be integrated into compact portable generators using hydrocarbon fuels³³. These components have continued to improve, but the key component which would permit their use, i.e. a barrier to protect the emitter from destructive oxidation by the flame, is still not available. Free-standing aluminum and silicon carbide shields, and silicon carbide plated on tungsten, have all given moments of hope to those groups seeking to use them, but the severe thermal stresses and susceptibility to imperfection have not been overcome to the extent necessary to even approach a practical reliability.

Given such a reliable barrier, the designs and supporting technology are available for demonstrating a light-weight built-in battery charger for the electric auto - in case the driver gets lost and there is no place to plug it in.

REFERENCES*

1. Reports of the Thermionic Conversion Specialist Conf. (1963-1967), IEEE, 345 E. 47th St., NY.
2. Report on the Internatl. Conf. on Thermionic Power Generation, London, 1965 Instn. of E.E.
3. Bullis, Hansen, Warner, Houston, Koskinen and Rasor, J. Appl. Phys. 38, 3425(1967).
4. N.Rasor and S.Kitrilakis, Ref. 1, 1964, p.227.
5. N.Rasor, Ref. 2, Section 3a.
6. S.Kitrilakis and F.Rufeh, *ibid*.
7. C.Warner and L.K.Hansen, J. Appl. Phys. 38, 491(1967).
8. N.Rasor, Proc. IEEE 51, 733(1963).
9. N.Rasor and G.Gammel, Ref. 1, 1966, p.324; also see Ref. 14.
10. N.Rasor and C.Warner, J. Appl. Phys. 35, 2589(1964).
11. J.Houson and P.Dederick, Ref. 1, 1964, p.77.
12. J.Houson, Rept. of 23rd Phys. Electronics Conf., MIT(1963), p.376.
13. P.Rouklove, (SET program). Ref. 2, Section 8; A.Kaznoff and B.Weidenbaum, Proc. of Joint Conf. Instn. Chem.E. and A.I.Chem.E., London (June,1965).
14. T.Alleau, B.Devin, J.Durand and R.Lesueur, Ref. 2, Section 3B.
15. W.Harbaugh, A.Basiulis and M.Yates, Ref. 1, 1966, p.243
16. See Ref. 1, 1965 (Session V) and 1966 (Session IIB); also Ref. 2 (Section 2).
17. J.W.Holland, Ref. 2, Section 8.
18. N.Rasor and R.Hirsch, US Patent 3,113,091 (Filed 1960, issued 1963). (Also see Figs. II-57 and II-59 in lecture by H.Dieckamp in this Series).
19. See Ref. 2, Section 7A.
20. A.Schock, Republic Aviation, private communication.
21. V.Pupko, et al, Ref. 2, Section 4.
22. (page 10 only) Public announcement, Thermo Electron Engineering Corp., March,1967.
22. (elsewhere) Institut für Kernenergetik der Technischen Hochschule, Stuttgart. See Atomkern Energie 10 (Sept.-Oct.1965).
23. Central Research Laboratory, Brown, Boveri Co., Heidelberg. See BBC Nachrichten 3 (1966). See also papers by Gross, Jester et al in Ref. 1, 1966, pp.413-424.
24. D.Budnick, joint presentation by Siemens, Interatom and BBC at the Colloquium for Thermionic Energy Conversion, Bad Godesberg (June,1967).
25. Central Research Laboratory, Brown, Boveri Co., Heidelberg.
26. H.Neu, Atomproaxis 12 (Apr.-May,1966).
27. Nuclear News, "General Electric's Project STAR", ANS (Sept.1961).

*This list makes no attempt to recognize all significant contributions. It only indicates where more information can be found on the viewpoint given here, and usually where more detailed reference lists can be found.

28. M.Millionshchikov, et al, Geneva A/Conf. 28/p/873, May, 1964. J.Morokhov, Sci. and Eng. USSR 29, 1(1966).
29. N.Rasor, (BBC), Conference on Nuclear Space Power, Stuttgart (1965). Also see Annual Rept. for 1966 (May, 1967) of Stuttgart group (Ref. 22); and N.Rasor, J.Greenborg and M.Mayer, Ref. 1, 1967.
30. R.Harvey, T.Robinson and F.Fitzgerald, 9th Annual ANS Meeting, Salt Lake City (June, 1963).
31. R.Gillot, N.Neu and E.van Andel, UKAEA/ENEA Symp. on Indust. Appl. of Isotope Power Gen., Harwell, (Sept.1966).
32. J.DeSteese and J.Holmgren, Ref. 1, 1967.
33. L.Lazaridis and P.Pantazelos, Ref. 1, 1966, p.126, R.Engdahl, *ibid* p.133.

TABLE II

		<i>Converter Type</i>	
		<i>Ignited Mode Cesium Emitter</i>	<i>Extinguished Mode Optimum Emitter</i>
Dimensions			
Reactor height		30 inches	
Reactor diameter		18	
Reflector thickness		3-1/2	
Core diameter		11	
Core length		23	
Critical Mass		70 kg U ²³⁵	
Number of Converters (typical)		100	
Rated Temperatures (°C)			
Max. fuel		1900	
Core surface		1750	
Emitter		1710	
Collector	700		680
Radiator	660		640
Temperature at Peak Power (°C)			
Max. fuel		2200	
Core surface		1950	
Emitter		1890	
Collector	810		800
Radiator	740		730
Weights			
Reactor system (unshielded)		750 lb	
Shield (non-hardened payload)		280	
Shielded weight		1030	
Specific weight: Shielded	160 lb/kWe		120 lb/kWe
Unshielded	120		90
Rated Power			
Input power		40 kWt	
Output power	6-1/2 kWe		8-1/2 kWe
Output potential/converter	0.8 volts		1.4 volts
Specific power: Shielded	6 watts/lb		8 watts/lb
Unshielded	9 watts/lb		11 watts/lb
Peak Power			
Input power		60 kWt	
Output power	13-1/2 kWe		16 kWe

Fig.1 Schematic drawing of cesium vapor thermionic converter

Fig.2 Caricature of current-voltage characteristic of cesium diode

Fig.3 Performance map for optimum operation in ignited mode. Parameters are: emitter work function (in eV), current density (in amp/cm²), and efficiency (in %). Cs reservoir temperatures (in °K) and spacings (in mils) are optimum for a rhenium emitter. Spacings twice or half optimum generally reduce voltage by 0.05 V; spacings 3 times optimum reduce it by about 0.15 volt

Fig.4 Performance map for optimum operation in extinguished mode. Parameters are same as in Figure 3, except that the spacings (in mils) are mandatory

Fig.5 Correlation of the work function of surfaces in Cs vapor with their vacuum work functions ϕ_0 . Regions important to the electrodes of thermionic converters, and the work function for neutral emission ϕ_n , are included

Fig.6 Heat pipe

Fig.7 Fast-spectrum, thermionic-fuel-element (TFE) reactor

Fig. 8 Fast-spectrum, externally-fueled thermionic reactor core configuration

Fig. 10 Fueled emitter for thermal spectrum in-core thermionic reactor

Fig. 9 Thermal-spectrum, TFE reactor

Fig. 11 Weight of thermal thermionic reactor system for different configurations and power levels, compared with thermoelectric system

Fig. 12 Double-diode thermal-spectrum thermionic reactor

Fig. 13 Heat pipe thermionic reactor

Fig. 14 Prototype module for heat pipe thermionic reactor

Fig.15 Thermionic version of Romashka reactor

Fig. 16 Temperatures in thermionic Romashka

Fig. 17 Optimum parameters for the Romashka thermionic reactor with converters operating in the ignited mode

Fig. 18 Radioisotope thermionic generator using Ac-227 fuel

Fig. 19 SET solar thermionic converter

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VI. ELECTROCHEMICAL SPACE POWER SOURCES

by

Ernst M. Cohn

NASA, OART, Code RNW
Washington, D.C., 20546

SUMMARY

Because of the convenience, efficiency, and simplicity of chemical energy storage combined with electrochemical production of electricity, galvanic batteries powered the first airborne and, 87 years later, the first spaceborne on-board electrical systems. After a general discussion of electrochemical energy storage and electricity generation in (aero) space, the paper presents the thermodynamic and kinetic electrochemical basis for these devices, as well as criteria for selecting electrochemically active materials and estimating densities. The following three sections cover primary (single use) and secondary (rechargeable) equipment, either now being used or of potential usefulness in space. The last two sections relate some design criteria for space power systems and consider possible earth-bound applications of space-oriented electrochemical research and development.

ELECTROCHEMICAL SPACE POWER SOURCES

Ernst M. Cohn

INTRODUCTION

Sputnik 1 is reported to have carried electrochemical batteries as the on-board energy sources for powering its transmitters. Hardly any spacecraft has been launched since then without one or more electrochemical energy converters in its "auxiliary" power system. In view of the fact that electrochemical devices are virtually indispensable as energy storage and conversion devices in aerospace, we shall consider, first of all, some typical applications and criteria for choosing from among the various available components; recall their first use in aerospace, which preceded Sputnik by 3 generations; and discuss the electrochemical foundations common to all galvanic cells. (A galvanic cell is an electrolytic cell capable of producing energy by electrochemical action. Electrochemistry, in turn, is that branch of science and technology which deals with reciprocal transformations of chemical and electrical energy.) We shall then consider the components, devices, and systems available as well as projected for aerospace use, their capabilities and their problems. And we shall close with some thoughts about the effects of aerospace-oriented electrochemical research and development on other users, i.e., military and civilian, of electrochemical power.

A Word About Semantics

Before proceeding, however, let us clarify some semantic problems that have arisen in the last ten or so years, when conferences, courses, books, and papers on "modern", "advanced", and "direct" energy conversion became so fashionable that these adjectives are almost invariably associated with aerospace energy devices. Among the electrochemical ones, fuel cells particularly have received these attributes. There is, however, nothing "modern" about them.

The general concept of the fuel cell, which we shall define more precisely later, was expressed almost simultaneously by Davy in England and Ritter in Germany, both in 1801. The first paper on an operating fuel cell was published by Grove on 1839.

Furthermore, there is nothing "advanced" about fuel cells. Those now being used or readied for space are still designed according to Grove's recipe. Even the more developed batteries we use are barely beginning to show improvement over their industrial counterparts. In general, what have been called "advanced" devices are, in reality, "retarded" ones, having been surpassed long ago by mechanical engines.

Coming now to the word "direct", we must ask ourselves what this really means. The solar cell converts part of the sun's radiation into electricity; a galvanic cell converts a portion of its available chemical energy to electricity; thermoelectric and thermionic devices convert heat to electricity; etc. The electricity thus generated is quite useless, for the most part. What we really want is a beam of light, a current of heated or cooled air, an audible signal, printed letters and numbers, almost anything except electrons traveling along a wire. Of course, we use electricity, because we have well-developed techniques for converting it to the type of energy needed for obtaining the desired result. But the so-called direct energy converters are not that at all. They are, in reality, unconventional generators of electricity. In time, some will become conventional. Furthermore, a unit (photovoltaic cell, electrochemical cell,

thermocouple, thermionic tube) generates electricity without the need for moving mechanical components; but the system sometimes does and sometimes does not incorporate pumps, blowers, etc.,

I mention this misleading nomenclature not so much because it is one of these linguistic atrocities against which we should be on guard, but because it can lead to serious mistakes in technology. A modern development is not expected to have a great deal of history behind it, at least in its modern state. Hence some novices have not looked into the older literature on energy converters, often to their great disadvantage. Many of the "advanced" concepts have turned out to be disappointingly backward and useless in the practical world. The "direct" converter may have beguiled a spacecraft designer into using it, when he should have studied the kinds of energy actually needed, and their best sources. In what follows, we shall assume that electrical energy is the type of energy most suitable for further processing. Why, then, use electrochemical energy storage and conversion?

The Role of Electrochemical Power in Space

If power is needed for a limited period, up to a few weeks, chemical energy can be conveniently packaged and stored for this purpose. That is particularly true for relatively low power levels and short times: A few hundred watts needed for a few tens of hours can be carried in the form of batteries, silent, static, and efficient (70 - 80%) sources of electricity with reasonable energy densities (30 to more than 100 watt-hours per pound, or about 15 to more than 50 watt-hours per kilogram) that work well at ambient temperatures and can be stored, ready for use, for up to 2 or 3 weeks without serious loss of energy.

Between 5 or 6 hours and, say, 3 months of service, fuel cells usually show higher energy densities than batteries. They, too, are efficient (40 - 65%) and composed of small modules. But, because of more difficult storage of reactants and of need for removal of products, the total system is more complicated and, except for small sizes up to 200 watts or so, requires moving mechanical parts.

Unless the chemicals that are used to store the energy can be resupplied at intervals, primary electrochemical systems quickly become too heavy as mission time increases. In space, we must then look for lighter-weight primary sources of energy. Solar radiation can be used in many cases; in others, nuclear energy may be the better or only choice. These energy sources and their associated converters are covered in the other lectures.

Studies made thus far indicate that there are relatively few space-power systems that will not use electrochemical energy storage in conjunction with other, primary, energy sources and converters. Even if a spacecraft need not function during dark time, storage batteries (or electrical accumulators) may be required for "housekeeping" functions, such as maintaining acceptable standby conditions for equipment. Batteries or fuel cells may be needed for peak loads at launch or during other maneuvers, to supply power during docking, before start-up of the main power plant or while it is being serviced, or as emergency power sources. We have already seen combinations of batteries and fuel cells in use in Gemini, and indications are that we shall continue using a mixture of energy storage and conversion devices, especially in manned spacecraft.

Choice of Devices

Every energy storage device and every conversion device has its own advantages and weaknesses that must be balanced against each other, and viewed in the light of the mission for which they are being considered. We must know mission duration, to start with. For a mission of, say, 3 to 4 hours and for relatively constant loads, chemically fueled engines may provide the lightest package. But, although engines have a low specific weight, their reactant consumption is more than twice that of fuel cells. On the other hand, I doubt that we would consider fuel cells for much less than 10-hour space

missions, in view of their weight and complexity. You may translate that to a simple, everyday situation and ask yourself whether you would want a direct or indirect hydrogen-air fuel cell in your car, when your maximum uninterrupted driving time ("mission") is 5 hours before refueling.

We must know, secondly, something about the load profile of the mission. Many energy converters work best and most efficiently under relatively constant loads. If you design a single converter for the average mission load, you may find it performing very poorly most of the time, when the profile consists of long periods at low and long periods at high load. At low load, the converter may consume excessive amounts of parasitic power; at high loads it may become inefficient.

Another important factor to know is whether any byproducts from energy conversion might be utilised, such as the heat of inefficiency or water produced by a fuel cell. It might pay, e.g., to size a primary fuel-cell system so as to produce just as much water as needed, and to use another energy source and converter for the balance of the requirements.

Even after a converter has been decided upon, one must carefully consider how best to use it. For reliability, an extra module may be designed into the system; is it better to keep it off the line in stand-by condition, or to operate it with the other modules, thereby lowering the load and stress on all modules evenly? If it is kept in stand-by, will it share loads well with the surviving units when put into operation? At this point it might be well to warn against implicit faith in reliability numbers. One can find reliability estimates for systems that have never been built, let alone operated. Be sure to know the basis for such estimates before taking them seriously.

From what has been said thus far, we must conclude that energy storers and converters are rarely competitive but often complementary. The space-power engineer who knows the characteristics of both missions and devices will find an optimum choice relatively easy. Of course, we are working on improvements of all devices that appear useful for space, and from time to time a new one enters the picture. This means that cost and specific mass should come down, while reliability, efficiency, and longevity increase. There will also be an occasional shift in optimum choice of devices, particularly if new devices are of sufficient merit to justify their qualification for space use.

In the Beginning

The choice of space power systems was relatively limited when the need first arose. That was in 1870, during the Franco-German War, when German troops were besieging Paris. The government at Paris found that its only reliable means of communicating with the outside world was by manned balloons. Lift power was derived from coal-gas filled cotton bags of 2000-m³ volume. After Paris had learned that the Germans had captured several crews, balloons, mail, and homing pigeons, they decided to institute night flights in mid-November 1870 (Fig.1). A light thus became desirable for reading a barometer, watching paper streamers and cigarette paper, keeping log books, etc. Since the appendix of the balloon was open, an open flame or arc would have invited almost certain fire and disaster.

There were only two coal-mine safety lamps available, the Davy petroleum lamp and the electric lamp first built by Ruhmkorff in 1862 for Dumas and Benoit (Fig.2). The third night balloon, the *Ville D'Orléans* shown in Figure 1, is the first one known to have carried a light. Its electric lamp, given to pilot Rolier by a personal friend, was built like that shown in Figure 2. It consisted of a Poggendorff battery, a Ruhmkorff spark coil, and a Geissler tube. Thus, it had all the attributes of a modern space-power system, energy source and converter, power conditioning, and load.

The first airborne power system landed in Norway on the afternoon of November 25, 1870. Together with the balloon and its appurtenances, it was given to Oslo University. The Norwegians never did figure out the purpose of the "electrical apparatus". Still, it

became useful for a quite unforeseen purpose, because its zinc plates and copper connectors were melted into a bronze. In January 1871, Jeweler Tostrup and his assistants struck tiny commemorative balloon coins from this alloy, at a bazaar for the benefit of French war victims.

Another one of these fluorescent light systems was carried later that same month on the *Jules Favre No. 2*. The passenger dropped it, thus proving (a) that the equipment was not very sturdy, because it broke; and (b) that it was fail-safe, because the balloonists continued their trip safely and in the dark.

Commercially, the portable fluorescent lamp was a failure for more than 100 years. It was not until 1966 that a dry-cell, solid-state inverter, fluorescent-bulb portable system (this time in an impact-resistant housing) re-appeared on the consumer market. We are hopeful that commercial uses of modern aerospace devices can be realized in a shorter time span.

ELECTROCHEMICAL BACKGROUND

In the course of an afternoon's talk about electrochemical energy conversion, it is impossible to cover all the electrochemistry embodied in this technology. I shall, therefore, recall to your minds only some basic principles and nomenclature, with which you are undoubtedly familiar from your college days; mention a few of the more useful methods for measuring the behavior of electrochemical systems; and provide some references for further study, if you feel so inclined. These references will be mostly to the American literature, though the basics are obviously covered in the relevant texts and journals of Europe as well. However, you may find the American nomenclature and sign convention a bit different from the European one at times.

The Nature of Redox Reactions

Certain kinds of material can be oxidized by other kinds of material. Chemically speaking, the former are reducing agents, the latter oxidizing agents or oxidants. Examples of slow oxidation are corrosion of iron by oxygen from air to form rust, or formation of patina on the surface of copper by sulfur compounds in the air, which change the copper color to a satiny, deep green. More rapid oxidation is the burning of a fuel; and still more rapid is the detonation of a fuel-air mixture in a combustion engine. In all cases, the oxidant contacts the reducing agent directly, and the energy liberated by the reaction is in the form of heat.

Electrochemical reactions are of this type, except that the "fuel" or reducing agent acts indirectly upon the oxidant. Such indirect action is made possible by separating the two reagents, extracting electrons from the reducing agent, and adding these electrons to the oxidant in a separate step. To avoid a build-up of charges and, hence, a quick end to the reaction, these charges must be neutralized, and that is done by ion transport through an electrolyte:

At the negative pole, electrons are generated by oxidation. They are transported through the wire to the positive pole and consumed by reduction. The sketch shows negative ions being transported in a liquid electrolyte from the positive to the negative, thus closing the electric circuit.

The reacting species may be gases, liquids, or solids, and so may the products and the electrolyte. Hence the sketch is not to be taken literally. The ions, for that matter, may be positive ions, in which case they simply must move in the opposite direction. All that is required is that the two poles or electrodes be electronically conductive, that the intervening electrolyte be only ionically conductive, and the pole/electrolyte/pole sandwich retain its layer structure.

When Faraday wrote to Whewell that he was considering calling the two poles alphode and betaode, voltaode and galvanode, zincode and platinode, dexiode and skiaode, oriode and occiode, eastode and westode, eisode and exode, orthode and anthode, Whewell replied he was "disposed to recommend... anode and cathode"; and that is what they are today¹.

In electrochemical energy converters, the reducing agent is at the anode or negative pole; the oxidant at the cathode or positive pole. (Warning: This nomenclature is not universal).

Conventional galvanic cells mostly have metal anodes and metal-oxide cathodes. When the cell is being discharged, the metal is converted to an oxide, and the metal oxide is converted to an oxide of lower valence or to a metal. In the usual space cells, the electrolyte is a water solution of caustic (KOH), so that hydroxyl ions (OH)⁻ travel from cathode to anode through the electrolyte. All these processes are reversed if and when the cells are charged again. Ideally, both electrodes are good electronic conductors at all states of charge and discharge; and all reactants and products are insoluble in the electrolyte. The electrolyte, in turn, does not conduct electronically (as that would produce a short circuit) but only ionically. Fortunately for those of us engaged in battery research, such ideal conditions do not occur.

Unconventional galvanic cells, nowadays called fuel cells, have liquid or gaseous reactants at one or both electrodes. To obtain electronic conductivity, the electrodes are made of "inert" metal or carbon, to which the reactants are conducted by some means. These reactants are added whenever electricity is to be produced; products are removed from the cell whenever necessary by some convenient means.

An obvious difference, then, between the two kinds of galvanic cell is that, in the conventional one, the reactants are stored in the electrodes - they are part of the electrodes, and they change chemically in proportion to the amount of electricity withdrawn or added. In unconventional or fuel cells, the reactants are stored externally, are channeled to invariant electrodes as needed, and the products can be taken out of the cell at any time. Given an infinite amount of reactants, a fuel cell should run forever. Such long-term experiments have not yet been possible.

Thermodynamics

Although corrosion and combustion are disordered redox reaction while electrochemical processes are ordered redox reactions, their thermodynamic characteristics must be the same. Regardless of the path of the reactions, given the heat contents of the reactants and of the products under known conditions, we can calculate the change in the enthalpy, ΔH ; the (Gibbs) free energy, ΔG ; and the entropy, ΔS . Thus, as usual,

$$\Delta G = \Delta H - T\Delta S,$$

where T is the (absolute) temperature. Since ΔS may be either negative, zero, or positive, ΔG may be greater than, equal to, or less than ΔH . In most practical instances, ΔG will be less than ΔH ; and only ΔG can be converted to electrical energy,

$$\Delta G = -nE_0F,$$

where n is the number of electrons transferred, E_0 is the ideal voltage, and F is the Faraday constant. We can thus calculate the ideal efficiency of an electrochemical reaction, as well as its ideal voltage, from purely thermodynamic consideration.

Consider the simple fuel-cell reaction

at room temperature and constant pressure. Since the efficiency of heat engines is based on the higher heat of formation of water, 68.4 kcal/mol, we use this value as a basis for comparison. The value of ΔG is 56.7 kcal/mol, so that the *ideal* efficiency is

$$\eta_i = \Delta G / \Delta H = (56.7 / 68.4) 100\% = 83\%$$

at room temperature. This value changes very little up to about 300°C. Statements about nearly 100% efficient $\text{H}_2 - \text{O}_2$ fuel cells are obviously not based on enthalpy calculations.

The ideal voltage of such a cell, again at room temperature, is

$$E_0 = \Delta G / nF = 56.7 \frac{\text{kcal}}{\text{mol}} \times 1.16 \frac{\text{watt-hr}}{\text{kcal}} \times 2 \times 26.8 \frac{\text{amp-hr}}{\text{mol}} = 1.23 \text{ volt}.$$

A large number of such thermodynamic data will be found in the following tables². Comparison of Table 2 with values for similar systems, given by different authors, will show noticeable differences, even for the theoretical energy content. The reason for this is not that their thermodynamics differ, but that the exact reaction mechanisms have not yet been determined. Considering the respectable age that some of these galvanic cells have already attained in practical use, this disagreement is indicative of the slow pace at which chemical research is proceeding in the battery field.

The discrepancy between theoretical and actual energy densities in Table 2 has at least two causes. (1) Since the theoretical values are based only on active chemicals, they can never be realized. A cell contains not only the active couple but also electrolyte; separator material that contains electrolyte and keeps the electrodes or plates from touching each other and thus from shorting the cell; grids or current collectors that hold the active chemicals, assure good electronic conduction, and end in terminals to which electric connections are made; and a case, in which the complete cell is contained.

(2) It is obvious that some actual values approach the theoretical ones much more closely than do others, and that some systems do not show any actual figures at all. This demonstrates that thermodynamics cannot be used to predict the practicality of chemical and electrochemical reactions. For that we need kinetics. In general, the less energetic systems are more easily realized.

Actual electrochemical systems do not achieve ideal efficiencies. In many cases, the current efficiency is virtually 100%. Since electric power is the product of amperage and voltage, the (kinetic) inefficiency becomes apparent from voltage losses. If v is measured voltage, then voltage efficiency is $100 v / E_0$. The *thermal* efficiency of an electrochemical cell is thus

$$\eta_t = 100 (\Delta G / \Delta H) (v / E_0)\%.$$

To give you an idea of fuel-cell performance, Table 3 shows some approximate thermal efficiencies of hydrogen-oxygen cells in use today.

Kinetics

The rates and mechanisms of reactions determine how fast we can withdraw electricity from electrochemical cells and how much of the energy of the reactants is available in useful form at any moment (electric power) and from the sum total of reactants (electric

power $\times$ time = electric energy). Some steps in the reaction scheme will be fast and require little or no energy, others will be slow and consume energy in measureable amounts. Undesired side reactions can and do occur: Species that are soluble diffuse to the opposite electrode, there to react chemically instead of electrochemically. "Inert" separator material slowly reacts with electrolyte. Reactants are oxidized only partly instead of completely, and vice versa. Such losses give rise to current or Faradaic inefficiencies.

Even well-behaved systems have certain unavoidable inefficiencies. They manifest themselves as voltage losses and are called polarization, overvoltage, or overpotential. The over-all loss can be divided into any number of components; the usual division is into 3 parts, ohmic, concentration, and chemical (also called activation) overpotential.

Ohmic overpotential resides partly in the electronic conductors, the current collectors that are the "backbone" of the electrodes; and partly in the electrolytic or ionic conductor, the electrolyte. It reflects the energy needed to move conducting species.

Concentration overpotential becomes worse at higher loads, when the conducting ions cannot move fast enough. Excesses of one kind and deficiencies of another kind of ion then accumulate at each electrode. Hence, the higher the rate of discharge, the lower becomes the voltage. At the limiting current density, the voltage collapses. Increases in concentrations of reactants, particularly gaseous reactants in fuel cells, reduce concentration polarization³.

The work expended on loosening chemical bonds in reactants, e.g., the O=O bond in molecular oxygen, represents a loss of energy that manifests itself as chemical overpotential. The activation energy varies with a molecule's surroundings. A hot surface or a catalyst effectively reduces this source of voltage drop.

In well-behaved systems, the efficiency is highest upon slow discharge, because losses due to overpotential are thus minimized. But when current or Faradaic inefficiency occurs, a faster discharge may actually result in the production of more electricity. This seemingly paradoxical behavior is explained by the fact that competing reactions occur during the discharge of such a cell. The losses due to faster generation of electricity are then more than compensated by the suppression of parasitic side reactions.

Selection of Electrochemical Systems

The thermodynamic data given are obviously far from exhaustive, particularly as concerns the availability of oxidants. To devise a workable cell, however, one also requires a knowledge of the kinetics and mechanisms of the reactions that become possible from the juxtaposition of anode/electrolyte/cathode as well as the structural materials and catalysts, if any.

Under Navy contract N0w-64-0653f, Dr R.J.Jasinski has compiled the compact Table 4, that summarizes all factors controlling battery performance⁴. He defined battery performance as

$$M_w = Q_0 K_1 K_2,$$

where M_w is the observed energy density; Q_0 the thermodynamic energy density of the reactants; K_1 is a dimensionless chemical efficiency factor; and K_2 dimensionless weight efficiency factor defined as $w_0 / \sum W$, where w_0 is weight of the redox couple and $\sum W$ is the weight of the total battery. This table represents a handy checklist for devising electrochemical power systems.

The chemical efficiency is first and foremost a function of the interaction of the active species (on the electrode) with the electrolyte. Numerous techniques have been developed for studying the behavior of electrode/electrolyte half-cells experimentally. Many of these techniques are of relatively recent origin. They are reviewed in several papers of a symposium on electrochemical processes⁵. Listings are found in the paper by Yeager and Ludwig (pp.10-18) and by Reilley (pp.43-49). In addition, new methods were described by several authors at that meeting. These are matters for the specialist, however, and we cannot enter into details here. Suffice it to quote the introduction to Yeager and Ludwig's survey:

"The electrochemist is faced with two types of problems in undertaking an experimental study of the kinetics of a particular electrode system. (1) Identification of all of the factors or parameters which must be known and controlled in order to carry out interpretable experiments. (2) Choice of the most promising instrumental techniques for the study. In conjunction with the first, it can not be emphasized too strongly that the real pitfall in electrochemistry is not the lack of sophisticated instrumental techniques and methods but rather that these techniques do not give adequate knowledge or control over many of the physical and chemical variables which have a major effect on electrode processes. The choice of techniques to be used to study the kinetics of a particular electrode process requires a projection as to the probable mechanism and the magnitude of the corresponding rate constants, the extent of mass transport control and ohmic losses, and then a best matching up of the requirements imposed by these factors to the available techniques. Only then can the experiment be properly designed.

"Both steady-state and transient techniques have found extensive use in kinetic studies of electrode processes. The most common means for perturbing electrode systems from equilibrium involve the application of some well-defined current or voltage function but such techniques are difficult to apply to electrode systems of high resistivity in the solution or electrode phase (e.g., oxides, organic semi-conductors). In such instances changes in temperature, pressure, concentration, or surface area may be used to perturb the electrode system with the relaxation followed by the measurement of the electrode potential - thus avoiding the passage of any appreciable current through the system."

Modern methods are often sweep methods. Thus, either voltage (or current) may be varied continuously or discontinuously as a function of time, while current (or voltage) is kept constant. The data, if correctly interpreted, give information on compatibility of materials and extent and reversibility of electrochemical reactions.

An older empirical method is also still useful⁶. A plot of overpotential as a function of the logarithm of current density (current per unit of geometric surface area) yields a straight line when the rate-determining step is a slow electron transfer and the overpotential is much greater than $2.3 RT/nF$; here R is the gas constant in joules/^oC-mole. The intercept of this straight line with the ordinate (at zero overpotential) is the so-called exchange current. The higher its value, the more reversible is the half-cell. The slope of the straight line is determined by the reaction mechanism, but it can also be affected by the porosity⁷.

Electrochemical techniques must be supplemented by physical and chemical analyses for a more complete understanding of half-cell and full-cell processes. Particular attention must be paid to the purity of components of high-energy cells, because many losses are due to trace amounts of extraneous materials. It also appears that functioning of some of these novel combinations may be possible only with the help of minute amounts of such impurities as water.

PRIMARY BATTERIES FOR SPACE

When fuel cells were re-discovered in the late 1950's, their advantages were claimed to be high efficiency (because primary and non-thermally regenerative fuel cells are not limited by Carnot-cycle consideration), silent operation, no moving parts, no power

consumption while idling, higher efficiency at part load (in contrast to engines), no noxious exhaust, modular construction, high peak-load capacity, etc. To the extent that these claims are true for fuel cells, they are also true for batteries. In fact, as already mentioned, conventional galvanic cells and batteries have no exhaust products at all.

Electrochemical cells connected electrically in series, parallel, or combinations thereof, constitute batteries. Each cell - in some instances, a battery - has its own case, one or more anodes and one or more cathodes that are electronically insulated from each other by intervening layers of separators, electrolyte contained in the separator for ionic conduction, and a closure or seal to retain the contents. This is a general description of simple, conventional cells. Some may incorporate auxiliary electrodes, electronic controls, gas regulating devices, and hermetic seals to avoid leakage to the vacuum of space. Primary batteries are those that are used once, secondary or rechargeable batteries can be re-energized, usually by supplying electricity from an external source. The term "primary" must not be taken too literally, particularly for space use. Since preliminary battery checks are necessary to insure proper working of the power supply, we like to use and recharge even our "primary" batteries a few times before the space-craft is launched.

Zinc-Mercuric Oxide

The earliest US space cells were commercial mercury cells, developed by Rubin early in WW II. Yeager, Yeager, and Daniel⁸ give the electrochemical reaction for the cathode as

and the anode reaction as

open-circuit 1.35 volt, typical operation at 1.30 volt, 40 amp-hr/lb, 53 watt-hr/lb. Although these cells may still be used in specific instances, we are not doing research or development on this system, because zinc-silver oxide cells have much higher energy densities. (The zinc electrode is discussed there).

Figure 3 is illustrative not only for this but for most other cells as well, though the numerical values will differ from case to case⁸. The resistance of the external circuit determines the rate as well as the voltage at which electricity is obtained. The lower this resistance, the shorter is the discharge period and the lower is the voltage. Thus the efficiency and the energy density are decreased as the external resistance is decreased.

At low power drains (high external resistance, low current densities), the *chemical* or activation *overpotential* accounts for most of the voltage drop and hence energy loss. As current density and load increase, the *internal cell resistance* contributes more heavily to the voltage drop. At still higher loads, *concentration overpotential* also becomes a significant factor in addition to the first two types of losses. Internal resistance and concentration overpotential can be minimized by good engineering. Chemical overpotential can sometimes be influenced by changing the reaction mechanism, e.g., by using additives or catalysts. Thus, both structural and chemical factors determine the quality of a cell, and different approaches and compromises are needed as requirements change.

Zinc-Silver Oxide

The first practical zinc-silver oxide cell was described by André in 1941, according to Yeager et al.⁸. This cell does have limited rechargeability but is described here, because in space it is normally used as a primary energy source. (It may be kept fully charged or even be partially recharged from solar cells.)

There are two silver oxides, argentic (Ag^{++}) and argentous (Ag^+) ions combining with oxygen to form AgO and Ag_2O , respectively. The former, being more highly oxidized, is richer in energy content. The exact reaction mechanism of this cell is not yet known, even though these and similar cells have been studied since before 1900. No doubt, however, exists that the oxide electrode is reduced in two steps when AgO is present.

The first step has a higher thermodynamic as well as actual discharge energy density and voltage than the second step. To avoid the complexity of voltage regulation at two levels, some battery designers have proposed using only the upper plateau, others only the lower one. Figure 4 shows that, for some cells at least, the argentous plateau predominates, making the latter approach preferable. Open circuit voltage is about 1.8 volt, operating voltage (lower level) 1.4-1.5 volt, energy densities range from 39 watt-hr/lb for fast (1-2 hr) discharge to almost 100 watt-hr/lb for slow (50 hr) discharge.

This type of cell deteriorates upon standing at open circuit and is therefore activated only when ready for use. Suitably constructed cells can be kept on wet stand for a week without serious loss of energy. As a matter of fact, even the dry, electrolyte-free cell does not retain argentic silver above about 70°C , whereas the argentous silver is stable to 150°C . This is another reason for working only at the argentous level.

Another difficulty with the cathode is the solubility of argentous oxide in the aqueous KOH electrolyte. To prevent silver from migrating to the anode, the separator must contain a material that stops such diffusion. André found that cellophane will do so, and cellophane sausage casing has been used in these cells ever since. It is good enough for limited rechargeability, but improved separators have been developed for better cycle life. Such modified cellulose or other materials are more resistant to oxidation by the ionic silver species, which eventually destroys the cellophane sheets.

The trouble with zinc anodes is that their oxidation product, the Zn^{++} ion, is quite soluble in the electrolyte. Here again, the product that is formed is not known, it may be K_2ZnO_2 or KHZnO_2 . Eventually, $\text{Zn}(\text{OH})_2$ precipitates from the solution; the conditions under which this happens and the form of the precipitate are the subject of a number of research reports presented at the 1967 Fall meeting of the Electrochemical Society.

During recharge, zinc is not smoothly replated on the electrode but forms irregular deposits that range from mossy to needle-like structures. Again, the condition of recharge strongly affects the shape of the zinc deposit and the life of the separator. Low overpotentials give smoother deposits and help to avoid zinc growth into and through the separator. Such growth leads to eventual short circuits. An asymmetric alternating current allows a faster recharge (higher average voltage) than pure d.c.

We shall return to the zinc-silver oxide topic when considering sterilizable cells. Suffice it to say that it appears likely that the major difficulties with this system will be brought under control in the next 2 to 4 years, thus moving it out of the primary into the true secondary category. However, this change will entail a penalty in power and energy densities.

Zinc-Oxygen

The cathodic materials discussed thus far are metal oxides. It has long been recognized that oxygen itself would be a satisfactory reactant, and that it need not be built into a battery but can be derived from the air. Such air "depolarized" zinc batteries are standard equipment for railway signals. ("Depolarizer" is an antique term for "oxidant".) Under normal conditions they can operate for a year; but their power output, i.e., rate of discharge, has been very low, due to the slow rate of reaction of oxygen. Now that relatively

high-rate oxygen electrodes have become available through research on fuel cells (*q.v.*) high-rate zinc-oxygen cells are a practical possibility. This, by the way, is an example of the complementary (rather than competitive) nature of even electrochemical power producers.

In space, oxygen must be carried along, of course. Zinc-oxygen cells are now being developed for NASA. Typical operating voltage will be 1.2 volt per cell, and energy density is expected to range from 120 watt-hr/lb for an 8-hour discharge period to perhaps 150 watt-hr/lb for a week-long discharge, including the total weight of the self-contained battery. Limited rechargeability (50 cycles at 20% depth of discharge) has been attained in the laboratory.

Conceivably, the zinc-oxygen and other metal-gas cells - battery/fuel cell hybrids - will, in time, supersede conventional cells with all-solid reactants.

High Energy-Density Cells

Organic Electrolytes. A great amount of manpower has been expended over the past seven or so years in an attempt to build galvanic cells with energy densities of the order of 200 watt-hr/lb. Braeuer and Harvey stated that more than \$3 million of US Government funds were used from 1962 to 1966 on cells with organic electrolytes alone⁹. This is the sector of the high-energy area that has received by far the greatest share of the total effort as well as some rather favorable publicity. Although nothing practical has emerged thus far, this subject deserves some attention.

The reasoning behind this thrust was approximately as follows: Thermodynamically, alkali metals and some alkaline earth elements have much greater energy densities than conventional anodes like lead, cadmium, zinc, etc. But they react spontaneously with water. Hence conventional aqueous electrolyte cannot be used. To operate such anodes near room temperature, let us try organic solvents instead of water; choose suitable solutes to optimize the conductivity of the electrolyte; and combine these with cathodic reagents of high energy density. Table 5 shows typical electrode couples and Table 6 organic solvents, as compiled by Braeuer and Harvey.

The problems are to find components, including separators and structural materials, solute-solvent combinations of high ionic conductivity, reasonably useful temperature ranges, and acceptable decomposition potentials (stability at the potentials of operation); high voltage and current efficiencies; and perhaps electrochemical reversibility (rechargeability).

Experience thus far has been that shelf life has been too short and rate of discharge too slow. Compatibility has been poor, perhaps because of trace impurities; but there are indications that some of these may actually be needed to obtain even the low rates of discharge that are usual in organic systems. Thus, despite the fact that better than 200 watt-hr/lb has been achieved in laboratory cells, we have no way of storing them or discharging them at reasonable rates.

Braeuer and Harvey make a number of valuable, concrete suggestions for future work, among them being one point in particular that may be easily overlooked: If such a system becomes operable, considerable heat will be evolved in a small volume and mass (at high rates of discharge), which will be difficult to remove in view of the low thermal conductivity of the organic electrolyte. One systems engineer has estimated that the additional equipment, needed for cooling, would reduce the over-all energy density to that of the zinc-oxygen system. But perhaps he was over-pessimistic.

Inorganic, High-Temperature Electrolytes. A completely different approach was taken by Swinkels, who chose to work on the system Li/LiCl/Cl_2 (graphite)¹⁰. Since lithium chloride melts at 608°C, at which temperature the conductivity may be still too low to be practical, Swinkels has operated the system at 650°C. An interesting feature is that

the reaction product itself forms the electrolyte. The open-circuit voltage, as measured between 608° and 850°C, was essentially the theoretical value. Pulses up to 40 amp/cm² were obtained at the anode, but the cathode sustained 1 amp/cm² at best¹¹. Further development is expected to improve cathode performance.

Another novel combination is Kummer and Weber's sodium-sulfur cell¹². At the operating temperature of 300°C, both reactants are molten. While sodium is being added to sulfur, the product remains liquid at 300°C until the atom ratio Na:S exceeds about 2:3. Since reactants and products are liquid, a suitable solid barrier must be interposed between anode and cathode (the latter being sulfur impregnated in porous carbon). Kummer and Weber found that derivatives of sodium aluminate, Na₂O.11Al₂O₃, are highly conductive to sodium ions at the operating temperature. Current densities up to 1.5 A/cm² are said to have been measured. The theoretical energy density, assuming product formation of up to Na₂S₃, is 346 watt-hr/lb. For 5-hour discharge cycles, energy densities of 150 watt-hr/lb and, for ¼-hour discharge, power densities of 100 watts/lb are forecast, assuming a 2-kW module with 4-kW peak capacity. The discovery of these modified sodium aluminates is particularly significant, because the best previously known solid electrolyte, yttria-stabilized zirconia, must be operated at 900°C or above.

At present, neither type of cell has yet been developed into a practical device. They indicate, however, that approaches other than by means of organic electrolyte solvents must be seriously considered for obtaining high-performance galvanic cells.

Special Purpose Devices

Sterilizable Cells. "Upon the recommendation of the scientific community, the National Aeronautics and Space Administration has established as a major goal the search for extraterrestrial life. So that the data obtained in this search will not be compromised, NASA has embarked on a program designed to prevent external contamination of the planets."¹³ Hence batteries powering planetary landing craft must be sterilizable. This means they must sustain days of exposure to 125°C or more without damage.

For several years, the Jet Propulsion Laboratory of California Institute of Technology has had contracts underway to devise novel battery separators that will not disintegrate during sterilization. A promising one is a low-density polyethylene, irradiated from an electron linear accelerator before being grafted with acrylic acid. A variant thereof is polyethylene cross-linked with divinyl benzene by gamma radiation and then grafted with acrylic acid. Both unsterilized and sterilized samples were built into zinc-silver oxide cells. Both cells behaved comparably, indicating that exposure of separators of this kind to 40% KOH at 145°C for three 36-hour heat cycles did not damage.

In the search for a zinc-silver oxide cell that might be operated at much higher than usual temperatures, up to 100°C, Astropower Laboratory developed an inorganic separator. Tests under NASA contracts have indicated that this separator can be used in sterilizable batteries as well. Still other separators, such as the electrodeposited calcium hydroxide studied by General Electric for NASA, may also be satisfactory for this purpose.

A few years ago, NASA Lewis Research Center became interested in batteries that would operate for periods of several days at temperatures of about 800°F.¹⁴ One possible use would be for probes sent to the planet Venus where the surface temperatures are expected to be in that vicinity. In this application, internal heating devices to activate the battery are not too great a concern. A research program was started at Lewis to investigate possible electrochemical systems which might be useful for this application. The magnesium-copper oxide system was finally selected for intensive investigation. Figure 5 illustrates one of several types of cells used in these studies. The cylindrical case has the same dimensions as a flashlight D cell. The copper can itself is the current collector for the cathode, and a stainless-steel shaft threaded into the anode conducts the current up through the insulated feedthrough. A woven glass separator material is employed.

The eutectic mixture of lithium chloride potassium chloride was picked for the electrolyte. It has a convenient melting point of 685°F, a high decomposition potential of about 3.5 volts, and an excellent ionic conductivity. Once the electrolyte has been picked, the electrode materials were selected on the basis of thermodynamic compatibility with it. Magnesium and cupric oxide both have high half-cell potentials, low equivalent weights, and were thought to have tolerable solubilities in the molten salt electrolyte. These hermetically sealed cells are placed in a furnace and discharged at a constant load. A typical discharge curve of this type of cell is shown in Figure 5. Here, the current voltage of the cell under load, and the periodically observed open circuit voltage are plotted as functions of time. Two aspects of this plot are to be noted - one being the rather flat current against time curve at these light discharge rates, and the other the large step in the open circuit voltage curve. This large step is due to a change in the electrochemical reaction during the latter part of the discharge. - This is one example of a high-temperature cell, all of which should be easily sterilizable.

High-Impact Cells. In anticipation of the possibility that sterilized batteries might strike a planet's surface with a force several thousand times that of the earth's gravity, we are also developing re-inforced battery plates (Fig.6) to take the landing shock. Impact tests have shown that this design is not satisfactory, even though cells continued to function during and after shock. But the extensive damage to the frame and lead wires makes redesign mandatory.

Multiple Reserve Cells. At the very beginning of galvanic cell technology - at least as early as 1804 - it was recognized that chemical side reactions might be tolerable, if a way could be found to minimize them while cells were not in use. The simple but effective solution to the problem was to incorporate a reservoir in the cell or battery, so that tilting would cause the liquid electrolyte to run into this storage compartment. The electrolyte was thus separated from the electrolyte and kept in reserve; it could be added to and withdrawn from the reaction chamber any number of times. The same effect was obtained by connecting all the zinc anodes to a lever and lifting them out of the solution when not in use.

Such multiple-reserve cells have long been out of style, because the shelf life of conventional cells has been greatly improved. Those systems that cannot tolerate prolonged wet stand are activated just before being used; examples are the "dry-charged" car battery and water-activated weather balloon batteries. The former are regularly recharged by the car's generator, once activated; the latter will run down irreversibly, once activated, if they are not used immediately. Both are examples of single-reserve cells.

Problems of incompatibility in organic electrolyte cells and the need for repeated "hibernation" of batteries on deep-space probes have revived interest in the multiple-reserve concept.

The most recent idea for multiple-reserve capability was proposed by Bernard Gruber of Monsanto: packaging the electrolyte separately from the electrodes and energizing only a portion of the cell at a time. One version of this "dry tape" would encapsulate electrolyte within the separator material, itself sandwiched between a dry anode and a dry cathode. The strip would be pulled between two fixed current collectors, breaking the encapsulation and releasing electrolyte and electricity. This idea proved not to be feasible for the present. In a modification, the electrolyte is contained in separate sausage links and fed at the same rate as the dry sandwich (Fig.7). Many modifications are possible, of course, though none has yet become practical.

In the course of screening potential cathodic reactants for this dry tape, 2,4,6-trichlorotriazinetrione has been identified as a promising candidate for aqueous or non-aqueous systems. It is a mass-produced commercial bleach and raises the interesting question as to whether some product of this type might be substituted for the now 100-year old manganese dioxide in the ordinary Leclanché dry cell. - Still, even the dry tape appears not to be amenable to construction of batteries with reasonable energy densities. After more than 150 years, a good idea for multi-reserve packaging is still lacking.

PRIMARY FUEL CELLS FOR SPACE¹⁵

Among the known fuel-cell reactants, hydrogen and oxygen thus far appear to be best suited for space use. Energy densities of the reactants in cryogenic forms, including also the requisite tankage, are close to the highest that can be attained. The reactants are relatively easily stored and handled, presenting no difficult compatibility problems. Although efficiency losses at the cathode leave room for improvement of low-temperature cathodic catalysts, reactivities of both reactants are high enough to permit equipment to operate at "low" temperatures (about 100°C) and reasonable thermal efficiencies. The chemical byproduct, water, is useful for various human purposes as well as spacecraft applications e.g., evaporative cooling and attitude control. Reactants and product thus offer a maximum of utility and a minimum of problems. No wonder, then, that H₂-O₂ cells were the first to be studied by Grove in 1838, the first to be built in kilowatt size by Bacon in the first half of this century, and the first to be used in NASA's Gemini program.

In fact, regardless of temperature of operation, choice of liquid electrolyte, or type of electrode structure, all gas-fed fuel cells are still built according to Grove's prescription for maximizing the 3-phase boundary, even though several electrochemists more recently established the fact that the locus of reaction is just below that line. I shall return to this point again later on. Suffice it to say that all hydrogen-oxygen systems contain gas plenums, porous electrodes, and electrolyte plenums in each cell.

Let us recall (Fig.8) that the main difference between a fuel cell and a conventional galvanic cell is that the former does not contain the reacting materials. In the galvanic cell, the anode is oxidized and the cathode is reduced during use. In the usual fuel cell, the electrodes remain unchanged while reactants are introduced, reactions take place, and products are removed. In some fuel cells, the whole anode is consumed and must be replenished during use. It is this feature of not being self-contained that gives the fuel cell its advantages over conventional cells for certain tasks; it also introduces a host of systems problems unknown to the designer of the usual electrochemical cell or battery.

To expand briefly on the remark that there are many kinds of fuel cells: The components and structure of a fuel cell vary with the physical state of the reactants; gases, liquids, and solids have been used. They vary with the chemical composition of the reactants, too; highly reactive hydrazine and almost inert carbon have drastically different requirements, just as fluorine and air must be handled differently. But even the same reactant pair, hydrogen and oxygen, is being utilized in a number of systems quite unlike each other, some of which will be discussed below. Regardless of the system, reactants must be admitted and heat and products removed approximately in proportion to the electric power demands.

A complete fuel-cell system (Fig.9) must provide for storage of at least one reactant, the fuel, or both reactants if air is not used as the oxidant. (Systems have also been considered in which one reactant is replaced by vacuum, but they do not appear to be useful). The system must have means for adjusting the flow of reactants according to need, and products and heat must be removed similarly. In some cases, the product has to be stored too. Supply the removal must be uniform to and from all cells in the fuel-cell stack. The cells must have good outside electrical connections and must behave uniformly. The system must be storable without major deterioration; startable within an acceptable time space and with a minimum of auxiliary power; quickly responsive to changes in power demand; capable of brief overloads without injury; operable with minimum consumption of parasitic power; be easily stopped, put in stand-by condition, and restarted; be fail-safe and relatively immune to abuse; be reliable for the life of its mission; and be economical.

"Economical" is a word that makes sense only in context. In a city, a lead acid battery is not an economical replacement for house power from the local electric company. But if, for example, there were a gassy coal mine near town, it might be more economical

to run battery-powered trucks in it than to install special low-voltage trolleys or rails. Similarly, a fuel-cell system highly loaded with platinum catalyst is not economical for most earth applications. But the cost of a manned space mission is \$3000 to \$5000 per pound, so that an ounce of properly used platinum can more than pay for itself. And that brings us to space fuel-cell systems.

They were chosen for the Gemini and Apollo missions because fuel-cell systems have a fraction of the weight that pure battery systems would have for the same job. Their advantage over combination solar cell-battery systems is that they require no protrusions from the spacecraft; they need not be oriented toward the sun and present no problem during docking or other maneuvers.

Gemini System

The Gemini on-board power system is based on a fuel cell that contains an ion-exchange membrane (Fig.10). This particular membrane has acidic functional groups, so that protons travel from anode to cathode; water formed at the cathode is removed by wicks. Because the membrane is a solid or pseudo-solid, the porosity of the electrode need not be closely controlled. Also, the fuel-cell sandwich can be made quite thin and light-weight. More than 30 cells are connected in series to form a stack with an output of around 28 volts, and three stacks in parallel form a section in a canister (Fig.11). Obviously, lower power requirements call for fewer stacks, and the NASA Biosatellite will have only 1 stack per can. For more power, more sections can be parallel. Hydrogen and oxygen are stored as super-critical fluids, thus minimizing flow problems in zero gravity. They are preheated before entering the fuel-cell sections.

Since neither reactant can be 100% pure, impurities accumulate in the stacks during use. To remove them, the gases are vented or purged as needed. Temperature is controlled by a liquid coolant that flows through tubes in each cell. If the metal coolant tubes were directly connected to each other throughout a stack, they would short-circuit the system, hence they are connected by plastic manifolds.

An electronic monitoring and control unit activates valves to regulate gas and coolant supplied. Since the gases are not recirculated and water is removed passively (by wicking), parasitic power demand is low. Another advantage of this kind of system is that it can be started and operated at room temperature.

Although the system (Fig.12) is operated at low temperatures, this is not exactly a matter of choice. It is dictated by the fact that the organic membrane is unstable at higher temperatures. In fact, it degrades under almost all conditions, though the rate of degradation can be kept low enough to obtain a useful life. Quite apart from this specific problem, which might be overcome by development of different membranes, an ion-exchange fuel-cell system appears to have one fundamental weakness: The electrical resistivity of known membranes is about 10 times that of free or immobilized aqueous KOH. As a result, the efficiency of reactant use is lower, so that more reactant is needed per kWh. That also means higher tankage weight and a higher radiator load, since the inefficiency appears as heat. Nevertheless, the membrane system was the lightest available power source for Gemini. All these systems have operated adequately during the Gemini fuel-cell missions.

Apollo System

The Apollo fuel-cell system is a modification of the Bacon fuel cell (Fig.13). It operates with concentrated KOH and above 400°F. Since the electrolyte is not immobile, care must be taken to avoid flooding the electrodes with free liquid. This problem is solved by using dual-porosity electrodes, the outer pores being relatively large and those in contact with the electrolyte being narrow. Reacting gases and liquid thus meet in the fine pores, as long as the gas pressure exceeds that of the liquid 1/3 to 2/3 atmosphere. The size distribution of the fine-pore layer must necessarily be very closely controlled

to prevent flooding by the electrolyte; and the two layers must adhere tightly to each other. In the original version of this cell, no catalyst was used. As engineering compromises are made and the performance is being lowered, however, catalysts are being used to minimize these losses.

The modified Bacon cell (Fig.14) has the highest efficiency of any known hydrogen-oxygen fuel cell. Even at 250 amp/ft^2 the thermal efficiency is on the order of 65%. The obvious question is - Why not use this system exclusively? There are extrinsic as well as intrinsic reasons for not putting all fuel-cell efforts into this one device.

First of all, parasitic power consumption is quite high, resulting partly from the fact that hydrogen has to be recirculated to remove product water. This exit gas mixture is cooled externally to the cell stack, to condense the water and then separate it from hydrogen in a centrifuge. Work is underway to reduce the power needs. But presently, at least, the *net* efficiency is less than for "low-temperature" systems now available.

Of more serious concern is an intrinsic problem, i.e., the "intermediate" temperature of operation. In rather loose fuel-cell terminology,

"low temperature" means up to about 150°C

"intermediate temperature" 150° up to about 400°C

"high temperature" 400° up to about 800°C

"very high temperature" 800°C and above.

The Apollo system operates around 200° to 250°C or roughly 400° to 500°F . To do so at 3 or 4 atmospheres pressure requires about 80% KOH, which is a solid at room temperature. Hence one of the problems is start-up and shut-down of modules. This must be done with great care and is time-consuming. There is also a danger of mechanical failure due to the unavoidable phase change. The other problem resulting from operation at intermediate temperature is cathode corrosion with resultant nickel ion transport to the anode and dendritic growth, ending with electrical shorts in cells. These reactions can be impeded and the life of a system prolonged.

Even without incorporation of preventive means, 13 power plants have already met and surpassed the Apollo life requirements. As for the parts of the over-all system, they are quite similar to any other fuel-cell system, the general requirements always being control of reactants, products, and heat. Only the details differ, depending on the reactants used, on the way the basic cell operates, and on the engineering ingenuity of the system designer. - The water from these plants has been free of bacterial growth and has a pH of 8 or less.

Asbestos System

The third and last system to be discussed may be thought of as a second-generation fuel-cell space-power system. The idea for the cell itself is far from novel. Mond and Langer published a paper in 1899 in which they recommended gypsum, cardboard, and asbestos as retainers for the electrolyte. Asbestos systems are being developed by several companies, asbestos being about as cheap as, and more durable than, gypsum and cardboard. The combination of asbestos and about 6N KOH, like an ion exchange membrane, obviates the need for closely controlled pore sizes to avoid flooding or drowning the pores with electrolyte. The concentration of electrolyte can be varied, of course, depending on operating conditions. A simple but ingenious system (Fig.15) was devised at Allis-Chalmers for passive or static moisture removal: A second asbestos membrane is located in the hydrogen gas space. As the vapor pressure of water increases in the electrolyte membrane, water evaporates to this separator membrane, which contains more concentrated KOH solution. It, in turn, gives off water vapor to a cavity that is kept at a partial vacuum. The water can then be either evacuated to space or condensed, as it is in the Gemini fuel cell, and collected. The latter version, the so-called closed system, is now being

developed. Provision has been made for sampling the water, either by pH or by conductivity, to determine whether to transfer it from the small collector to a reservoir or to get rid of it. Thus far, the pH has been 9-10 which may be too high for drinking. Since this is unbuffered water, a small amount of KOH has a large effect. Although this pH can undoubtedly be lowered, the water will most likely be taken through an ion-exchange bed for final cleaning. This treatment seems mandatory for all potable fuel-cell water, anyway.

The asbestos fuel-cell system (Fig.16) represents a compromise between the convenience of room-temperature and the cell efficiency of intermediate-temperature operation. Thus far, at least, its only noticeable material problem is slow deterioration of asbestos. It does not need an auxiliary heat source for starting, and its over-all efficiency equals or exceeds that of the modified Bacon cell. As might be hoped for a second-generation system, it is more convenient to operate, appears to be more flexible for a wider range of applications, and it is less prone to be permanently damaged or wrecked by a number of possible malfunctions or conceivable misuses.

Present modules consist of 33 pairs of cells, each pair having a common water-removal chamber. The electrolyte is about 6N KOH and the operating temperature is 90°-100°C. The anode is American Cyanamid's AB-40 (40 mg Pt/cm²), and the cathode is silver. Since these electrodes are not interchangeable in their functions, reversing the gases (which are dead-ended, except for purging) results in no power. That's exactly what happened in one test. After the error was discovered and corrected several hours later, the stack continued performing as usual.

Perhaps the most sensitive variable is the moisture content of the asbestos membranes, which requires good control. An example to illustrate this point is shown in Figure 17, where cell voltage is plotted as a function of KOH concentration in the water-removal membrane. This, of course, controls KOH in the fuel-cell membrane, also. The four curves represent four cells in the same stack and in the same test. They clearly indicated the need for greater uniformity of cell components, which has been much improved since that test was made.

The Mond and Langer fuel-cell idea, of which several variants are being developed at different laboratories, is not necessarily the best one for H₂-O₂ fuel cells. I do think, however, that an operating range of perhaps 50° to 120°C is the most desirable one for most applications.

It may be amusing to note *en passant* that the first flown system was based on Niedrach and Grubb's idea of the 1950's, the second one for manned spaceflight is based on Bacon's work of the 1930's, and a possible third choice may be based on Mond and Langer's paper of 1889; what next?

Problems and Forecast

A performance forecast was made for the near and long term for hydrogen-oxygen fuel cells quite recently.

Table 7 shows characteristics of single cells. The performances of fresh Apollo and asbestos cells are quite comparable. Even active cell areas are more similar than would appear from the table, since two asbestos cells are wired in parallel in the system. Similarly, the power is drawn from cell pairs in the latter device.

It remains to be seen whether the voltages and reactant consumption rates projected for 1975 can actually be obtained; perhaps a better cathodic catalyst, more severe operating conditions, or both will lead to this goal for a "low-temperature" system. Thus far, we have not found durable catalysts significantly better than platinum, palladium, or silver. Much higher cell power densities have been obtained by raising the temperature as high as 150°C, but with concomitant materials and life problems.

As concerns degradation, more stable ion-exchange membranes are said to be under development now. Stability of the Bacon cell is improved by lowering the operating temperature and compensating for the lesser activity by using catalysts. The main difficulty with the asbestos cell appears to be gradual reaction of the matrix with the electrolyte, so that asbestos must be either stabilized or replaced. It is known that cells with the same electrodes, but suitably wet-proofed to operate with free-flowing electrolyte, maintain their activities virtually unchanged for several hundred hours.

Opportunities for research on conventional space-type cells appear to be limited primarily to

- (a) improvement of electrode structure, to increase limiting current densities by facilitating access of gas to the electrolyte;
- (b) improvement of cathodic catalyst, to minimize chemical over-potential and hence inefficiency due to activation of oxygen; and
- (c) replacement of membrane or matrix (if used) by a more durable structure to eliminate performance degradation due to this source.

The new structure should also have high ionic conductivity and minimum thickness – consistent with safety and acceptable electrolyte capacity – for minimizing ohmic overpotential. There is no point in attempting to replace platinum as the anodic catalyst for space cells, though it represents a very severe handicap for commercial purposes.

Data for fuel-cell modules are given in Table 8. The power rating of these units is stated for sustained rather than for peak loads. Obviously, present systems can be derated, i.e., used at lower average power levels, if one wishes to improve efficiency and life for specific purposes. Conceivably, too, a system may eventually be improved to the point where its sustained load can be increased significantly without the penalty of lower efficiency and shorter life.

Improved Bacon modules exist today that weigh about 70% and measure about half of the values quoted. Parasitic power consumption is being lowered as more efficient auxiliary equipment becomes available and engineering design is improving. Module life is generally a fraction of cell life, apparently mainly because of lack of quality control. This is not to say that the modules are being put together carelessly. It simply means that the factors that must be controlled, and the severity of slight variations, are often not recognized until after a number of units have been built and operated.

For example, uneven gas distribution, due to small variations in manifolding or occasional liquid plugs, may "starve" a cell. Since the gas plenum requires uniform pressure, impure residual gas may seep into that cell from its neighbors. The resulting degradation may be alleviated only briefly, if at all, by purging the stack. Since this problem has been recognized, better purge control can be achieved by means of simple inserts (that maintain individual cell pressure differentials). Such difficulties are not always easy to foresee.

An important characteristic of any device is its capability to tolerate abuse and to recover from overstress. To my knowledge, no fuel-cell system has yet been thoroughly evaluated for these properties. We have underway a first, and only partial, set of tests of this kind: A series of 8 full-size asbestos stacks is being systematically mistreated, to determine how they react to repeated start/stop operation; overloads; pressure unbalances; overheating, etc. The same procedures will eventually have to be applied to the mechanical, electrical, and electronic auxiliaries as well, if they are to be fully characterized.

In these tests, we have already learned that an asbestos stack need not be filled with helium for storage, an important simplification of procedure and equipment. Power spikes of up to 5 kW were tolerated without catastrophic damage; duration of these spikes was limited only by the cooling capacity of the stack. Multiple starts and stops appeared to have no effect. Starting at room temperature, a stack was warmed to operating condition

using its own waste heat, by running it at constant voltage or constant amperage. Warm-up times ranged from 59 to 6.5 minutes, with temperature differences through the stack varying from 2°F (1°C) for the hour-long start, to 27°F (15°C) for the fast start.

In contrast to the limited research opportunities in electrochemistry, engineering research on space fuel-cell systems has barely begun. Today's fuel-cell stacks are little more than assemblies of oversize laboratory cells with superimposed mechanical and electrical controls. We still don't know whether Grove-type cells are optimum, since no other concept has yet been engineered. The Grove cell combines two functions near and at the electrode surface, (1) dissolution of gas in electrolyte and (2) electrochemical reaction. While it would be senseless to separate these functions for a single cell or even a few cells, a separate gas saturator combined with flow-through electrodes might be feasible for large cell stacks. Will the size and complexity of such equipment, together with the power needed for pumping electrolyte through electrodes, make this scheme useless? Or what about the slurry system proposed by chemists in France and Germany? Some preliminary design studies are now being made for NASA to determine the prospects of success for these approaches. Still other ideas are as yet unexplored.

The plumbing and electronics today are essentially afterthoughts – appendages that had to be provided to make the stack operable. Perhaps one should consider a fuel-cell plant to be a chemical reactor, with electricity as a byproduct, in order to arrive at novel design concepts. Admittedly, such a reactor must operate under far from ideal conditions, particularly when compared with a reactor in a chemical factory. Nevertheless, there are many well-established and novel engineering concepts, for optimizing chemical plants and for integral regulation and control, that may be directly applicable to fuel-cell plants. If the projections, shown in the last column of Table 8, are ever to be attained, we must surely re-orient our engineering approach to fuel-cell systems.

Reactant Storage

Apart from electrical leads and means for removing heat and water, a fuel-cell system also needs a supply of reactants. In space, both hydrogen and oxygen are stored cryogenically to avoid the weight penalty of high-pressure tankage. However, in this form the reactants are not storable for indefinite periods, because heat leaks into the storage vessels and causes some of the liquid to evaporate and boil off. The boil-off must either be used electrochemically or vented to avoid pressure build-up.

The precise ratio of weight of tankage to weight of cryogenic fluid depends on the size of the vessel, quality of insulation, ambient temperature, vessel pressure, rate of reactant usage, and state and temperature of reactant (slush, subcritical liquid, supercritical gas). Representative figures for supercritically stored oxygen for current fuel-cell applications are 3-3.5 lb/lb tankage; and for hydrogen 0.3-0.4 lb/lb tankage. These numbers are for 20-30 lb (9-13.5 kg) of hydrogen and eight times as much oxygen. Both figures of merit might be raised by developing lighter structures for the outer shells of the Dewar vessels. A projected single tank to store both reactants would hold 4.25 lb/lb tank. Furthermore, subcritical oxygen storage might raise the above number to 5 lb/lb tankage. – Theoretical storage volumes are 4.4 lb H₂/ft³ (0.07 g/ml) and 71.2 lb O₂/ft³ (1.14 g/ml) at atmospheric pressure and at their respective boiling points. Some 95% of the stored reactant can be made available to the fuel cells.

Heat Balance

Since the combination of hydrogen with oxygen is exothermal, heat generally must be removed from a fuel-cell power plant. During start-up or standby, however, heat may have to be added to the system. Depending on the particular system design and capabilities, starting may be a simple "boot-strapping", i.e., self-heating process; or else one needs an auxiliary heat source. This last requirement complicates the system and makes it less flexible.

Heat may be discarded by evaporative cooling. For relatively short missions, one may wish to evaporate the product water, which will extract about 1/3 of the heat evolved. The remainder can be transferred out of the system by venting hydrogen.

A transient heat load can be handled by re-injecting stored water and letting it warm up.

In general, however, most of the heat of reaction will be removed by a heat exchanger and eventually radiated to the surroundings. The size of the radiator area varies with a number of factors, among them the system's efficiency (itself a function of load); the temperature at which water leaves the fuel cell (again dependent on load as well as on the specific system); shape, position, and efficiency of the radiator; and temperature of the radiator and of the heat sink. For a complete power supply, one would also have to consider the heat load imposed by the inefficiencies of power conditioning.

For Gemini, the radiator exit temperature was 65-75°F (18-24°C) and the area about 180 ft² (16 m²) per average electrical kW. A representative temperature for Apollo is 160-170°F (71-77°C) and the effective area needed in earth orbit is about 24 ft² (2.2 m²); half as much area is required in deep space. Under worst lunar conditions, the radiator may overheat for a few minutes. The numbers for an asbestos-cell system with water collection are the same as for Apollo. Radiator weights range from 1 to 2 lb/ft² (5-10 kg/m²), depending on mission requirements.

Cost and Size

The cost of space fuel-cell plants, exclusive of reactants, tankage, and radiator, is of the order of \$150,000-\$300,000/kW (sustained power) today. The extraordinarily high figure reflects the fact that systems are essentially hand-made and must pass rigid inspections. The same equipment, made to less exacting standards, costs perhaps half as much. Even semi-automation should reduce the cost substantially below the \$75,000-\$150,000 figure. Another approach to lower cost would be to improve the performance of the fuel cell so that the same size stack could produce higher power in sustained operation.

Considering the immediate space program only, the 1-kW power-plant, with 2-2.5 kW peak capacity, is adequate, especially in view of the fact that several such systems must be carried for reliability reasons. Future missions, however, may require 10 or more times that amount of power. Hence larger modules should be useful in the 70's or 80's. They should be cheaper per kW as well as lighter and more compact, assuming that performance, geometric surface area, or both these properties of electrodes can be scaled up. If the cathode remains the limiting electrode, its effective surface area is easily doubled by sandwiching one anode between two cathodes. Parasitic power per stack might not decrease much in absolute value, but should be a considerably smaller percentage of total stack output.

Uses

Finally, we must consider the future of the fuel cell in space. For long space missions, the primary source of energy can obviously not be chemical, because the weights of fuel and oxidant would become prohibitive, unless reactants can be resupplied at intervals. Nevertheless, fuel cells are likely to play a continued role in the space program.

They may be emergency and peak primary power sources in connection with both solar and nuclear power plants. They may supplement or replace secondary batteries, with the astronauts using the byproduct water before it is electrolyzed again. And they may be the sole, primary power sources for lunar surface vehicles, from which the water would be returned to an electrolyzer at the base for re-processing. On the other hand, if water should be readily available on the moon, the vehicle might use the water for evaporative cooling by day or even as a heat source at night, thus extending its mission time. Lastly,

fuel cells may eventually replace primary batteries as the electric on-board power source in rockets, although the fuel-cell system would admittedly have to become much simpler than it is now, to make it attractive for this use.

The forecasts made here are based on present-day engineering approaches. In the drive to obtain usable devices as quickly as possible, engineers have done an excellent job of building what appeared feasible. But this rush toward hardware may also have meant pushing aside any promising, untested ideas. Now that operable systems are at hand, we should consider the more speculative approaches in an attempt to upset these predictions.

Also, more thought must be given to optimizing the total power package, which includes not only the fuel-cell system but power conditioning as well. Perhaps a lower voltage output from the fuel cells, more electrical paralleling, and appropriate changes in power conditioning would result in greater reliability and longer useful life, with little or no penalty in weight and volume. Alternatively, fuel-cell modules might be placed near the using devices to minimize transmission losses; and a large percentage of the electrical appliances might be designed to operate directly on low-voltage, direct-current power.

SECONDARY BATTERIES FOR SPACE

Secondary or rechargeable galvanic cells and batteries are simply those in which the components are compatible with each other; that have reasonably good stand life under the conditions under which they may be stored (with or without a trickle charge); that undergo few, if any, chemical side reactions and thus show high current efficiency; and that can, therefore, be electrically recharged.

A good summary of the status of space-type batteries of this kind was published in 1965 (Ref.16), though progress has been made meanwhile: "In the field of secondary (rechargeable) batteries, the nickel-cadmium couple is receiving the greatest use. Typical conservative secondary-battery specific weights are 2 watthr/lb for a 300 mile orbit, 5 watthr/lb for a 2500 mile orbit, and 10 watthr/lb for a 20,000 mile orbit. The advantages of the nickel-cadmium couple over other secondary batteries include small voltage excursion, high rate charge acceptances, long shelf life, and low temperature operation. The silver-cadmium secondary battery approaches the long life of the nickel-cadmium and the high energy density of the silver-zinc batteries.

"The silver-zinc secondary battery is the highest energy density battery in common use. However, it does not yet have the good cycle life of the nickel-cadmium battery. Silver-zinc cycle life is still measured in hundreds of cycles as compared with thousands of cycles for nickel-cadmium batteries.

"Principal problems associated with batteries include inability of hermetic seals and separators to operate 2 years or more, the narrow useful temperature range, and control and protection problems. In spite of the fact that batteries have been around for years, the technology is still in many cases developed as an art and not as a science. Much remains to be done to gain a better understanding of the fundamentals, including electrode reactions, solubility and migration problems, and separator composition and structure."

French-speaking space technologists will find the pertinent portion of Dr Lespinasse's course useful¹⁷.

Only two secondary batteries are now being used in space, both having cadmium anodes and using aqueous KOH electrolyte. One contains nickel oxide, the other silver oxide cathodes; each has its advantages and limitations.

Cadmium-Nickel Oxide

The cadmium-nickel oxide cell was invented by Jungner in Sweden over 70 years ago. It is presently the "work horse" of space batteries. As late as 1962, the reaction mechanism was not known for the nickel electrode, though the anode reaction is known to be

During the past 3 years, a series of papers by Aia¹⁸ and Kober¹⁹ has elucidated the cathode process by combining various physical, chemical, and electrochemical techniques in the attack on that problem. While we still cannot write a stoichiometric half-cell equation, the structure and temperature-range of stability for the active material are now known. The process of charge and discharge involves a change in the crystalline structure, its water content, and its "active" oxygen content. A simplified representation might be²⁰

Rodolphe Herold reviewed the beginnings of NiCd technology, mentioning the important point that only a switch from the pocket or tube to the sintered structure made possible modern developments²¹.

"In conventional alkaline cells, the active materials are contained in pockets or tubes made out of thinly perforated steel strips; one of them is hydrate of nickel, which is a bad conductor, thus requiring an addition either of graphite or nickel flakes. This type of assembly whilst giving a high mechanical ruggedness involves a rather high internal resistance thus leading to somewhat insufficient results at very high rates of discharge.

"Electrodes following the new technique incorporate a support made out of a screen or strip of nickel, or nickel plated steel, perforated or not, onto which is sintered a layer of nickel powder with a very low density, inferior to 1, within a neutral and protecting atmosphere.

"A support which looks like a metallic sponge having very small pores is so obtained. The porosity of this support reaches 80% or more. This support is impregnated with nitrate or chloride of cadmium or of nickel, then dipped into a hot alkaline solution in order to precipitate the corresponding hydrate on the sides of the pores of the sintered support. Electrodes are thus obtained in which the active materials show a surface of a few hundred times larger than that of the active materials contained in pockets or tubes; further the sintered nickel support offers a very good conductor to carry the current to the terminals.

"Active surfaces and conductivity are considerably increased and, further, active materials are in direct contact with the electrolyte...

"These batteries were showing much better electrical performance than the conventional alkaline batteries, as, for the first time, the high rate discharge results were superior to those of the best lead acid batteries. However, the life cycle figures were still inferior to that of conventional alkaline batteries. The reason for this was probably a lack of homogeneity in the repartition of active materials which were predominant at the surface of the electrodes; thus the porosity was insufficient and the electrochemical exchanges were disturbed. Finally the cost was very high as a result of plates being produced individually and the quality control difficult.

"It appeared that important progress could still be obtained by using thinner plates very close to each other and by using as a separator some thin sheets of very porous insulating plastic material. Thin plates, thinner than 40 mils, embrace a permanent and excellent porosity. Separators, saturated with electrolyte are closely fitted to the plates keeping them evenly wet. Thus ohmic losses are becoming negligible and the speed of electrochemical reactions very high. Electrodes are always ready to immediately take

the charge or to be discharged with high efficiency and the obstacles to the diffusion have then but a negligible effect.

"These electrodes do not warp whatever the magnitude of the crossing current, so these batteries can be discharged at very high rates without appreciably reducing their capacity.

"The use of thin plates induced to consider manufacturing them by a continuous process, thus reducing the cost below that of thicker plates.

"This new technique of alkaline storage battery construction has led to revolutionary consequences with an unpredicted decrease of the internal resistance. The ruling dogma, declaring that alkaline storage batteries could not be discharged quickly, due to their very high internal resistance, has now deserved its place in the museum for erroneous statements."

When, some ten years after industrial NiCd cells became practical, space cells were required, their quality and reliability were too low. New separators, particularly felted nylon, and new seals had to be developed, apart from the fact that quality control generally needed to be greatly improved. Hermetic seals are now such that about 3-year life can be expected from space cells in 90-minute orbits. That means 60-minute charge and 30-minute discharge periods.

Memory Effect - In space, these cycles are never regular, so that batteries are not constantly going through the same use rhythms. In laboratory tests, they do. This can give rise to the so-called memory effect. It is illustrated on Figures 18 and 19 for the same 12-amp-hr NiCd cell (Ref.22). After hundreds of *identical* cycles with no more than 40% discharge, the capacity of the cell has become that of the cycle itself.

However, reconditioning by overcharge can erase the memory effect. The absence of such regularity in actual use also means that memory has not been observed in space. Battery testing today provides for occasional exercise of the cells so as to avoid build-up of memory. Its causes might be sought in a slow annealing of defects, or a change of pore size, within the unused portion of the nickel oxide.

Deterministic Statistics - The only meaningful method by which one can obtain information on the reliability of any device is to subject it to tests, either during use or in the laboratory, measure the required magnitudes under reasonable conditions (laboratory must simulate real use), and apply proper mathematics. In view of the lack of data on sealed NiCd batteries and because of their importance in space, we have undertaken a major test program in cooperation with the Naval Ammunitions Depot at Crane, Indiana.

Originally, the program comprised 660 cells from four commercial sources, ranging from 3-amp-hr to 20-amp-hr capacity. Cells were tested to two depths of discharge at each of three different temperatures; they were grouped into 84 batteries of 5 or 10 cells each. When more than half of the cells had failed, the whole pack was considered to have failed. These failures had increased from 29 packs in one year to 51 packs in two, and 58 in three years. In general, failure rate increased with higher temperature (0° to 40° or 50°C) and greater depth of discharge (15-40%). However, I am not sure whether it was really depth or discharge, extent of overcharge (115-160% recharge), or both, that may have contributed to the higher mortality. Such overcharge causes gassing in the cell, oxygen being evolved at the nickel oxide electrode faster than it is being consumed at the cadmium electrode. Continued pressure cycling would obviously contribute to eventual failure of the ceramic-to-metal hermetic seal.

After a while, we were swamped with paper tapes full of battery test data. In the process of devising means for coping with all of this information, John H. Waite (then with RCA) rediscovered an unusual variety of statistics that appears to have been used in connection with a relay problem in WW II.

Briefly, the procedure is as follows: A statistically meaningful sample of a population is tested to destruction under normal operating conditions, while significant data are being recorded. The data are manipulated so that they show differences, particularly for the initial portion of the life test, among samples that passed and those that failed the test for a variety of reasons. One can then take another member of the population, obtain initial life data, and match its data to those previously obtained, in order to predict whether this member will complete its mission or, if not, what the cause of its failure will be.

The trick consists in selecting "significant" variables and in manipulating the data properly. The former is in the realm of the natural sciences, the latter is that of mathematics. The beauty of this approach, if valid, is that it is deterministic instead of probabilistic (or at least much less probabilistic than garden-variety statistics) and thus leads to much higher confidence in selecting a tool for a mission - anything from snow shovels to space ships. The difficulty is to gain acceptance of the concept, following which suitably statistical relationships and experimental procedures remain to be developed. Preliminary indications are that not only will the approach work for batteries, but that it can be made fail-safe. That is to say, the criteria can be chosen such that the indicators will point to failure for a battery that, in laboratory testing, will actually survive. But the indicators won't clear a battery which will subsequently fail to perform a given mission.

Problem Areas - Some nickel-cadmium batteries have now survived 3 years, both in space and in test laboratories. It is presently doubtful whether we have 5-year batteries. One problem is that it takes 5 years to find that out. In other words, we need meaningful methods for accelerated testing. Techniques that have been worked out for lead batteries are not necessarily applicable here.

One of the weakest parts of the cell, for long life, is the ceramic-to-metal seal. We are now experimenting with special rubber seals to determine their life span.

In contrast to acid batteries, where a hydrometer is a fairly good indicator for state of charge, no satisfactory device is available for this purpose, applicable to NiCd cells. Coulometers (essentially ampere-hour meters) and equivalent external devices work up to a point, except that the state of charge of a cell varies with temperature. An indicator electrode, e.g., a fuel-cell electrode, can be used to sense the onset of oxygen evolution, which occurs at 80-90% of full charge. Such third electrodes (in addition to the two working electrodes) are now available for controlling the end of fast charging. Among other devices for accomplishing this indication are miniature fuel cells, inserted in a cell but not necessarily electrically connected with it.

J. Sherfey of NASA has been in charge of a program to use cells in an unorthodox fashion. He calls it the upside-down cycle. Whereas the normal cycle is between a partial discharge and an excess of charge, his cycle is between full discharge and about 80% charge. Indications are that life might thus be doubled, probably mainly because pressure cycling is avoided. By completely discharging a battery every fifth cycle or so, it never has a chance to develop memory, either.

Secondary space cells are generally sealed in a starved condition, i.e., they contain only enough electrolyte to wet the separator. During long life, cells have been noted to dry out, even when the seal is intact. This gradual change points to electrolyte migrating into the electrodes, where it is retained in cavities and interstices. A pre-soaking of electrodes under vacuum, to displace air pockets, should alleviate this condition, similar to the preconditioning necessary with Teflon-type fuel-cell electrodes.

Sealed, starved cells are also subject to "thermal runaway" when charged at too high a constant voltage. This happens because an almost fully charged cell starts to gas. Such oxygen evolution is exothermal and raises the temperature. As the cell heats up, more current can pass at a fixed voltage; the process is self-accelerating and ends in the cell bursting open. After this danger became known, control of overcharge was switched from constant voltage to constant current.

Just as overcharge causes gassing, overdischarge also causes gassing and might damage or break a cell. Here again, the remedy is an auxiliary electrode connected to the cadmium plate²³. A fuel-cell type third electrode can use up H_2 faster than can the cadmium electrode,

Thus, both recombination and signal auxiliary electrodes may be desirable in galvanic cells. Furthermore, should both hydrogen and oxygen be present, these two gases will combine chemically at the surface of the platinum catalyst.

For a typical 90-minute orbit, we have obtained on the order of 18,000 cycles (3 years) at about 20% depth of discharge (based on rated capacity) but as few as 250 cycles at 75% depth. By improved methods of operation and temperature control - $0^\circ C$ is preferred -, using some of the devices just described, I think that we can increase cycle life, depth of discharge and hence energy density, as well as reliability of NiCd batteries quite markedly.

Cadmium-Silver Oxide

When we consider actual energy densities achieved in satellites thus far, capacities of AgCd cells (6-8 watthr/lb) have been notably higher than those of NiCd cells ($\frac{1}{2}$ -2 watthr/lb). These more energetic cells have lasted 2-2.5 years thus far, approaching lives of NiCd cells (3 years). But there is a considerable difference in cycle life: Whereas NiCd cells run typically 16 cycles/day, AgCd cells may run 3 cycles or so. This gives them a longer charging time and lower charging rate, which is presently needed. Only one test program has thus far shown cycle lives of AgCd's comparable to those of NiCd's. In other tests, lives are typically 3000-6000 cycles at 30% of discharge at $25^\circ C$, though they have been improving with improved materials and manufacturing techniques.

It is doubtful whether AgCd would have been flown in space even now, had it not been for the fact that nonmagnetic batteries were needed that would not interfere with sensitive magnetometers. Nickel being ferromagnetic, a NiCd cell would not do. Even the nickel grid of the usual silver oxide cathode had to be replaced by a silver grid; and the external connecting wires had to be arranged so they would not set up an interfering field. But having proven itself, the AgCd cell is an accepted space battery.

Separators - Considerable effort has been spent on improving separators for secondary cells with silver cathodes^{24,25,26}. Hennigan mentions the incorporation of antioxidants in cellophane, use of methyl cellulose, and modifications of methyl cellulose as having been effective steps in prolonging the life of cells and decreasing their sensitivity to temperature effects. McClure discusses the theoretical foundations underlying the approaches to separator modifications. Cooper and Fleischer's book contains experimental methods for evaluating separators. The details of these publications are beyond the scope of this lecture. It should be mentioned, however, that some of the approaches used in making sterilization-resistant separators, not normally considered for the usual space battery, may bring added benefits by providing particularly durable materials.

Secondary Fuel Cell

Depending upon the reactants and products of a fuel cell, several methods of regeneration can, in principle, be used - thermal, photochemical, radiolytic, and electrolytic. All of these have been tried; thus far, materials problems for thermal regeneration have not been solved, and efficiencies of photochemical and radiolytic recharging have been too low to be practical. Of several electrolytic schemes, only the electrolysis of water has been pursued in depth.

A recent paper by Findl and Klein²⁷ describes the equipment and progress to date. "The cell is basically a combination of a hydrogen/oxygen primary fuel cell and a water electrolysis cell in one compact package. During the charge mode of operation, water, contained

within an asbestos matrix separating the electrodes, is electrolyzed to produce hydrogen at the anode and oxygen at the cathode. As gas is evolved, it is fed by appropriate manifolds to integral tankage. During discharge, the stored gases are recombined at the electrodes to form water which returns to, and is absorbed, by the asbestos matrix. The same electrodes serve as the reacting surface for both the charge and discharge mode of operation. Concentrated aqueous potassium hydroxide, contained in the asbestos matrix, serves as the electrolyte, and the source of water for electrolysis. The quantity of electrolyte employed is such that the solution is totally absorbed by the asbestos matrix and no free liquid exists within the system. With the integral gas tankage, there is no flow of materials in and out of the unit, and it can be operated as a sealed box similar to conventional secondary batteries."

On a volume basis, the energy density is about 1/3 that of conventional cells, due to the tankage requirement for gas storage. Because of diffusion and chemical (rather than electrochemical) reaction of the gases at the catalyzed electrodes, especially in view of the fact that pressures up to 14 atmospheres occur, energy cannot be retained for more than a few weeks. Operation below 50°C is impractical because of the high resistivity of aqueous KOH below that temperature. Optimum operating temperatures are between 70° and 100°C.

Present materials of construction permit exposure up to 150°C, making the unit sterilizable. On a weight (rather than volume) basis, 6 watt hr/lb have been obtained with a 5-hour cycle. The authors have projected 15 watt hr/lb and an eventual 25 watt hr/lb.

Although a 600 watt hr, 500 watt, 34 lb, 28 V unit has been built and operated at peaks up to 1300 watts, this 34-cell module had unsatisfactory cycle life. Gold plating of nickel parts has reduced corrosion, but then it was found that the asbestos matrix reacted slowly with the electrolyte. Meanwhile, a new potassium titanate/Teflon matrix has been developed and will be incorporated in the module.

For the time being, this regenerative system offers some advantages over conventional ones. Eventually, it may be surpassed by hybrid systems of the metal-gas variety.

Metal-Gas Hybrids

We have already discussed the prime exponent of this combination, the zinc anode combined with the fuel-cell oxygen cathode. Work on a rechargeable zinc-oxygen hybrid has not yet progressed very far, and its future is still uncertain. By sacrificing some of the energy density of zinc and replacing it with, say, cadmium, we can avoid the problems due to zinc dissolution and dendrite growth. A cadmium-oxygen cell should, therefore, have lower energy density but much longer cycle life. Whether this prediction will be fulfilled remains to be seen.

DESIGN OF ELECTROCHEMICAL POWER (SUB)SYSTEMS

The introduction has already briefly covered some of the criteria that determine where and when electrochemical energy storage and electricity production are applicable in space. Information on designing the electrochemical portion of spacecraft power systems or subsystems is widely scattered in documents about various rockets, satellites, and probes. No attempt appears to have been made to collect and systematize this knowledge. Nor have I particularly searched for it in writing this paper; rather, I have drawn upon a few references in our technical files.

Primary Batteries

A useful summary chart, Figure 20, was presented by Banes and Uchiyama²⁸ for designing primary batteries. It clearly shows the complexity of the many interrelated tasks and bits of information that must be known and combined into choosing a spacecraft battery.

Banes and Uchiyama found that, in spacecraft built for the Jet Propulsion Laboratory alone, battery weight varied from as little as 2.2% to 27.5% of the weight of the total spacecraft. Among the more important factors to be considered in system design are power profile; limits of voltage regulation; load sharing with other power sources, such as solar panels; possibility of trickle charging and recharging; temperatures to which the battery will (or must not) be exposed; response to transient loads; variation in capacity among cells, i.e., cell matching in a battery; excess capacity for emergency conditions; and packaging to withstand shock, acceleration, and vibration.

Great care is taken in the various types of testing, from delivery to immediate pre-launch checks. For reliability, redundant parts may be added, provided that the complications introduced into the circuits do not actually reduce the reliability. Monitors for battery temperature, voltage, pressure, etc. are sometimes included in a spacecraft and have been used to analyze and clear faults from the ground.

Secondary Batteries

The case history of the power systems for Telstar I has been well documented by Bomberger et al.²⁹. Special care was taken to select "only those cells which fell into a tight grouping around the variable mean". The 19-cell battery contained an extra cell to make sure the minimum voltage would be 19.8 V, even if one cell should be short-circuited. The overcharge current, at 20°C and a maximum cell voltage of 1.48 V, was not allowed to exceed C/15. (C is the current that would be obtained if the battery were fully discharged in one hour at constant current.) The battery was sized to meet peak load requirements during 3 consecutive periods of longest eclipse. For obtaining long life, this energy drain represented only 20% of the battery's total capacity. (But note the remarks on the upsidedown cycle, above.) In actual use, the Telstar battery was not discharged below 60% of capacity.

Leisenring and Binckley²² have provided design data for cadmium-silver oxide and cadmium-nickel oxide batteries, based on then available data, to help system designers calculate battery capacity, weight, and life for a wide range of use conditions. They stress the importance of adequate thermal design and temperature control as well as mentioning that erasing of "memory" will prolong cell life considerably. Such reconditioning occurs upon discharge (until the cell voltage has dropped to 0.5 V) into a fixed resistance of 2 ohms/cell.

In a very recent study, a comparison was made between cadmium-nickel oxide and cadmium-silver oxide batteries for manned spacecraft³⁰. The main variables were orbital altitude and duration. The authors took the following factor into consideration (not all their criteria are included here):

	NiCd	AgCd
Max. depth of discharge, %	50	50
No. of cells in series	29	32
Watt hr/lb, incl. structures	7.7	13.2
Watt hr/ft ³ , total external volume	353	620
Average cell voltage (to full discharge)	1.2	1.1
Shortest charging period, hr	3	5

Their analysis indicated "that neither battery type is superior across the entire range of conditions studied. In general, it can be stated that at the synchronous altitude, the silver-cadmium battery weight is lower than the corresponding nickel-cadmium weight. For altitudes below 2000 miles, the two systems are almost equal in weight for missions (resupply periods) up to approximately 150 days. However, for longer missions at the low altitudes, the silver-cadmium battery would be heavier than nickel-cadmium..... In conclusion, it can be said that each battery type offers a clear choice, based on weight. Specific mission studies can be restricted to one battery type, but as long as the overall parametric approach is to be maintained, the study must include both NiCd and AgCd battery types."

Primary Fuel Cells

Not only are there hybrid electrochemical devices, but hybrid power systems have been studied as well. Stafford and Mahefkey considered a combination primary fuel cell/solar cell, i.e., the fuel-cell water would not be electrolyzed³¹. Their conclusions are summarized in Figure 21, showing that the specific weight of such a hybrid would be less than that of a conventional solar cell-battery system for up to 15 days, depending upon orbital altitude. Credit was taken for human use of the product water from the fuel cell, particularly since it had no other use. But even in the case of regenerative fuel cells, the water can become available at times for other purposes before it is electrolyzed again.

R.R.Desai and coworkers have worked out an IBM 704 Fortran computer program for minimizing fuel-cell system storage requirements and weights³². The results were design charts showing optimum storage temperature and insulation thickness for maintaining small systems in low-temperature environments. In some cases, the combination primary fuel cell/rechargeable battery resulted in lower weights than use of fuel cells only. A mathematical model was developed to represent the operating characteristics of fuel cells. A system with cells connected in parallel was found to be more reliable than one with series connections.

Among the factors that must be considered for sizing a fuel-cell system is the rate of degradation experienced by the cell. Figure 22 shows a typical system's electrical performance at the start, after 28, and after 56 days. The horizontal dashed lines indicate the voltage limitations prescribed for the system. As cells degrade, the reactant consumption increases because of lower efficiency. Figure 23 shows this change as well as the variation of specific reactant consumption with total power output. Note that the figures increase sharply toward low outputs, because much of the consumption is now for internal or parasitic power, such as fans and pumps.

Two nomographs were developed for approximately the minimum weight of fuel-cell systems, one of which is shown in Figure 24. Keeping certain factors fixed, one finds that system weight depends not only on total energy (which determines reactant and tankage weight to a first approximation) but also on peak power requirements.

The absolute values shown here apply only to the system as it was developed 2 years ago. Much has been learned and improved since then. These figures illustrate in general the type of questions one must ask and answers one will find when designing fuel-cell power systems.

But minimum weight is by no means the only consideration. Foremost for a manned space mission is reliability. (An unmanned mission would be a wasted effort, of course, if the power source failed.) Maximum reliability and minimum weight are mutually exclusive, so that some weight penalty must always be paid. One way of achieving reliability is to use modular powerplants with switching or cross-over capability. We may have 2 or more independent fuel-cell reactors, each with its own set of auxiliary devices and sized so that something less than the full powerplant can complete a mission in an emergency. Or we might use stand-by modules for the same purpose, if they can be activated at a moment's notice. Batteries or engines might be used as interim power sources until a slow-starting stand-by unit has reached an acceptable operating level. Quite obviously, it makes more sense to consider all available power sources to be complementary rather than competitive and to explore the merits of using 2 or more instead of considering only one at a time.

OUTLOOK FOR ELECTROCHEMICAL POWER

We have considered the past, present, and a little bit of the future of electrochemical space power up to now, at least from the technological point of view. Remember that, in 1870, it was a "spin-off" from the coalmining industry that gave us the first aerospace electric system. Now, in 1967, it is well to ask what the normal civilian economy might expect from aerospace and space power developments. And just as electrochemical power became the first

aerospace electric power source, electrochemical space power has made the first contribution to progress in ground power.

Batteries

Although auxiliary electrodes were invented in the 1930's³³, they were perfected and put to practical use only during the past five years, largely under NASA sponsorship^{34,35}. Such third and fourth (signal and gas-recombination) electrodes, built into commercial cells, are now becoming available in consumer products because smaller, lighter cells result, which can be recharged in a fraction of the time required for the older cells. Better separators, methods of construction, uniformity, and life of cells and batteries have become possible as a result of information obtained from space battery programs.

Some of the new battery separators, particularly those developed for zinc anodes and sterilizable batteries, are likely to find commercial acceptance for rechargeable zinc-anode cells. In laboratory cells, we have obtained over 2000 cycles at room temperature and 30% discharge with an inorganic separator; these cells are far from being optimized. This is the first indication that truly secondary zinc cells can be constructed.

New gas recombination devices, methods of use of batteries, charge control systems, and seals are all candidates for ground application. Some of the novel anodes, cathodes, and electrolytes may also be useful industrially or for consumer purpose. Thus, the promising cathodic reactant, 2,4,6-trichlorotriazinetrione (or trichloroisocyanuric acid) as well as dichloroisocyanuric acid (Fig.25) might become economical substitutes for present dry-cell oxidants, as mentioned above.

Our attempts at revival of the method of testing and selection by means of deterministic statistics have ended in abysmal failure thus far. Should they ever succeed, it will be interesting to watch the mathematical development needed for this non-destructive test method. Its applications should be as important and far-reaching as those of conventional, probabilistic statistics are today.

As a result of space needs, research on galvanic cells has been considerably enlivened and gained a great deal in imagination. This stimulus is, I think, as important a benefit to the economy as is the factual knowledge that would not even have been looked for were it not because of space requirements.

Fuel Cells

Thus far, all fuel cells considered for, or used in, spacecraft are hydrogen-oxygen cells. There is a school of technologists that thinks this is the chemical couple of greatest terrestrial interest, also. If they are right, then the commercial benefits from space R&D in fuel cells will be quite direct. Whenever there is more than one "school", however, it means that things are not yet settled; so they may be wrong. Even so, I shall endeavor to show at least some of the more obvious earthly consequences of space fuel-cell work.

The most immediate one is that the Gemini fuel-cell system, as the first functional one, has demonstrated capability for practical use. The first useful application of anything, in a case where it has demonstrable advantages over its competitors, is always a tremendous step. But G.E. is already applying the principles of the Gemini cell to a device that comes close to commercial application (Fig.26). This is a 1-year, 5-watt power source, designed for unattended operation, capable of brief 500-watt bursts thanks to a secondary nickel-cadmium battery. A long-lived power source for use in inaccessible places, where reliability is a major consideration, is important to communications, pipelines, and unattended weather stations, for example. To be sure, it will have to prove itself for this purpose in competition with conventional and with such novel power sources as an alcohol-air fuel cell, gas-fired and nuclear-powered thermoelectric devices.

In more basic research, NASA is undertaking a study of the optimization of oxygen electrodes, including the effects of pore size, pore distribution and electrode thickness. Though we are sponsoring this work specifically for oxygen, it is obviously and equally useful for any gas electrode. But let us stay with the cathode for the moment, the weakest link in the H_2-O_2 cell at present. When any kind of load is put on a cell, the voltage immediately drops. For practical purposes, 1 volt is presently tops, or about 80% voltage efficiency. Since the theoretical thermal efficiency of such a cell is about 83%, we get, at best, 66% gross efficiency, assuming 100% current efficiency. In fact, however, 60% gross efficiency - i.e., not counting parasitic power losses - is more usual and still considered very good today. Most of this loss is due to chemical overpotential, also called activation polarization, at the oxygen electrode. The remedy, if there is one, must be sought in a catalyst superior to the presently used noble metal or silver.

Unfortunately, there is no theory of electrocatalysis, or even ordinary catalysis, available for predicting the behavior of new catalysts. The search is still in art. It occurred to me some time ago that an empirical screening effort is the only means of obtaining guideposts pointing toward promising materials. A contract with Tyco for such a survey is beginning to pay off. Not only have several substitutional alloys shown corrosion resistance and activity but interstitial alloys are showing hopeful signs, too. Additional interstitial materials are being synthesized for us at the Bureau of Mines. Since excess quantities take no more time and very little more money to prepare, samples are being made available to other laboratories for evaluation in potential terrestrial fuel-cell systems. I say little more money, because we are talking about a few grams more of mainly iron, cobalt, and nickel converted to carbides, nitrides, and borides. Even if no catalyst superior to noble metal or silver is found, and hence if the project is a failure for space, a moderately active and reasonably stable interstitial preparation might be quite useful as a cheaper substitute for earth-bound fuel cells.

Research and development of kilowatt-size and larger fuel-cell systems with all necessary controls, investigation of new concepts for building compact and light-weight modules (we are still building 1839-type modules today!), and basic research in fuel-cell chemistry - all these efforts help train up-to-date fuel-cell technologists and scientists, thus speeding commercial developments indirectly as well as directly.

The \$100 Watch

There are also much subtler contributions from space research, be it on electrochemical power or otherwise. How does one evaluate, for example, support for the compilation of data in any field of science? Or of critical studies or handbooks? Support of basic research in industry? Training of graduate students, particularly in an otherwise relatively long neglected field with a shortage of expert manpower? Writing of texts by professors? Foundation of an interdisciplinary institute at a university? Support of an information clearing house that helps coordinate research and engineering throughout the US?

All of these activities are part of our electrochemical space power program. Not every project can be successful, of course. We failed with biochemical fuel cells and with pulsing of fuel cells for increased output. These were relatively new and untried fields. But if the pay-off, in the short or long run, looks good enough, we expect to support new concepts again. We are doing so now. And, hopefully, some will pan out. This constitutes another intangible terrestrial application - the stimulation and support of fresh ideas in young minds (regardless of bodily age).

"Spin-off" was not planned in 1870, but it was clearly recognized. Today we are consciously directing efforts conversely, i.e., towards channeling new, non-commercial technology into industrial and consumer applications. The problem has no simple solution, however. As R.L. Sproull expressed it³⁶:

"Of course the military KC-135 becomes the civilian Boeing 707. Of course, improvements in the internal combustion engine benefit civilian industry even if the work is done for

military trucks. But most Departments of Defense, NASA, and AEC research and development is by no means so directly applicable to nonmilitary scientific progress. It would indeed be a cynical comment on management to assert that a million dollars spent on a lunar landing vehicle would contribute as much to the development of new nonspace products as would a million dollars directed specifically toward the latter goal.

"Thus the benefits that accrue to American industry and to the American consumer as a result of these large applied military and space programs can be only a fraction - and usually a very small fraction - of the benefits the same expenditures could have produced if focused directly on civilian technology. And as the management of these large programs continues to improve, the 'spillover' or 'fallout' for the civilian economy may become even less, since better management will accomplish the specific research and development mission with less peripheral expense.....

..... "Is there any way in which the spillover can be made more effective?

"I doubt it. Management of these programs focuses funds with ever-increasing precision on each specific mission, and that mission is not the stimulation of American industry. Furthermore, consumer-oriented industry operates in an entirely different cost régime than do programs of the big three. The cost per pound for space vehicles - minus fuel - is greater than the cost per pound of one-hundred-dollar watches. Air frames and nuclear fuels are only a little less expensive. The technology of these advanced systems cannot be expected to contribute much to the technology of the building industry or even, with a few exceptions, of the automotive industry - in fact, to the technology of just about any industry other than one-hundred-dollar watches. The funds simply go into different activities"

Nevertheless, I hope I have shown, by means of selected examples, how considerable electrochemical work directed at \$100 watches is likely to benefit users of electrochemical power.

REFERENCES

1. Medawar, P.B. *The Art of the Soluble*. Methuen & Co., London, 1967, p.148.
2. Szego, George C. Private communication (Table I).
3. Eisenberg, M. *Thermodynamics of Electrochemical Fuel Cells*, in *Fuel Cells*. W.Mitchell, Jr, ed., 1963, Academic Press, p.39.
4. Jasinski, R.J. *High-Energy Batteries*. Plenum Press, 1967, pp.vi-vii.
5. Yeager, E.
Chairman *Symposium on Electrochemical Processes*. Pre-prints of Division of Fuel Chemistry (Vol.11, No.1), Am. Chem. Soc., 153rd Natl. Mtg., April 9-14, 1967.
6. Tafel, J. *Z. Phys. Chem.*, Vol.50 (1905) 641; from K.R.Williams, *An Introduction to Fuel Cells*, 1966, Elsevier Publ. Co., p.30.
7. Justi, E.W.,
Winsel, A.W. *Kalte Verbrennung*, 1962, Steiner Verlag, p.171.
8. Yeager, J.F.
et al. *Batteries and Cells, Electric*; in *Encyclopedia of Chemical Technology*. John Wiley & Sons, Vol.3, 1964, pp.99-139.

9. Braeuer, K.H.M.,
Harvey, J.A. *Status Report on Organic Electrolyte High Energy Density Batteries.* US Army Electronics Command, Fort Monmouth, N.J., 1967, iv +51 pp.
10. Swinkels, D.A.J. *Lithium-Chlorine Electrochemical Energy Conversion*, Allison Research and Engineering, Vol.7, 1965, pp.15-20.
11. Swinkels, D.A.J. *Lithium-Chlorine Battery.* J.E.C.S., Vol.113, 1966, pp.6-10.
12. Kummer, J.T.,
Weber, N. *A Sodium-Sulfur Secondary Battery.* Soc. Automotive Engineers, Automotive Engineering Congress, Detroit, paper 670179, 1967, 7 pp.
13. Hale, L.B. *Foreword*, in *Space Sterilization Technology.* NASA SP-108, 1966.
14. Schwartz, H.J.,
et al. *Batteries and Fuel Cells*, in *Space Power Systems.* Advanced Technology Conference, 1966, NASA SP-131, p.15.
15. - This section is based on the author's *The Growth of Fuel Cell Systems*, pp.252-265 in *Engineering Developments in Energy Conversion*, 1965, ASME International Conference on Energetics; and *Primary Hydrogen-Oxygen Fuel Cells for Space*, presented at AGARD, 29th Meeting of the Propulsion and Energetics Panel, 1967, Brussels.
16. NASA and DOD *Electrical Power Generation Systems for Space Applications.* NASA SP-79, 1965, pp.9-10.
17. Lespinasse, B. *Cours de Technologie Spatiale.* Sciences et Industries Spatiales 5/6, 1965, pp.63-68.
18. Aia, M.A. J.E.C.S., Vol.113, 145-7 (1966); *ibid.* Vol.114, 418-23 (1967); and others.
19. Kober, F.P. J.E.C.S., Vol.112, 1064-67 (1965); and others.
20. Gillibrand, M.I.,
Wilde, B.E. *Thermodynamic Properties of Electrochemical Storage Cells.* *Electrochim. Acta*, Vol.9 (1964) 401-11.
21. Herold, R. *Battery Problems Considered from the Point of View of Sintered Plate Nickel Cadmium Cells Technique.* Paper 4 in *Second International Symposium on Batteries*, 1960, Bournemouth, England.
22. Leisenring, J.G.,
Binckley, W.G. *Study and Analysis of Satellite Power Systems Configurations for Maximum Utilization of Power; Phase I.* Technical Report, NASA Contract NAS 5-9178, 1966. (TRW Systems), pp.5-9 to 5-14, 5-53 to 5-72, 6-7 to 6-12, 7-9 to 7-12, A-1 to A-5.
23. Catotti, A.J.,
Read, M.D. *Development of a Nickel Cadmium Storage Cell Immune to Damage for Overdischarge and Overcharge.* NASA CR-62019, 1965.
24. Hennigan, T.J. *Separator Materials for Silver Oxide Zinc and Silver Oxide Cadmium Electrochemical Cells.* NASA X-716-65-331, 1965.
25. McClure, C.F. *Battery Separator Mechanisms.* Literature Survey Report, 1966, NOLTR 64-136.
26. Cooper, J.E.,
Fleischer, A.
editors *Characteristics of Separators for Alkaline Silver Oxide Zinc Secondary Batteries.* US Air Force Aero Propulsion Laboratory, Dayton, Ohio, 1964.

27. Findl, E.,
Klein, M. *Electrolytic Regenerative Hydrogen-Oxygen Fuel Cell Battery.*
Proceedings 20th Annual Power Sources Conference, 1966,
pp. 49-52.

28. Banes, R.S.,
Uchiyama, A.A. *System Aspects in the Design of Primary Batteries for
Spacecraft Application, in Background Material for the Study
of the National Space Power Program.* Power Information
Center PIC 120/1, 1964.

29. Bomberger, D.C.,
et al. *The Spacecraft Power Supply System.* Bell System Tech. J.,
1963, pp. 943-972 (NASA SP-32, Vol. 1, 1963).

- Bomberger, D.C.,
 Moose, L.F. *Nickel-Cadmium Cells for the Spacecraft Battery.* Ibid, 1963,
pp. 1687-1702 (NASA SP-32, Vol. 3, 1963).

30. - *Manned Mission Photovoltaic Power Supply Study.* NASA Contract
NAS 9-5266, 1967, RCA Report No. AED-R-3155, Vol. II, pp. x-111
x-145.

31. Stafford, G.B.,
Mahefkey, E.T., Jr *Hybrid Fuel Cell - Solar Cell Space Power Subsystem Capability.*
US Air Force Report APL-TDR-64-111, 1964, 39 pp.

32. Desai, R.R. *A Digital Program for Designing Minimum Weight Fuel Cell Power
Systems.* Allis-Chalmers report on NASA Contract NAS 8-5392,
1965.

- Desai, R.R.,
 et al. *Study of Energy Conversion Systems.* Summary Report on
Contract NAS 8-5392, 1965, 116 pp.

33. For details see
P.F. Greiger *Evaluation of Auxiliary Electrode Materials,* 19th Annual
Power Sources Conference, 1965, pp. 58-62.

34. Carson, W.N., Jr *Auxiliary Electrode for Charge Control.* 18th Annual Power
Sources Conference, 1964, pp. 59-61, H.N. Seiger et al., The
Adhydrode in Charge Control, *ibid.*, pp. 61-64.

35. Catotti, A.J.,
Read, M.D. *Auxiliary Electrodes for Overcharge and Overdischarge Control.*
19th Annual Power Sources Conference. 1965, pp. 63-66.

36. Sproull, R.L. *Federal Support of Science and Technology, in Science and
Society.* Xerox Corp., 1965, pp. 38-39.

TABLE 1A

Thermodynamics of Metal-Oxygen Reactions

<i>Reaction</i>	ΔH_{298}° cal/g mole of Fuel	ΔG_{298}° cal/g mole of Fuel	$\Delta G^{\circ}/\Delta H^{\circ}$, Maximum Efficiency	ΔH_{298}° kcal/kg, Fuel Only	ΔH_{298}° Btu/lb, Fuel Only	ΔH_{298}° W-hr/lb, Fuel Only	No. of electrons transferred/ reaction	$E^{\circ} = \frac{\Delta G^{\circ}}{nF}$
$2\text{Na} + \frac{1}{2}\text{O}_2 \rightarrow \text{Na}_2\text{O}(\text{C})$	-99,400	-90,000	0.90543	-2162	-3891	-1140	2	1.9520
$2\text{K} + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{K}_2\text{O}(\text{C})$	-86,400	-76,282	0.88288	-1105	-1989	-583	2	1.6544
$2\text{Li} + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{Li}_2\text{O}(\text{C})$	-142,400	-133,684	0.93879	-10,261	-18,470	-5412	2	2.8994
$\text{Pb} + \frac{1}{2}\text{O}_2 \rightarrow \text{PbO}(\text{red})$	-52,400	-45,250	0.86354	-253	-455	-133	2	0.9814
$\text{Pb} + \frac{1}{2}\text{O}_2 \rightarrow \text{PbO}(\text{yellow})$	-52,020	-45,050	0.86518	-251	-452	-133	2	0.9770
$3\text{Pb} + 2\text{O}_2 \rightarrow \text{Pb}_3\text{O}_4$	-175,600	-147,600	0.84055	-283	-509	-149	8	0.7334
$\text{Pb} + \text{O}_2(\text{g}) \rightarrow \text{PbO}_2$	-66,120	-53,559	0.81002	-319	-575	-168	4	0.5808
$2\text{Cs} + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{Cs}_2\text{O}(\text{C})$	-75,900	-66,977	0.85609	-286	-514	-151	2	1.4092
$\text{Be} + \frac{1}{2}\text{O}_2 \rightarrow \text{BeO}(\text{C})$	-146,000	-139,000	0.95205	-16,003	-28,805	-8440	2	3.0147
$\text{Mg} + \frac{1}{2}\text{O}_2 \rightarrow \text{MgO}(\text{C})$	-143,840	-136,130	0.91460	-5916	-10,650	-3121	2	2.9525
$\text{Ca} + \frac{1}{2}\text{O}_2 \rightarrow \text{CaO}(\text{C})$	-151,900	-143,400	0.94429	-3789	-6820	-1998	2	3.1080
$2\text{Al} + \frac{3}{2}\text{O}_2 \rightarrow \text{Al}_2\text{O}_3(\text{C})$	-399,090	-376,700	0.94411	-7395	-13,312	-3901	6	2.7220
$\text{Zn} + \text{O}_2 \rightarrow \text{ZnO}(\text{C})$	-83,170	-76,050	0.91439	-1272	-2290	-671	2	1.6483

TABLE 1B

Thermodynamics of Hydrogen Compound- and Carbon-Oxygen Reactions

Reaction	ΔH_{298}° cal/g mole of Fuel	ΔH_{298}° cal/g mole of Fuel	$\Delta G^{\circ}/\Delta H^{\circ}$, Maximum Efficiency	ΔH_{298}° kcal/kg, Fuel Only	ΔH_{298}° Btu/lb, Fuel Only	ΔH_{298}° W-hr/lb, Fuel Only	No. of electrons transferred/ reaction	$E^{\circ} = \frac{\Delta G^{\circ}}{nF}$
$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$	-68,320	-56,690	0.830	-33,889	-61,003	-17,875	2	1.2295
$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g)$	-57,800	-54,640	0.945	-28,672	-51,610	-15,123	2	1.1850
$NH_3(g) + \frac{3}{4}O_2(g) \rightarrow \frac{1}{2}N_2 + 3H_2O(l)$	-91,190	-81,090	0.887	-5369	-9665	-2832	3	1.1725
$NH_3(g) + \frac{3}{4}O_2(g) \rightarrow \frac{1}{2}N_2(g) + 3H_2O(g)$	-75,660	-77,985	1.031	-4443	-7997	-2343	3	1.1275
$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2(g) + 2H_2O(l)$	-173,670	-167,910	0.967	-5420	-9757	-2859	6	1.2139
$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2(g) + 2H_2O(g)$	-152,630	-163,810	1.106	-4764	-8575	-2513	6	1.1842
$N_2H_4 + O_2 \rightarrow N_2 + 2H_2O(g)$	-144,795	-149,000	1.029	-4518	-8132	-2383	4	1.6158
$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O(l)$	-530,610	-503,926	0.950	-12,035	-21,662	-6348	20	1.0929
$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O(g)$	-488,530	-495,726	1.015	-11,093	-19,967	-5851	20	1.0751
Natural gas + $O_2 \rightarrow CO_2 + H_2O(l)$	-232,487	-215,728	0.928	-13,132	-23,638	-6926		-
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(l)$	-212,798	-196,500	0.923	-13,264	-23,876	-6996	8	1.0654
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(g)$	-191,761	-191,400	0.998	-11,915	-21,519	-6306	8	1.0377
$C_2H_6 + \frac{1}{2}O_2 \rightarrow 2CO_2 + 3H_2O(l)$	-372,824	-350,731	0.941	-12,399	-22,317	-6539	14	1.0869
$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O(g)$	-341,264	-344,580	1.010	-11,349	-20,428	-5986	14	1.0676
$C + O_2 \rightarrow CO_2$	-94,050	-94,260	1.002	-7831	-14,096	-4130	4	1.3787

TABLE 1C

Thermodynamics of Alkali- and Alkaline Earth-Halogen Reactions

<i>Reaction</i>	ΔH_{298}° cal/g mole (Product)	ΔG_{298}° cal/g mole (Product)	$\Delta G^{\circ}/\Delta H^{\circ}$, Maximum Efficiency	ΔH_{298}° kcal/kg (Metal + Oxidizer)	ΔH_{298}° Btu/lb (Metal + Oxidizer)	ΔH_{298}° W-hr/lb (Metal + Oxidizer)	No. of electrons transferred/ reaction	$E^{\circ} = \frac{\Delta G^{\circ}}{n\mathcal{F}}$ (volts)
$\text{Li} + \frac{1}{2}\text{F}_2 \rightarrow \text{LiF}$	-146,300	-139,500	0.9535	-5640	-10,132	-2969	1	6.0512
$\text{Li} + \frac{1}{2}\text{Cl}_2 \rightarrow \text{LiCl}$	97,700	-102,000	1.04401	-2406	-4330	1269	1	4.4217
$\text{Na} + \frac{1}{2}\text{F}_2 \rightarrow \text{NaF}$	-136,000	-129,300	0.95073	-3239	-5830	-1708	1	5.6087
$\text{Na} + \frac{1}{2}\text{Cl}_2 \rightarrow \text{NaCl}$	-98,230	-91,790	0.93443	-1681	-3025	-887	1	3.9817
$\text{K} + \frac{1}{2}\text{F}_2 \rightarrow \text{KF}$	-134,460	-127,420	0.94764	-2314	-4165	-1221	1	5.5272
$\text{K} + \frac{1}{2}\text{Cl}_2 \rightarrow \text{KCl}$	-104,180	-97,592	0.93676	-1397	-2515	-737	1	4.2333
$\text{K} + \frac{1}{2}\text{Br}_2 \rightarrow \text{KBr}$	-93,730	-90,630	0.96692	-788	-1418	-415	1	3.9314
$\text{K} + \frac{1}{2}\text{I}_2 \rightarrow \text{KI}$	-78,310	-77,030	0.98365	-472	-849	-249	1	3.3413
$\text{Ca} + \text{F}_2 \rightarrow \text{CaF}_2$	-290,300	-277,700	0.95659	-3718	-6694	-1961	2	6.0230
$\text{Ca} + \text{Cl}_2 \rightarrow \text{CaCl}_2$	-190,000	-179,300	0.94368	-1712	-3082	-903	2	3.8888
$\text{Ca} + \text{Br}_2 \rightarrow \text{CaBr}_2$	-161,300	-156,800	0.97210	-807	-1452	-426	2	3.4008
$\text{Ca} + \text{I}_2 \rightarrow \text{CaI}_2$	-127,800	-126,600	0.99061	-484	-872	-255	2	2.7458
$2\text{Al} + 3\text{Cl}_2 \rightarrow 2\text{AlCl}_3$	-166,200	-152,200	0.91576	-1246	-2244	-657	3	2.1986
$\text{Mg} + \text{F}_2 \rightarrow \text{MgF}_2$	-263,500	-250,800	0.95180	-4229	-7612	-2230	2	5.4361
$\frac{1}{2}\text{H}_2 + \frac{1}{2}\text{Cl}_2 \rightarrow \text{HCl (g)}$	-22,060	-22,700	1.02900	-605	-1089	-319	1	0.9840

TABLE 2

Thermodynamics and Energy-Density Estimates of Some Common Batteries

<i>Cell</i>	<i>Material</i>	<i>Theoretical watt hr/lb</i>	<i>Actual watt hr/lb</i>
Lead Acid	$\text{Pb}/\text{H}_2\text{SO}_4/\text{PbO}_2$	74	20 - 30
Nickel-Cadmium	$\text{Cd}/\text{KOH}/\text{NiOOH}$	96	12 - 25
Le Clanché (Common Dry Cell)	$\text{Zn}/\text{NH}_4\text{Cl}/\text{MnO}_2$	153	2 - 30
Mercury	$\text{Zn}/\text{KOH}/\text{HgO}$	116	25 - 50
Alkaline Dry Cell	$\text{Zn}/\text{NaOH}/\text{MnO}_2$	149	15 - 35
Edison Air Cell	$\text{Zn}/\text{KOH}/\text{O}_2$	420	10 - 50
Lalande	$\text{Zn}/\text{NaOH}/\text{CuO}$	109	6 - 20
Magnesium Dry Cell	$\text{Mg}/\text{MgBr}_2/\text{MnO}_2$	247	25 - 45
Silver-Zinc	$\text{Zn}/\text{KOH}/\text{AgO}$	193	25 - 100
Silver-Cadmium	$\text{Cd}/\text{KOH}/\text{AgO}$	113	11 - 50
Magnesium-Chlorine	$\text{Mg}/\text{MgCl}_2/\text{Cl}_2$	954	-
Sodium-Chlorine	$\text{Na}/\text{NaCl}/\text{Cl}_2$	849	-
Aluminum-Fluorine	$\text{Al}/\text{Na}_3\text{AlF}_6/\text{F}_2$	1940	-
Lithium-Fluorine	$\text{Li}/\text{?}/\text{F}_2$	2760	-

TABLE 3

Approximate Thermal Efficiencies of Today's H_2 - O_2 Fuel Cells

	<i>Efficiency, %</i>
Ideal voltage, 1.23 V	83
Working voltage, 1.09 V	68
0.9 V	61
0.8 V	54

TABLE 4
Factors Controlling Battery Performance (M_w)

<i>F. of M. Term</i>	<i>Positive Plate</i>	<i>Interface</i>	<i>Electrolyte</i>	<i>Interface</i>	<i>Negative Plate</i>	<i>Accessories</i>
Q_0	1. Plate loading	1. Oxidation potential 2. Rate of electron transfer 3. Number of electrons transferred per molecule	1. Decomposition potential 2. Electrolyte Stoichiometry	1. Reduction potential 2. Rate of electron transfer 3. Number of electrons transferred per molecule	1. Plate loading	
K_1	2. Availability of active material for discharge: pore structure, surface area, thickness of plate, solubility, forming procedures 3. Conductivity of plate, depolarizer, binder; variations in conductivity with dimensions of plate and progress of discharge 4. Changes in physical properties on wet stand, e.g. loss of surface area from recrystallization 5. Spontaneous decomposition on dry stand; loss of adherence to grid 6. Thermal stability	4. Mass transport of reactants into and out of the interface, through a film of product 5. Corrosion and solubility 6. Oxidation of separator 7. Effect of temperature on reaction kinetics 8. Adsorption of impurities onto surface from electrolyte 9. Surface morphology	3. Mass transport across electrolyte; concentration gradients 4. Ionic conductivity and variation with the progress of discharge 5. Chemical stability of the separator 6. Degradation on cycling 7. Thermal stability of solvent, solute, and separator 8. Effect of temperature 9. Surface morphology	4. Mass transport of reactants into and out of bulk electrolyte, through a film of product, soluble or insoluble 5. Corrosion and solubility 6. Penetration of separator by dendrites 7. Effect of temperature on reaction kinetics 8. Adsorption of impurities onto surface from electrolyte 9. Surface morphology	2. Availability of active material for discharge (see item 2-positives) 3. Conductivity of the plate and the variations with plate dimensions and progress of discharge 4. Changes in plate on wet stand and operation, e.g. dendrite growth and recrystallization 5. Oxidation on dry stand; loss of adherence to grid 6. Thermal stability of active material	
K_2	7. Weight and extent of grid and support structure; quantity of conductive binder to provide mechanical stability and minimal ohmic loss		9. Extent of separator systems to prevent diffusion of reactants and products out of electrode cavities 10. Weight and volume of electrolyte		7. Weight and extent of grid or support structure for mechanical stability and minimal ohmic loss	1. Weight of container, leads 2. Activitating mechanisms for reserve batteries 3. Gas recombination or venting 4. Sealing mechanisms 5. Recharging equipment 6. Heat sinks, radiators, heaters

TABLE 5

High Energy Density Electrode Couples

<i>Reaction</i>	<i>Equiv. Weight (g/equiv)</i>	<i>Capacity amp-hr/gr</i>	<i>- F° of Reaction (kcal/mole)</i>	<i>E° (volts)</i>	<i>Energy Density (W hr/lb)</i>
$2\text{Li} + \text{CuF}_2 \rightarrow 2\text{LiF} + \text{Cu}$	57.6	0.465	163.2	3.55	749
$2\text{Li} + \text{CuCl}_2 \rightarrow 2\text{LiCl} + \text{Cu}$	74.2	0.362	141.4	3.07	503
$2\text{Li} + \text{NiF}_2 \rightarrow 2\text{LiF} + \text{Ni}$	55.5	0.483	130.4	2.83	620
$2\text{Li} + \text{NiCl}_2 \rightarrow 2\text{LiCl} + \text{Ni}$	71.5	0.375	118.3	2.57	437
$2\text{Li} + \text{AgF}_2 \rightarrow 2\text{LiF} + \text{Ag}$	79.9	0.336	238	5.16	786
$\text{Li} + \text{AgF} \rightarrow \text{LiF} + \text{Ag}$	133.8	0.200	95.3	4.14	375
$\text{Li} + \text{AgCl} \rightarrow \text{LiCl} + \text{Ag}$	150	0.178	65.5	2.84	229
$2\text{Li} + \frac{1}{2}\text{O}_2 \rightarrow \text{Li}_2\text{O}$	15.0	1.78	133.9	2.91	2365
$\text{Ca} + \text{CuF}_2 \rightarrow \text{CaF}_2 + \text{Cu}$	70.7	0.38	161.7	3.51	604
$\text{Mg} + \text{CuF}_2 \rightarrow \text{MgF}_2 + \text{Cu}$	62.7	0.427	134.8	2.92	566

TABLE 6

Solvent Properties

<i>Solvent</i>	<i>Dielectric Constant</i>	<i>Viscosity (Centipoise)</i>	<i>Melting Point °C</i>	<i>Boiling Point °C</i>
Propylene Carbonate (PC)	64.4	2.2	-49	242
γ -Butyrolactone (BL)	39	1.67	-4	206
Dimethylsulfoxide (DMSO)	48	1.93	6	189
Nitromethane (NM)	39.4	0.619	-29	101
Acetonitrile (AN)	38.8	0.36	-42	82
N,N-Dimethylformamide (DMF)	36.7	0.633	-61	153
Methylformate (MF)	8.5	0.330	-99	+31
N-Nitrosodimethylamine (NDA)	53.0	0.865	-	153
Ethylene Carbonate (EC)	89	1.9	36	248
Dimethyl Carbonate (DMC)	15	0.60	1	90
Formamide (FM)	111.5	3.76	3	211
2-Pentanone	22	0.47	-78	102
Cyclohexanone	18	2.8	-16	156
Methyl Acetate	7.2	0.41	-98	57

TABLE 7
Characteristics of Individual Cells

	<i>Goals</i>				
	<i>Gemini</i>	<i>Apollo</i>	<i>Allis-Chalmers</i>	<i>1975</i>	<i>Long Term</i>
Current density, A/ft ² ($\simeq$ mA/cm ²)	15	92	100	200	400
Initial voltage, volt	0.8	0.97	0.95	1.0	1.1
Power density, W/ft ² ($\simeq$ mW/cm ²)	12	89	95	200	440
Active cell area, ft ² ($\simeq$ 0.1 m ²)	0.375	0.4	0.2	—	—
Cell power, watts	4.5	35.6	19	—	—
Reactant consumption, lb/kW ($\simeq$ 0.45 kg/kW)	0.9	0.8	0.8	0.76	0.7
Degradation rate, mV/1000 hr	50–100	60	40	4	< 4
Principal degradation mode	membrane decomposes	cathode corrodes	asbestos reacts		

NOTE: Data are for sustained, not peak, power.

TABLE 8
Characteristics of Fuel-Cell Modules

	<i>Goals</i>				
	<i>Gemini</i>	<i>Apollo</i>	<i>Allis-Chalmers</i>	<i>1975</i>	<i>Long Term</i>
Module size, kW (sustained power)	0.5	1	1	2.5–5	5–10
Module weight, lb/kW ($\simeq$ 0.45 kg/kW)	140 ^a	268	165	< 70	< 30
Module volume, ft ³ /kW ($\simeq$ 28.3 l/kW)	6	10.7	5.7	—	—
Stack volume, ft ³ /kW ($\simeq$ 28.3 l/kW)		4.75	2	< 0.9	< 0.35
Parasitic power, W/module	0 ^a	75 ^b	50 ^c	< 50	< 50
Life under load, hr	400–800	400–1500	1000–2000	10,000	10,000+
Storage at room temperature and below	good ^d	good ^e	good	wide temp. range	
Heating time, room to operating temp., min	0 ^a	60	15–30	< 15	< 15
Auxiliary heater, kW	0	3	0	0	0
Recovery from abuse	poor	poor	good	broad tolerance	

NOTE: (a) Integration of the fuel-cell and environmental control systems complicate these estimates; a separate power system would have weighed more and required parasitic power.

(b) This is alternating current and does not reflect losses in power conditioning.

(c) This is the total power drawn from the d.c. supply.

(d) This is before activation; once activated, the stored system degrades by 0.2–0.7 volt/1000 hr.

(e) System stores well even up to 200°F (94°C).

Fig.1 Night flights - Mid-November 1870

Fig.2 First airborne electric system

Fig. 3 Typical discharge curves for a 0.20 cu-in alkaline-mercuric oxide-zinc cell

Fig. 4 Discharge of a zinc-silver oxide cell

Fig.5 Long-lived thermal cell

Fig.6 Reinforced battery plate

Fig.7 Features of the dry tape battery

Fig.8 Basic fuel cell

Fig.9 Components of fuel-cell system

Fig.10 Solid polymer electrolyte fuel cell

Fig. 11 Gemini fuel battery (simplified schematic)

Fig.12 Gemini fuel cell

Fig.13 Closed cycle Powercel system

Fig. 14 Modified Bacon cell

Fig. 15 Fuel cell construction using static moisture removal system

Fig.16 Asbestos fuel-cell system

Fig. 17 Non-uniformity of fuel cells

Fig. 18 Discharge of new NiCd cell

Fig. 19 Discharge of "memorized" NiCd cell

Fig. 20 Battery system design factors

Fig. 21 Hybrid and conventional power system comparison

NOTE:

- 3 MODULE SYSTEM
- 32 SECTION MODULES

Fig. 22 System electrical performance

NOTE:

- 3 MODULE SYSTEM
- 32 SECTION MODULES

Fig. 23 System reactant consumption

Fig. 24 Nomogram for approximating minimum weight of H_2-O_2 fuel-cell system

Fig. 25 Dry tape battery cathodes

Fig. 26 G.E. battery/fuel-cell system

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VII. PHOTOVOLTAIC DEVICES AND SYSTEMS

by

M. Rodot* and H. Daspet†

*Directeur de Recherches,
Laboratoire de Magnétisme et de Physique du Solide,
Centre National de la Recherche Scientifique,
92 Meudon-Bellevue, France

†Ingénieur de Recherches,
Direction des Programmes et du Plan,
Centre National d'Etudes Spatiales,
91 Brétigny-sur-Orge, France

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VII. PHOTOVOLTAIC DEVICES AND SYSTEMS

M. Rodot and H. Daspet

1. OUTLINE OF NATURE OF SOLAR RADIATION

1.1 The Radiation Emitted by the Sun

Electromagnetic radiations and particles are both emitted by the sun.

1.1.1 Electromagnetic Radiations

These radiations extend from X-Rays to far-infrared wavelengths. Figure 1 illustrates the wavelength dependence of the solar irradiance, as determined by the Smithsonian Institute. It is not very different from a blackbody distribution at 6000°K; however the spectrum is cut-off on the ultra-violet side and lies below the 6000°K curve in the infrared. The ultra-violet spectrum is complex but its intensity is low (of order 10^{-5} W/cm²μ). The energy distribution in various ranges is given by Table I.

The *solar constant* is defined as the quantity of solar energy received by 1 cm² at normal incidence outside the atmosphere at the mean sun-earth distance. It is nearly constant although variations of ± 1% occur in relation with the presence of sunspots. There is also a small variation (< 0.5%) during the year, with generally a minimum in July and a maximum in January. The absolute value of the solar constant is known with an accuracy of 2%:

$$G_0 = 139.5 \text{ mW/cm}^2 \pm 2\% .$$

A value of 140 mW/cm² is currently used.

In the solar system, the energy received by 1 cm² varies as the inverse-squared distance from the sun, as shown by Table II.

1.1.2 Particle Radiation

In addition to the steady-state electromagnetic radiation, the sun emits high energy particles (protons and electrons). The flux of particles varies with time according to an 11-year law (solar flares). The energy of the protons lies between 1 keV and 500 MeV. Typically 10⁴ protons/cm²s are emitted in connection with a major flare, and they may be accompanied by 10⁷ to 10⁸ electrons/cm²s.

The solar emitted particles, as well as the galactic radiation (cosmic rays), are at the origin of the particle belts around the earth. These consist of trapped electrons and protons, with a repartition which will be found in other reviews*.

1.2 Influence of Atmosphere

1.2.1 Definition of Air Mass

Due to the atmosphere absorption, a part of the solar electromagnetic flux is absorbed before reaching earth's surface. The zenith distance z of the sun is its angular distance

* e.g. Cooley and Janda, *Handbook of Space-Radiation Effects on Solar-Cell Power Systems*. NASA SP 3003.

from the zenith in the vertical circle containing the zenith, the nadir and the sun. The amount of absorption of solar radiation will depend on the length of its path in the atmosphere (and thus of the geometrical parameter z), on the mean density of the atmosphere (which can be described by the pressure p) and on the absorptivity of the atmosphere for each radiation. The two first factors may be combined in one parameter which is proportional to the mass of air contained in a tube of constant section around the path of radiation. This dimensionless parameter is called the *air mass* m (often written AM) and is defined by

$$m = \frac{p}{p_0} \frac{1}{\sin z}, \quad (1)$$

where p_0 is the normal sea-level pressure.

m is equal to 1 at sea-level when the sun is at the zenith. It tends to increase when the sun is low on the horizon until, for $z > 80^\circ$, formula (1) is no more valid due to refraction effects and the curvature of the earth. It tends to decrease at high altitudes due to the diminution of p . Note that formula (1) is valid when the absorbent molecules are homogeneously scattered in the atmosphere; exceptionally the effect of such absorbers as O_3 , which is localized on the upper part of the atmosphere, is not described by formula (1).

1.2.2 Effect on Solar Radiation

Assume that the absorption coefficient of the atmosphere for each wavelength λ is $\alpha(\lambda)$. Then the intensity of the radiation received at normal incidence on a site where the air mass is m is simply given by

$$G_{m\lambda} = G_{0\lambda} \exp - [m\alpha(\lambda)]. \quad (2)$$

Of course $\alpha(\lambda)$ depends on the composition of the atmosphere. In a clean atmosphere, the air molecules have characteristic absorption lines, so that the solar spectrum on the receptor is given by Figure 2a. The absorption is still stronger if the atmosphere is humid and turbid (Fig. 2b).

Figure 3 gives an illustration of the formula (2) for different radiations of the spectrum. Also shown by this figure is a *mean* variation of G_m with m for the whole solar spectrum. This curve M is *not* a straight line, because of the integration of $G_{m\lambda}$ on the entire range of wavelengths.

It can be seen, that, for $m = 1$, the intensity G is about 100 mW/cm^2 .

1.3 Solar Simulators

1.3.1 Need for Solar Simulators

In space technology, one is only interested in one sun, which is our sun, at least at the present state of space missions. While measurements of solar cell performances during orbiting outside the atmosphere, where they receive energy G_0 , are quite accurate*, on-earth measurements under the solar flux are hardly useful for testing the cells. Even if the AM of the test site were known, two factors may vary widely in an uncontrolled manner: the absorptivity $\alpha(\lambda)$ of the atmosphere and the amount of radiation diffused by the sky, which adds with direct radiation. As a result of intensity G may become much lower than 100 mW/cm^2 (for instance 30 to 90 mW/cm^2 in Paris at noon according to season and weather). Good measurements of solar cells under direct irradiation by the sun are very difficult and must be performed in specialized stations (see Section 3.2.2). For current measurements solar simulators are widely used.

* However it must be considered that the cells may receive also the solar energy diffused back by the earth (albedo flux) and the thermal energy radiated by the earth, cf. Delpont, Faugere and Philippon, *Calcul des puissances radiantes reçues par un satellite sur orbite terrestre*, CNES, Note technique No.6.

1.3.2 Solar Simulators

Small solar simulators (Spectrolab's models X-25 "Spectrosun" or A-9090; Aerospace Controls Type 302 H) generally use xenon or mercury-xenon arc lamps as primary sources. With a 2500 W lamp, collimated beams of section 15 to 30 cm² are obtained with intensities varying from 1/2 to more than 1 solar constant. With regulated power supplies, typical stability is $\pm 2\%$; uniformity is of order $\pm 5\%$. Spectral match is obtained by filters and is illustrated by Figure 4. Carbon arc lamps have also been used without filters to obtain a pretty well-fitted spectrum.

Large-size solar simulators reach up to 5 meters for the diameter of the collimated beam, with a uniformity of $\pm 10\%$.

Other special simulators may provide an intensity reaching 10 solar constants or more.

2. SOLAR PHOTOCELLS

2.1 Principle of Photocells

A solar photocell is a device in which (1) solar energy is absorbed and converted into potential energy of an electron gas, (2) this electron gas, drifting through a potential barrier, is the active fluid of a current generator.

The two tasks of absorption and collection of photoelectrons can be filled in one and the same device, using:

- as the absorber an adequate semiconductor,
- as the potential barrier an adequate physical discontinuity between two solid materials, one of which is the absorber.

The two main parts of this section (Sections 2.2 and 2.3) try to describe respectively semiconducting materials and collection mechanisms. In this introductory part (Section 2.1) we shall summarize the well-known theory of the simplest and mostly used solar photocell, the silicon cell. The purpose here is to put in evidence, in a well-known case, the factors affecting the conversion efficiency of the cell. But we must recall that the efficiency is not the only valuable criterion of performance: other ones will be discussed later (stability, specific weight and area, cost), and this will be the matter of the last part (Section 2.4) in which performances of actual photocells will be compared.

The solar spectrum (Fig.1) is such that solar photons have mean energies $h\nu$ of the order of some 10^{-12} ergs (the maximum of the curve is for $h\nu = 3 \times 10^{-12}$ ergs). As one-photon transitions in the absorber are the most probable, we need solids having two different electronic states distant of a few electron-volts ($1 \text{ eV} = 1.6 \times 10^{-12} \text{ erg}$). While several other absorption mechanisms could be envisaged, the most currently used is the transition of an electron from the valence to the conduction band (or the rupture of a valence bond) which requires for silicon the energy $E_0 = 1.1 \text{ eV}$ (Fig.5a).

One photon of energy larger than E_0 generates one electron-hole pair. If the silicon is n-type, the photoelectrons (majority carriers) have a concentration which is low compared to the electron equilibrium concentration. An exact theory shows indeed that the photoelectrons created in n-Si play a negligible part in the photocurrent. On the contrary in n-type Si the concentration of photo-holes (minority carriers) is high compared to the equilibrium hole concentration; these photo-holes can be collected by a p - n junction as shown in Figure 5b. In a Si p - n junction photocell, the total photocurrent is the sum of two contributions arising from the minority carriers created by the photons in each part of the device (Fig.5b).

2.1.1 Absorption Efficiency

A monochromatic radiation of energy $h\nu$ just higher than E_0 would be absorbed with an efficiency near 100% by a silicon plate of thickness l larger than $1/\alpha$ (where α is the absorption coefficient, in cm^{-1} , for radiation $h\nu$). But the solar spectrum has a large amount of radiation with energies higher and smaller than the silicon cut-off energy E_0 . Radiations of smaller energy (i.e. of wavelengths higher than 1.1 micron) are not absorbed, and this loss amounts to c.a. 25%. Radiations of higher energy ($\lambda < 1.1\mu$) are converted with a quantum efficiency equal to 1, i.e. produce one electron-hole pair per photon: then the energy ($h\nu - E_0$) is lost and, if integrated on the whole solar spectrum, this loss amounts to 30% for Si. The very energetic photons (ultra-violet) can indeed produce more than 1 pair/photon, due to impact ionization of valence electrons by high energy photocarriers; but due to their high absorption coefficient, these photons are absorbed just at the semiconductor surface, i.e. in a most perturbed zone where the collection efficiency will be low.

Finally, taking into account the fraction of useful photons which are not absorbed by the Si plate (either transmitted through the plate or reflected by its surface), the absorption efficiency is

$$\eta_a = \frac{E_0 \int_{E_0}^{\infty} (1 - R) e^{-\alpha l} G(h\nu) d(h\nu)}{\int_0^{\infty} h\nu G(h\nu) d(h\nu)}, \quad (3)$$

where $G(h\nu) d(h\nu)$ is the number of photons impinging on 1 cm^2 and having energy between $h\nu$ and $h\nu + d(h\nu)$, and R is the reflectivity, (about 30% for pure Si, R can be minimized to a few % only by surface treatments). The numerator may be written $E_0 N_L$, where N_L is the number of electron-hole pairs generated by cm^2 and by s. η_a is little dependent on the light intensity, it is worth c.a. 40% for silicon. N_L is proportional to the light flux; from the value of the solar constant and of E_0 , it follows that $N_L \simeq 6 \times 10^{17} \text{ cm}^{-2}$.

2.1.2 Collection Efficiency

2.1.2.1 Recombination Losses. Not all of the N_L minority carriers will reach the junction. $(1 - R)N_L$, where $R < 1$, are recombined before reaching it, by a mechanism inverse of the absorption (or by different mechanisms). The maximum photocurrent of a 1 cm^2 cell is called the short-circuit current:

$$I_{sc} = I_L = R q N_L \quad (q = 1.6 \times 10^{-19} \text{ coulomb}). \quad (4)$$

The factor R depends on the values of the minority carrier diffusion lengths L_n and L_p . L_p is the mean distance that holes can travel in n-type Si before recombining. It is related to the hole mobility μ_p and lifetime τ_p by the formula

$$L_p = (D_p \tau_p)^{\frac{1}{2}}; \quad D_p = \frac{kT}{q} \mu_p. \quad (5)$$

(k = Boltzmann constant, T = temperature in $^{\circ}\text{K}$, D_p is called the diffusion constant). The lifetimes τ_n and τ_p (mean free time between two recombination events) are controlled by impurities as will be discussed further, and are worth between 10^{-7} and 10^{-4} s in silicon. For the quality of silicon generally used in solar cells, this leads to diffusion lengths of the order of some microns. In these conditions the factor R is typically 0.9, and the short-circuit current, according to formula (4), is then 43 A/cm^2 : this is in excellent agreement with experiment.

2.1.2.2 *Open-Circuit Voltage.* The solar cell is usually described (Fig.6) as a current generator I_L , shunted by a diode which behaves as the cell in the dark. The relation between the voltage at the terminals of the device and the current through it is:

$$I = I_L - I_0 \exp \left[\frac{q(V - IR_s)}{\lambda kT} - I \right] + \frac{V - IR_s}{R_{sh}}. \quad (6)$$

This formula is valid for "ideal" diodes (see Shockley's classical theory) in which the coefficient λ has a value equal to 1 and I_0 is the saturation current,

$$I_0 = qn_i^2 \left(\frac{D_p}{L_p n} + \frac{D_n}{L_n p} \right). \quad (7)$$

Here n and p are the majority carrier concentrations in the two regions (n-type and p-type) respectively, and n_i is the intrinsic carrier concentration in silicon. For silicon I_0 is near 10^{-12} A/cm². In silicon photocells, the shunt-resistance R_{sh} is infinite and the series-resistance R_s is negligible, so that:

$$V = \frac{\lambda kT}{q} \log_e \left(1 + \frac{I_L - I}{I_0} \right). \quad (8)$$

In this approximation, the open circuit voltage can be written as

$$V_{oc} = \frac{\lambda kT}{q} \log_e \left(1 + \frac{I_L}{I_0} \right). \quad (9)$$

With $I_0 = 10^{-12}$ A/cm², $kT/q = 0.025$ volt and $I_L = 4.3 \times 10^{-2}$ A/cm² for solar light, and assuming that $\lambda = 1$, we find $V_{oc} = 0.6$ volt.

This value is in fair agreement with experiment; however the above derivation of V_{oc} is far from convincing, because real photocells are not ideal diodes. The coefficient λ has two reasons for being larger than 1: the physical origin of the inverse current (which is not only Shockley's diffusion current) and the large area of the diodes*. Not only real photocells exhibit λ 's of the order of 3, rather than 1, but even the inverse dark current is not a constant I_0 , as implied by formula (8).

Nevertheless this order-of-magnitude calculation has a certain interest. Firstly it shows that V_{oc} is much lower than E_0/q : the maximum voltage output is thus only a part of the potential difference between electrons and holes in silicon, which implies a partial efficiency of the order of $qV_{oc}/E_0 \simeq 0.6/1.1 = 56\%$. This value of 44% for the "voltage losses" is very high indeed. Secondly, from formula (9), the dependence of V_{oc} on light intensity G is logarithmic (as I_L is proportional to G according to formula (4)). This turns out to be the correct behaviour of real cells. However it must be noted that this logarithmic law is valid only for small light intensities. V_{oc} cannot increase infinitely with G . From Figure 7, which represents the band scheme in the dark and under light, it can be seen that qV_{oc} is limited to E_B/q , where E_B is the barrier height of Figure 5, and that E_B has a value given by the difference of the Fermi levels (in the dark) in n-Si and p-Si:

$$E_B = \zeta' - \zeta. \quad (10)$$

As it is known that, in the n-region,

$$n = N_c \exp \left(-\frac{\zeta}{kT} \right) \quad (11)$$

* See the discussion by Y. Marfaing, Solid State Electr. 7, pp.1-16, 1966.

and similarly in the p-region

$$p = N_v \exp \frac{-E_0 + \zeta'}{kT}, \quad (12)$$

where N_c and N_v are the density-of-states effective masses, one finds for silicon, taking $n = 10^{18} \text{ cm}^{-3}$ and $p = 10^{15} \text{ cm}^{-3}$: $E_B = 0.8 \text{ eV}$. So the value expected for V_{oc} in the limit of infinite light flux is 0.8 volt for the above doping of n and p -Si.

We have given this long discussion of V_{oc} in Si-cells only in order to suggest that one of the major problems in building new types of solar cells is to maximise the barrier height E_B , and then to obtain with solar flux a potential difference approaching E_B/q as much as possible.

A complementary approach of this problem will be given in Section 2.3: there, the semiconductor will be supposed pure enough for the photocarriers to be more numerous than both the majority and minority equilibrium carriers in the dark. This "photoconductor" approximation leads to formulae which are more general than the preceding ones, and which cover the high light flux case.

2.1.2.3 Curve-Factor. Having values of I_{sc} and V_{oc} , we must now realize that the cell cannot be simultaneously in conditions of short-circuit (maximum current) and open-circuit (maximum voltage). The real I and V in the exterior charge are classically given (Fig.8) by the intersection of the V - I characteristic of the cell with the load-line $V = RI$, where R is the resistance of the load. The "curve factor"

$$f_c = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (13)$$

is an important element of the efficiency, generally of the order 85%-90%. It depends on the series-resistance R_s , which is the slope of the characteristic at the point V_{oc} , and which must be kept small. By this factor the Joule losses inside the cell itself are also taken into account. Finally the collection efficiency is:

$$\eta_c = \frac{V_m I_m}{E_0 N_1} = \mathcal{R} \frac{qV_{oc}}{E_0} f_c. \quad (14)$$

For silicon η_c is of the order of 45%.

2.1.3 Total Efficiency

For silicon, the total efficiency

$$\eta = \eta_a \eta_c \quad (15)$$

is of the order of $0.40 \times 0.45 = 18\%$. This is only a rough approximation, as can be seen from the above derivation of η_c . The maximum practical efficiency which has been measured with Si-cells is about 15% for air-mass 1 which is not far from the above theoretical value. This means that the technology of Si is well in hand.

It should be observed that no Carnot efficiency appears in η . Nowhere in the conversion cycle appears an increase of the kinetic energy of a fluid. Indeed the photocells may be opposed to thermoelectric devices, which also use semiconductors. In the latter, the solar energy is used to create an e.m.f. in a conducting medium, so as to put the electrons into move. In the former, the solar energy is used to create electrons in an insulating medium where pre-exists an e.m.f. due to a built-in heterogeneity. If a semiconductor is to be chosen in both cases, it is because of the necessity of maximising the output-power, and not the voltage or current separately. However the thermoelements turn out to be more heavily doped than the photoelements.

Figure 9 shows how the theoretical efficiency η depends on bandgap E_0 .

2.2 Semiconducting Materials

Silicon is not the only material that can be used in solar cells. While the first silicon cells with 6% efficiency were available in 1954, as early as 1957 extensive researches were devoted to thin-film photocells using materials with larger band gaps E_0 than Si. The initial purpose was to better approach the optimum E_0 , which turns out to be 1.4 to 1.6 eV. Roughly speaking, when E_0 increases I_{sc} decreases because a smaller part of the solar spectrum is converted, while V_{oc} increases because I_0 tends to decrease. The curves of Figure 9 were calculated by Halsted, Loferski and others and show that materials such as InP, GaAs, CdTe match the solar spectrum better than Si. Indeed valuable solar cells have now been obtained with all these materials, as well as with Si and CdS, and some of them will be described further.

Now it turned out that the main interest of semiconducting compounds was not the optimization of E_0 , but the possibility to build efficient thin film cells: this allows an important reduction of the weight of solar cells and should also allow a drastic reduction of their cost if mass-production became technically and economically possible. This will be discussed in Sections 2.4.3 and 2.4.4.

A full discussion of the properties of semiconducting materials should lead to an understanding of the mechanisms involved in the absorption of light and in the diffusion and recombination of charge carriers. A second reason for such a discussion is to put in evidence the importance of defects and impurities, which influence not only these mechanisms, but also the stability of photocells and their sensitivity to ionizing radiations.

2.2.1 Absorption and Band Structure

For the most important materials the energy gap E_0 has, at 300°K, the values given in Table III. The electron transition from the valence to the conduction band may be direct (i.e. conserve the wave vector): α is then very high for all photons $h\nu > E_0$ (GaAs, InP, CdTe). This transition may also imply the simultaneous absorption or emission of a photon (Si, AlSb, GaP): then α is low in a large spectral band. Figure 10 illustrates this difference. It can be shown that $\alpha \propto (h\nu - E_0)^2$ for direct transitions while $\alpha \propto (h\nu - E_0)^2$ for indirect transitions. The result is that a much thicker plate is needed to absorb 90% of the photons $h\nu > E_0$, in the case of indirect transitions: no thin-film cells can be built with such materials.

In all these materials, the absorption of photons is an intrinsic property of the crystal. The imperfections have several secondary effects (which become important in the case of CdS). They bring narrow absorption bands in the infrared; when this concentration is over 10^{19} cm^{-3} , they change the value of the absorption edge. This results from two contradictory effects: the displacement of the Fermi level inside the band, especially in materials with low effective masses, such as n - GaAs, and the decrease of E_0 due to an impurity band overlapping a band of the perfect crystal.

CdS behaves anomalously: it may have a large absorption band of low intensity for $h\nu < \Delta E$, because of direct electronic transitions using impurity levels. Photoelectric effects are associated with such transitions*; their intensity depends on the relative position of the Fermi level and the impurity levels, which may explain some peculiarities of the spectral photovoltaic response of CdS solar cells, (see below, Section 2.4.2).

Another property, related to the value of E_0 , has some bearing on the properties of photocells: it is the electronic affinity χ . Figure 11 shows the band scheme near the surface of a semiconductor: χ is the energy difference between electrons at the surface and in vacuum. V_p is called the surface potential and ϕ is the work function. The energy Φ may be directly measured (threshold of the external photoelectric effect). Values of qV_p and χ for clean surfaces are indicated in Table IV.

* H. Palz and W. Ruppel, Phys. Stat. Sol. 15 p.649, 1966.

2.2.2 Diffusion and Recombination of Charge Carriers

Table IV gives the best carrier mobilities for different materials in single crystal state. An order of magnitude of carrier lifetimes is also given. Generally the capture cross sections of a given impurity for electrons and holes are different, so that, if this impurity controls the recombination, the lifetimes of majority and minority carriers will be quite different: this is known as trapping. Only in silicon these capture cross sections are known with some accuracy*. They generally decrease when the impurity concentration increases†. Trapping phenomena dominate the behaviour of large bandgap photoconductors such as CdS.

The thin films of GaAs, CdTe and CdS are materials much more imperfect than single crystals. Formed either by evaporation or by chemical reaction on a substrate of plastics, Al or Mo, they have a grain-structure, with sometimes a preferential orientation. The band scheme is structure-sensitive: disordered crystals or amorphous materials have an important absorption tail beyond threshold**, so that the steepness of the absorption edge may be used as a criterion of perfection. The carrier mobility is structure sensitive too. Finally in thin films the carrier lifetimes could be very small, but no systematic measurements are available.

For studying the different methods of preparing thin films, we refer to the Proceedings of the Marseille International Conference in Rev. Phys. Appl. (Fr.) Vol. I, No. 3, 1966. The chemical transport method, when it can be used, gives the best results (GaAs, CdTe) because the films are then formed near thermal equilibrium conditions. Evaporation and sputtering can also be used (CdS). Controlling the doping levels implies both the addition of impurities and the control of the departure from stoichiometry, i.e. the vapour pressure of the more volatile component (as in GaAs, Cd in CdTe, S in CdS). While Si polycrystalline films have always degraded properties ($\mu < 50 \text{ cm}^2/\text{V.s.}$), one has obtained $25 \text{ cm}^2/\text{V.s.}$ for CdS, 200 to 400 for CdTe and up to 1000 for GaAs (cf. the values of single crystals, Table IV).

To summarize, one now knows how to obtain thin films of GaAs, CdTe and CdS which, though polycrystalline, exhibit electron properties not far from the corresponding single crystals.

2.2.3 Point Defects and Their Consequences

We shall present here only a short discussion of point defects. These include:

- lattice vacancies and interstitial atoms noted for instance V_{Cd} and Cd_i in CdTe, which is called Frenkel disorder,
- substitutional or interstitial impurities (for instance In in Cd site in CdTe, noted In_{Cd}),
- associations of simple defects.

Each crystal is characterized by a normal *intrinsic disorder*, which is an exponentially increasing function of temperature. For instance the formation of a Frenkel pair in CdTe:

obeys a mass action law relating the concentration of the defects to the Frenkel energy W_F and temperature:

$$[\text{Cd}_i][V_{\text{Cd}}] = K_F = C_F \exp(-W_F/kT). \quad (16)$$

* For Au, In, P, Cu, Fe in Si, see M.L.Schultz, Infr. Physics, 4, 1964, p.93.

† Exception: p-Si doped with Au, in the case of "surcompensation" studied by A.Vapaille (Thesis, Orsay 1966). But then the lifetime is very small.

** See e.g. the study of GaAs by Rappaport, Rev. Phys. Appl., Vol.1, No.3, 1966, p.154.

A Cd pressure p_{Cd} on the crystal under preparation changes its concentration of defects through the reaction

and the mass action law

$$[\text{Cd}_i]^{-1} p_{\text{Cd}} = K_G = C_G \exp(-W_G/kT), \quad (17)$$

but does not affect the product $([\text{Cd}_i][V_{\text{Cd}}])^{\frac{1}{2}}$ which is the intrinsic disorder (compared to the case of electron and hole concentrations in a semiconductor).

These are the *native* defects. The disorder may be made artificially larger than the intrinsic disorder: such is the case of an irradiated crystal. The *radiation-generated* defects are metastable and, contrary to lattice defects, can be annealed by a proper heat-treatment.

The point defects are as many "quasi-chemical" species which can interact in the solid matrix. For instance in silicon, lithium (interstitial) and gallium (substitutional) can form pairs of defects:

According to the value of the energy W_p , these pairs may be more or less dissociated at room temperature.

The main characteristics of point defects in crystals are thermodynamical and electronic ones:

- energies of formation and transformation, solubility limits, segregation coefficients, diffusion coefficients,
- ionization energies, determining the positions of impurity levels, and capture cross sections for carriers.

The ionization of a, say, donor impurity; is described by ($\oplus$ being here the symbol of an electron):

$$\frac{n[\text{Cd}_i^+]}{[\text{Cd}_i]} = K_d = C_d \exp\left(-\frac{W_d}{kT}\right). \quad (18)$$

Because the concentration of electrons (or holes) is present in all formulae such as (18), the concentrations of the various point defects are interdependent. In particular, in CdTe and CdS, the concentration of lattice defects after a given treatment depends on the concentration of the electrically active impurities. This is a consequence of the general law of displacement of equilibria. This phenomenon has been recently studied under the name of self-compensation (by Mandel*, who could explain why some crystals, including CdS, cannot be obtained p-type).

The specific situation of CdTe and CdS is the following.

2.2.3.1 Native Defects in CdTe. Many donors have a low ionization energy, but all acceptors have a high one (Fig.12). Associations ($V_{\text{Cd}}\text{In}_{\text{Cd}}$) have been identified, they are acceptors (0.3 eV) which dissociate above 600°C. Only some diffusion coefficients have been determined, and no capture cross sections at all.

* Phys. Rev. 134 (1964) A 1073, 136 (1964) A 826.

2.2.3.2 Native Defects in CdS. Here the donor levels are shallow too, but the acceptor levels are at about 1 eV from the valence band. The disorder is most probably a Schottky disorder (V_{Cd} and V_S). The thermodynamical properties of defects are little known. Recent studies of luminescence and photoconductivity have given some data on the carrier lifetimes and capture cross sections on samples in which unfortunately the nature of the defects was generally not known. Duc Cuong and Blair* have obtained evidence of recombination centers, of concentration $1.3 \times 10^{17} \text{ cm}^{-3}$, with a level at 1.4 eV above the valence band and capture cross section $\sigma_n = 1.2 \times 10^{-23} \text{ cm}^2$ and $\sigma_p = 2.1 \times 10^{-20} \text{ cm}^2$. Palz and Ruppel† have determined lifetimes $\tau_p = 10^{-8}$ to 10^{-14} s for majority carriers and $\tau_n = 10^{-3}$ to 10^{-9} s for minority carriers.

2.2.3.3 Radiation Defects in Si. As almost nothing is known on radiation defects in CdS and CdTe, we shall limit ourselves to Si. Irradiation generates complex defects, such as A-centers ($V_{Si} + 0$, acceptor $W_d = 0.16 \text{ eV}$), E-centers ($V_{Si} + P$, acceptor 0.43 eV), donors ($Si_i + B$), at 0.45 eV on other centers, depending on the type of radiation used** and the impurities contained in silicon.

The generation of these defects raises the resistivity and lowers the lifetime. For instance the capture cross section of A-centers for electrons and holes is of order $1.5 \times 10^{-15} \text{ cm}^2$. But not all recombination centers have such high capture cross sections. For instance, if Si is Li-doped, lithium can migrate towards the E-centers, even at room temperature, and form another more complex center, which turns out to have a low capture cross section. Li-doped silicon is perhaps able to form radiation-resistant photocells. This result, obtained recently†† illustrates the interest of studying radiation defects more extensively.

Radiation damage of photocells is essentially related to the variation of diffusion length L of minority carriers under a flux of electrons or protons. Experimentally it is found that an integrated flux ψ of charged particles causes the diffusion length to change, from its initial value L_0 , to a value L such as

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K\psi.$$

The electron or proton-damage coefficient K is about ten times lower for p-Si than it is for n-Si. That is why current solar cells use p-type Si as the base material and an n-type superficial layer***. Furthermore K depends on the carrier concentration of Si and on the energy of the particle. This dependence is shown in Figure 13, for p-type Si of different resistivities.

2.3 Photovoltaic Mechanisms

2.3.1 Potential Barriers

The use of semiconductors in photocells implies building a collecting structure, which may be either:

- a metal-to-semiconductor contact,
- a p-n junction,
- a hetero junction between two different semiconductors,
- or eventually a more complex structure.

* J. Appl. Phys. 37, p.1660, 1966.

† Phys. Stat. Sol. 15, pp.649 and 665, 1966.

** V.A. Van Lint, E.B. Wirkner, I.E.E.E. Trans. on Nuclear Science, Vol. NS-10, No.1, p.80, 1963.

†† Wysocki et al. Appl. Phys. Lett. 9, p.44, 1966.

*** In the superficial layer there exists an important drift field due to the inhomogeneity of the diffused layer. Thus the minority carrier diffusion length in this region has little effect on the cell's efficiency.

What happens when two different materials are put into contact may be analysed by reference to Figure 11 which described the vacuum semiconductor interface. In all cases a displacement of charges occurs, to ensure the equality of Fermi levels on the two sides of the interface. The height and width of the potential barrier thus-produced depend both on the electronic affinity and doping of the two materials, which are known, and on the "surface states"* which are not known.

Let us consider the simple case of a metal-to-semiconductor barrier or Schottky barrier†. The barrier height E_B (Fig.14) may be experimentally obtained:

- either from the current-voltage characteristic and its temperature dependence. In direct bias, the current results from the injection of majority carriers from the semiconductor into the metal and follows a Richardson law:

$$J = AT^2 \exp\left(-\frac{E_B}{kT}\right) \left[\exp \frac{qV}{kT} - 1\right]$$

- or from the diode capacity C , measured as a function of the bias voltage V :

$$C = S \frac{q \epsilon^{\frac{1}{2}} n}{2(V_d - V)^{\frac{1}{2}}}; \quad d = \frac{2 \epsilon (V_d - V)^{\frac{1}{2}}}{qn}.$$

(S defines the diode area, ϵ the dielectric constant, n the concentration of majority carriers and d the width of the space-charge region).

- or from the spectral response of the photovoltaic current, or more exactly of its photoemissive component (the origin of which is a passage of electrons from the metal into the semiconductor by the impact of a photon $h\nu > E_B$).

Some results are given by Table V and Figure 15.

It is seen that the barrier height depends little on the metal electronegativity or work function for compounds like GaAs (or InP, CdSe, CdTe) where the surface Fermi-level is a constant, determined by high-density surface states generally present in the inferior third of the band gap; on the contrary for ZnS (or CdS), E_B depends strongly on the metal, probably because surface states have levels near the edges of the band.

Potential barriers in p-n junctions have the form of Figure 7.

In the case of a heterojunction between two materials 1 and 2, the band scheme is given by Figure 16. The barrier heights for electrons and holes, Φ_{n0} and Φ_{p0} (which become Φ_n and Φ_p under the light flux) have the same difference ΔE_0 as the bandgaps of the two materials. From the formulae (11) and (12) written for the two materials, one gets

$$\exp\left(-\frac{\Phi_n}{kT}\right) = \frac{n_2}{n_1} \frac{Nc_1}{Nv_2}; \quad \exp\left(-\frac{\Phi_p}{kT}\right) = \frac{p_2}{p_1} \frac{Nv_1}{Nv_2}. \quad (19)$$

The detailed form of the band scheme near the interface has little bearing on the photovoltaic currents.

2.3.2 Photovoltaic Current and Voltage

We shall not deal here with semiconductor-metal contacts, but with heterojunctions and p-n homojunctions, according to an analysis due to Keating**. The band structure of Figure 16a is submitted to a *high injection*, i.e. the concentrations of injected carriers

* cf. W.Shockley, Phys. Rev. 56, p.317, 1939; D.Pugh, Phys. Rev. Letters 12, p.390, 1964; J. Van Laar, J.J.Scheer, Surface Sci. 3, p.189, 1965.

† cf. C.A.Mead, Solid State Electr. 9, p.1023, 1966.

** J. Appl. Phys. 36, p.564, 1965.

are high compared to the equilibrium concentrations. In one of the materials, in stationary régime, the rate of injected carriers g , the rates of recombining carriers n/τ_n or p/τ_p and the electron or hole current densities are related by

$$g - \frac{n}{\tau_n} + \frac{1}{q} \frac{dJ_n}{dx} = g - \frac{p}{\tau_p} + \frac{1}{q} \frac{dJ_p}{dx} = 0 \quad (20)$$

in every section of the structure. Because of the continuity conditions

$$J_n + J_p = J \text{ (total current)}; \quad \frac{dJ_n}{dx} + \frac{dJ_p}{dx} = 0, \quad (21)$$

it follows from formula (20) that

$$n = g\tau_n \left(1 - \frac{1}{gq} \frac{dJ_n}{dx} \right); \quad p = g\tau_p \left(1 + \frac{1}{gq} \frac{dJ_n}{dx} \right). \quad (22)$$

In every section the current J_n is the sum of a conduction current in an electric field E and of a diffusion current

$$J_n = nq\mu_n E + qD_n \frac{dn}{dx}; \quad J_p = pq\mu_p E - qD_p \frac{dp}{dx}. \quad (23)$$

Injecting n and p from formula (22) into formula (23) and using formula (21), one obtains the differential equation for J_n :

$$\frac{d^2 J_n}{dx^2} - \frac{J_n}{L_a^2} = - \frac{J}{2L_p^2}, \quad (24)$$

where $L_p = (D_p \tau_p)^{\frac{1}{2}}$ is the hole diffusion length and L_a the ambipolar diffusion length

$$\frac{1}{L_a^2} = \frac{1}{2} \left(\frac{1}{L_n^2} + \frac{1}{L_p^2} \right). \quad (25)$$

The solution of formula (24) has the form

$$J_n = A \exp \left(-\frac{x}{L_a} \right) + \frac{JL_a^2}{2L_p^2}; \quad J_p = -A \exp \left(-\frac{x}{L_a} \right) + \frac{JL_a^2}{2L_n^2} \quad (26)$$

and formula (22) becomes

$$n = g\tau_n \left(1 - \frac{A \exp(-x/L_a)}{gqL_a} \right); \quad p = g\tau_p \left(1 - \frac{A \exp(-x/L_a)}{gqL_a} \right). \quad (27)$$

A combination of formula (26) and formula (23) leads to the electrical field in every section, and then to the voltage drop in the considered material, which is found approximatively equal to

$$V_B \simeq \frac{JL}{g\tau_n q \mu_n} \frac{L_a^2}{2L_p^2} \quad (L = \text{material thickness}). \quad (28)$$

In a heterojunction between materials 1 and 2, μ_n is given by formula (19) where n and p are equal to their values (27); one easily finds

$$\Phi_n = -\frac{\Delta E_0}{2} + kT \log_e \left(\frac{\tau_{n1}\tau_{p2}}{\tau_{n2}\tau_{p1}} \frac{N_{c1}N_{v2}}{N_{c2}N_{v1}} \right). \quad (29)$$

The open-circuit voltage is $(I/q)(\phi_{n0} - \phi_n)$, where ϕ_{n0} is the barrier height in the dark and ϕ_n is given by formula (29); thence

$$qV_{oc} = \Phi_{n0} + \frac{1}{2}\Delta E_0 - \frac{kT}{2} \log_e \left(\frac{\tau_{n1}\tau_{p2}}{\tau_{n2}\tau_{p1}} \frac{N_{c1}N_{v2}}{N_{c2}N_{v1}} \right). \quad (30)$$

On the other hand the voltage drop due to the series-resistance of the two materials of thickness L_1 and L_2 is, after formula (28),

$$qV_B = J \left(\frac{L_1 L_{a1}^2}{2g\tau_{n1}\mu_{n1}L_{p1}^2} + \frac{L_2 L_{a2}^2}{2g\tau_{n2}\mu_{n2}L_{p2}^2} \right). \quad (31)$$

Finally Keating calculated the short-circuit current density by an indirect method; he assimilated it to the current density J for which the carrier density at the junction became low enough so as to make the hypothesis of high injection invalid. He found

$$J_{sc} \simeq gq \frac{L_{a1} + L_{a2}}{\beta}; \quad \beta = \frac{L_{a1}^2}{2L_{p1}^2} - \frac{L_{a2}^2}{2L_{p2}^2}. \quad (32)$$

Consequently the characteristics at *high* injection levels have the form of Figure 17a: V_{oc} is independent from light flux, the series-conductance and short-circuit current are proportional to it. This will be the case of *photoconducting* materials (i.e. very low doping).

One can apply these formulae to the particular case of homojunctions, for which one finds the classical characteristics of Si p-n junctions, which gives the load characteristic of Figure 17b (with a logarithmic variation of V_{oc} with g).

We give in Table VI Keating's results for homojunctions only (the formulae are quite similar for heterojunctions). For *semiconducting* materials (i.e. medium to high doping level) the last formulae apply to the case of low injection while the first apply to the case of very high injection: the difference of the dependences $V_{oc}(T)$ and $V_{oc}(g)$ in the two cases is remarkable.

The formulae for low injection, which are the most important for usual photocells, have been obtained here as by-products of a more general analysis: for a more detailed study of this particular case, we refer to classical handbooks* and to references quoted in Section 2.1.

2.3.3 Interpretation of Photovoltaic Effects in Thin Film-Photocells

Si-photocells are p-n junctions and their photovoltaic mechanism is quite clear†. On the contrary thin-film photocells, and especially with CdTe and CdS, have properties which are not perfectly understood. Anticipating Section 2.4, let us indicate here only that they are built by superposing n-CdTe and p-Cu₂Te (or n-CdS and p-Cu₂S), so that the question arises: what is the origin and form of the photovoltaic barrier?

* e.g. J. Tauc. *Photo- and Thermoelectric effects in semiconductors*. (Pergamon Press Inc., New York, 1962).

† Note however that, according to Vul et al. (Rev. Phys. Appl. I p.209, 1966), measurements of V_{oc} at very high illuminations indicate that the saturation value is smaller than the barrier height; but the light flux was not surely homogeneous in this experiment.

2.3.3.1 *CdTe*. Cusano* described his cells as heterojunctions between n-CdTe and p-Cu₂Te. A different conclusion was reached by Bernard et al.*. Considering the properties of Cu₂Te and the measured characteristics $C(V)$ and $I(V)$ of the cells in the dark (especially the presence of traps which could be identified with Cu atoms in the space-charge region), these authors concluded that copper diffused in n-CdTe which became superficially p-type: the barrier was thus between n-CdTe and p-CdTe (homojunction), the copper telluride playing only the role of a transparent electrode.

It is probable that, according to the details of its preparation, the cell can either look like a heterojunction (Fig.18a) or a homojunction (Fig.18b). Indeed the capacity varied with voltage as $C \propto V^{-\frac{1}{2}}$ in Cusano's cells, which implies a steep barrier, but as $C \propto V^{-1/3}$ in Bernard's cells, which implies a progressive junction.

This question has not only an academic interest. It is likely that steep junctions will be more sensitive to heat (which tends to help copper diffusion), whereas progressive junctions will be more sensitive to radiation damage (because the initial diffusion length is larger in the intermediate region of high resistance). So it would be useful to discuss more finely the value of the barrier height in CdTe cells, and to measure V_{oc} up to high injection levels, as a function of light intensity and temperature, so as to compare the experimental results with those of Table VI.

2.3.3.2 *CdS*. The nature of the photovoltaic effect in the CdS-Cu₂S cells has been discussed by many authors. Williams and Bube† proposed a mechanism of photoemission, Grimmeiss and Memming** considered these cells as heterojunctions between n-CdS and a p-type superficial layer produced by copper diffusion; Balkanski and Chone†† described them as heterojunctions, which is also the conclusion of Keating.

It is quite possible that cells of different fabrications have different profiles. About the photocells of high efficiency produced by Clevite C⁰, according to an interpretation by Reynolds***, they behave as indicated, Figure 19: there should be two successive barriers, but the active junction would be between "intrinsic" CdS and base n-type CdS, which could explain the relatively small barrier height. This scheme is near what Bernard proposed for CdTe. But there is a difference: in Reynolds' view, the photo-carriers are generated in Cu₂S (whose absorption edge is at 1.2 μ). This hypothesis is an alternative to the two-photon processes in CdS mentioned in Section 2.2.1. Further measurements would be useful in this connection.

2.4 Performances of Actual Photocells

Table VII summarizes the performances of present photocells: silicon single-crystal cells, which have been described in many reviews and will just be briefly reviewed here; GaAs, CdTe and CdS thin-film cells (according to Rappaport, Cusano and Shirland respectively), with a possible comparison of such cells with single-crystal ones of the same compound.

2.4.1 *Si Photocells*

Two major problems have governed the design of Si solar cells: optimizing the efficiency under the flux G_0 (air-mass zero conditions) and minimizing the radiation damage.

Present photocells are of p-type. p-type single crystals of resistivity 2 to 10 ohms (generally 10 ohms) are cut in slices and then in rectangular plates. With presently

* Rev. Phys. Appl. I, No.3, 1966.

† J. Appl. Phys. 6, p.968, 1960.

** J. Appl. Phys. 33, p.2217, 1962.

†† Rev. Phys. Appl. I, No.3, 1966.

*** Comm. Meet. Prop. and Energ. Panel AGARD (Liège, 1967).

available crystals, $1 \times 2 \text{ cm}^2$ and $2 \times 2 \text{ cm}^2$ plates are usual. Larger-size crystals (up to 6 cm diameter) are being developed. An n-type layer is formed by diffusion from a gaseous phosphorus source and metallic electrodes are applied. On the front surface the electrode takes the form of a fine grid in order to provide the optimum between maximum photosensitive area and minimum electrical resistance.

The I-V characteristic is measured with a space sunlight simulator under 140 mW/cm^2 . A typical cell has properties given by Figure 20 (from S.A.T., France) and Figure 21 (from Hoffman, USA). On Figure 20 is shown the temperature variation and on Figure 21 the light flux normalized variation of the I-V characteristic. The spectral response may vary as shown by Figure 22, one important factor being the depth of the diffused region. To enhance radiation resistance, it is important to minimize this depth (0.25μ to 0.5μ), in order to increase the efficiency in the blue part of the spectrum. "Red" cells are more damaged by radiations because most of the damage is due to the decrease of the diffusion length in the base p-Si where long-wavelength photons are absorbed.

To describe the effects of radiation damage, we shall select only some important features.

In Section 2.2.3.3 we described the variation of the diffusion length in the base region, when silicon is irradiated by electrons or protons. The short-circuit current of a cell is tightly correlated with diffusion length. Many experiments have shown that I_{sc} varied proportionally to the logarithm of the diffusion length over the range from $L = 10$ to 200 microns and Kleinman* has accounted for this behaviour. However this logarithmic law is not exactly satisfied for all kinds of light sources and the real law in space may be a little different. Along with the (not so fast) variation of V_{oc} due to irradiation, the whole effect of high-energy particles is a fast decrease of the efficiency, as illustrated for protons by Figure 23. Figure 23 shows that the optimal charge voltage changes under irradiation. The damage by electrons is similar (see e.g. Rosenzweig et al.†) except that the cover plates are less efficient to shield the cell from electrons than for protons.

Typically, the maximum power output is decreased to 72% of its initial value (and I_{sc} to 75%) when the diffusion length is decreased from 150 to 11μ ($L/L_0 = 0.075$ for $L_0 = 150 \mu$) or from 125 μ to 16μ ($L/L_0 = 0.13$ for $L_0 = 125 \mu$).

It is thus possible to calculate the degradation of a cell orbiting in a space region where the proton and electron spectral fluxes and densities are known. Such a calculation for equatorial orbits is given by Cooley and Janda (*op. cit.*). The proton spectral flux on an equatorial orbit is assumed to be:

$$\rho(\epsilon) = \rho_0 e^{-\epsilon/\epsilon_0} \quad (\epsilon = \text{proton energy}),$$

where $\rho_0 = 1570 \text{ protons/cm}^2 \text{ sec MeV}$, and $\epsilon_0 = 306 \text{ } \mathcal{L}^{-5.2} \text{ MeV}$. ($\mathcal{L} = \text{Mc. Ilwain's parameter, altitude dependent as shown on Figure 24}$). The proton damage coefficient $K = A/\epsilon$ (cf. Figure 13) with $A = 1.5 \times 10^{-5}$. According to the formula given in Section 2.2.3.3, the variation of L with time t is given by

$$\frac{1}{L^2} - \frac{1}{L_0^2} = \frac{1}{2} \int_{\epsilon_0}^{\infty} \rho(\epsilon) K(\epsilon) d\epsilon,$$

where the cut-off energy for protons is 14 MeV if the cell shielding is a 30 mil sapphire plate. Thus it is found that

$$\left(\frac{1}{L^2} - \frac{1}{L_0^2} \right) \text{cm}^{-2} = 9.4 \times 10^{-3} t(\text{sec})$$

* Bell Syst. Tech. J. 40, p.85, 1961.

† W. Rosenzweig, H.K. Gummel, F.M. Smits, Bell Syst. Tech. J. 42, p.399, 1963.

and that, for $L_0 = 125 \mu$, the time required for a 25% degradation of I_{sc} is 505 days.

The same calculation, for *electrons*, gives 156 days.

Figure 24 shows the results of such calculations for 1 ohm cm, n/p cells, shielded by 30 mil sapphire, placed on equatorial cells of different altitudes.

2.4.2 Thin-Film Cells

CdTe and CdS cells will be described now*.

2.4.2.1 CdTe Solar Cells (GeCo, USA; Radio technique, France). The structure of these photocells is illustrated by Figure 25. The substrate is an Mo foil, the base layer is n-CdTe obtained by chemical reaction between Cd vapour, CdI_2 and Te (thickness $\simeq 10 \mu$, resistivity 100 to 10000 Ω cm). A CdS layer, strongly doped by (Ga + CdI_2) or by $CdBr_2$, may be formed previously in the same reaction chamber, to ensure a low-resistance ohmic contact. A layer of high resistance CdTe, strongly counter-doped by CuCl or Sb, is formed on the top of the CdTe base layer. Copper telluride is then formed, in the original GeCo procedure, (due to Cusano), by dipping the CdTe in an aqueous solution of cuprous ions for some seconds. Finally a thin evaporated Au grid is used as a contact.

Some variations have been tried in this preparation. The base CdTe layer may be obtained by transport via H_2 or by evaporation, but such layers are less convenient than by the above Cusano's procedure. Copper telluride may be obtained by flash evaporation (35% at. Te, thickness 50 Å), and this method is effectively used with success in France.

A 5% efficiency is now currently obtained for a surface of the order of 30 to 50 cm^2 ; this is still lower than the 9% which has been obtained with CdTe single crystals (optimum purity: $n \simeq 2 \times 10^{15} cm^{-3}$). Figures 26 and 27 show the I-V characteristic and spectral response of a good cell. The specific output power is typically 165 W/kg. The temperature coefficient is rather large: η increases 20% between 20°C and - 8°C. V_{oc} increases logarithmically with light flux; its value of 0.6 volt for solar energy is only one half of the junction barrier height (which is estimated between 1.0 and 1.3 eV). A tendency to saturation of V_{oc} for very high pulsed light flux (10^6 times the solar flux) has been observed.

In 1966, the stability of the GeCo cells, although very good at room temperature, was not excellent at 65°C and higher. Obtaining a good stability up to 80°C is still the major problem with CdTe cells, although important improvements have been obtained recently. We shall probably soon be able to assert that not too steep junctions are highly reliable.

The stability under radiation, though little studied up to now, seems to be good: very high doses, such as $3 \times 10^{13} cm^{-2}$ protons (of 2.4 MeV) or $5 \times 10^{16} cm^{-2}$ electrons (of 1.5 MeV) cause only damages of the order of 15%.

To summarize, by comparison with Si cells, present CdTe cells have

- An efficiency more than 2 times lower,
- A specific power better by a factor 3,
- A stability without or under irradiation still not very regular, but encouraging.

2.4.2.2 CdS Cells (Clevite, USA; Harshaw, USA)[†]. The structure of CdS cells is similar to that of CdTe cells. The sensitive element is a junction CdS-Cu₂S (see comments of Section 2.3.3.2 about the photovoltaic mechanism). The cells are currently formed on a polyimide substrate, able to withstand both temperatures up to 300°C and ionizing

* For GaAs cells, which have a definitely lower efficiency, see the results reported by Rappaport in Rev. Phys. Appl. I, No. 3, 1966.

† More detailed information in F. Shirland, Adv. Energy Conv. 6, No. 4 p.201, 1966.

radiations. A metallic solder some microns thick (e.g. Ag covered by Zn) is first deposited on this substrate, then a CdS layer (by evaporation). CdS thickness may be of some 100 μ , and its resistivity of the order of some tenths of Ω cm. Cu_2S is formed chemically, then annealed at 250°C. A thin metallic grid and a plastic protective coating are finally formed on the cell (Fig.28).

The I-V characteristic (Fig.29) follows the law, formula (4), with a not negligible R_{sh} term. V_{oc} is at best 0.5 volt, I_{cc} 30 mA/cm² and the conversion efficiency 6% to 8%. The spectral response is found to be different without and with a continuous white illumination superposed to the monochromatic flux (Fig.30). This seems to be related to the anomalous absorption mentioned above in CdS, and due to a filling of traps by the white light. The efficiency is decreased as temperature increases, irreversibly over 150°C (probably because of Cu diffusion). It has been stated in 1967 by D.C.Reynolds that CdS cells are now perfectly stable without irradiation. They are also rather radiation resistant: 20% damage by 10^{13} cm⁻² 100 keV protons, while 10^{18} cm⁻² 425 keV electrons leave the cells unaltered.

To summarize, CdS cells have about the same properties as CdTe cells, with a somewhat better efficiency and a stability which is now quite satisfactory. They are very near reaching spatial qualification. The use of a plastic substrate and the preparation in one operation of cells as wide as 100 cm² are clearly important advantages of these cells, for which specific outputs of 200 W/kg have been obtained.

2.4.3 Comparison of Thin Film and Si Photocells and Short-Range Perspectives

We give in Table VIII a summary of the technical and economical characteristics of Si, CdS and CdTe cells, with a tentative evaluation for year 1970.

This table does not include stability considerations, since this problem is practically solved – except for the radiation damage, which is important for silicon and still unknown, but probably low, for thin film.

The tendency of silicon photocells is towards a decrease of the thickness – and thus of weight. Very thin cells (1/100 mm, protected by plates of 1/100 mm) are envisaged for the near future*. The evolution of the cost is only related to the amplitude of production and cannot be very important. Some improvements of the substrate structures are still possible.

The present performances (1967) of thin film photocells would already justify spatial applications. Since the stability of CdS and CdTe cells was proved recently, spatial tests are being attempted. It is anticipated that spatial qualification will be proved in the near future. Adequate structures for supporting these cells have not yet been studied. The cost of thin-film cells can be lowered a great deal in case of mass production. A progressive but slow improvement of the efficiency is expected.

2.4.4 Possible Impact of Earth Applications

Though this course is devoted to spatial power sources, a short digression on earth applications will be useful here. Numerous applications seem to be feasible, especially in sunny underdeveloped countries, but no serious study of this problem has been published. The availability of thin-film cells justifies such a study, because of their intrinsic possibility of low cost. Such applications would enhance the production of thin-film cells and lower their cost, which will be essentially a function of their rate of production in the next years. So it seems that this field offers an interesting possibility of mutual interactions between spatial and terrestrial technology.

* F.C.Treble, Comm. Meet. Prop. and Energ. Panel, AGARD, Liège 1967.

2.4.5 Some Long-Range Possibilities

Although it is felt that the occurrence of thin-film CdTe and CdS cells is by far the most interesting feature in the present evolution of solar cells, it is worth evaluating other suggestions that have been made.

2.4.5.1 Large-Current-Density Ge or Si Cells. It is possible to concentrate solar energy on photocells, in an intention to multiply the output energy without changing the cell area. Special cells must be used, in order to minimize the series-resistance, and it has even been proposed to use Ge instead of Si. A difficult problem is to avoid heating of the cells, another one is to point the concentrator on the sun. A recent study of this problem* has led to pessimistic conclusions on such devices for space applications in the near future.

2.4.5.2 New Semiconducting Materials. HgTe-ZnTe alloys, indium phosphide or cadmium selenide are potentially interesting materials. However, it must be recalled that the development of a well-controlled new material is a long and costly task.

2.4.5.3 New Metallurgical Processes. Te-Velde† has prepared assemblies of Si or CdS micro-grains, lodged in a plastic substrate, with no contact between the grains. Each grain may include a micro-junction between two n-and p-regions or even between two different materials. While the possible impact of these researches on solar photocells can hardly be imagined, we cannot neglect the intrinsic interest of such new metallurgical processes.

2.4.5.4 Variable Bandgap Cells. The photovoltaic mechanisms themselves may be improved, as shown by the following example. We know** how to prepare graded composition alloys, i.e. crystals in which the composition y varies continuously in one direction x . It follows that the parameters E_0 , μ_n , μ_p , τ_n , τ_p , n , p , ... vary with x . It seems possible to find a composition profile which would allow a predominance of the variation of E_0 with x . This would lead to two simultaneous advantages: first the cell could be better fitted to the solar spectrum (increase of η_a), second pseudo-electric fields acting on the photocarriers could improve the collection efficiency η_c . Further studies on these structures seem reasonably promising.

3. PHOTOVOLTAIC SYSTEMS

3.1 Theoretical Considerations for a Preliminary Design

3.1.1 Definitions

A photovoltaic system is an assembly of elementary photocells, each of small surface area in comparison to the total surface of the system, capable of converting the incident sun's energy into electrical energy.

Such a system possesses no means of storing electrical energy produced when it is sunlit, and such energy ceases immediately the sun's rays cease. Practically, the solar generator should be equipped with some storage means by which the continuous supply of current is assured during the periods of obscurity.

Several systems can be devised (thermal, mechanical, or electrochemical). Practically the only one in use is made from electrochemical batteries; Nickel-Cadmium, Silver-Cadmium, or Silver-Zinc.

* J. Tavernier, P. Sibillot, E. Le Grives, Comm. Meet. Prop. and Energ. Panel, AGARD, Liège 1967.

† Comm. Meet. Prop. Energ. Panel, AGARD, Liège 1967.

** G. Cohen-Solal, Y. Marfaing, F. Bailly, Rev. Phys. Appl. (Fr.) I, 1966, II.

The most robust is that made with nickel and cadmium electrodes. It possesses a long cyclage life, a good over-charge tolerance and allows a considerable high duty discharge. However, it is penalised by a low energy-density (number of Wh per kilo) compared to Ag-Cd and Ag-Zn. As well, it is magnetic, which excludes its usage on certain magnetically stabilised satellites.

If the lighting conditions are intermittent (alternating sunlight-shade) and if a permanent supply of power is needed on the satellite, the power source utilising solar energy conversion comprises two principal parts:

- the assembly of solar cells which we will again call "solar cell array" or "solar generator"
- the electrochemical batteries.

The association of these two sub-systems necessitates an electronic circuitry. The batteries are placed in tandem, and this fixes to a certain degree the conception and realisation of the solar generator. The end of charge voltage at the battery terminals determines the maximum voltage at the solar array terminals; which fixes the number of cells to be placed in series.

The electronic circuitry comprises, due to the characteristics of the electrochemical batteries and to the electronic needs of the spacecraft: a low voltage battery cut off; a battery discharge gate with its relay; a main regulator, and at least a DC to DC convertor for the production of the diverse voltages used in the spacecraft circuitry. (See for example, the block diagram of Telstar power system).

The converter efficiency depends on the input and output voltages and the power; it varies around 85% in general.

A regulated voltage is necessary if the electronic circuits used in the satellite are to be reliable.

The mission defines the average consummation which will be needed at the output of the voltage regulator; the batteries have the ability to provide, during several seconds, powers two to three times greater than the average level demanded, although the solar generator should be designed to supply an average power during the whole duration of the mission.

In what follows, we will only be interested in the problems posed by the conception and realisation of a solar generator. However, for the examples of operational systems, it will sometimes be necessary to take into account the complete characteristics of the power source used. In effect, much the essential role played by the electrochemical battery during the obscured parts of the terrestrial orbits is at the time of the placing of the satellite in orbit before the solar panels are deployed and should not be forgotten.

This essential role has a bearing on the total weight of the power source which comprises: the weight of the solar generator, the weight of the battery and the weight of the accompanying indispensable circuits (relays, regulators, convertors etc.).

3.1.2 *Theoretical Considerations Necessary for the Conception of Solar Array*

3.1.2.1 *Introduction.* A certain number of problems will be analysed which arise from the conception and realisation of the solar array capable of producing energy in given conditions of lighting, temperature, and space environment.

The lighting conditions depend on the orbital characteristics and the satellite attitude in this orbit. The available power evolves in space and time following the lighting conditions which the satellite encounters. The photovoltaic system should be designed so as to have the maximum efficiency. In particular, the form of the solar generator should be such that for the given lighting conditions, the total conversion efficiency is the highest possible. The system is optimised *ipso facto* in weight and in surface.

Particular orbits for certain launching conditions can simplify the necessary apparatus for orienting the panels towards the sun (e.g. Nimbus).

The lighting conditions influence the equilibrium temperature of the solar cells which are particularly sensitive to their open circuit voltage. It is therefore necessary to try and obtain the optimum equilibrium temperature. The solar infra-red radiation beyond 1.2μ is not converted into electricity by the solar cells and only serves to heat them.

Finally, the space vehicle evolves in the course of its mission in a space environment: particle radiation (electron and proton, Van Allen belts) ultra-violet radiation and micrometeoritic bombardment.

The particle radiation degrades the solar cell's characteristics. The energy efficiency is reduced, which means that for a particle dose received after a given time in orbit, the available power is less. It is therefore necessary to know precisely the effects of such radiation and to over-dimension the solar generator as a consequence. The micrometeoritic bombardment is of little importance; in the exosphere, the particle flux is given as 60 collisions/cm² of the solar array per year, on the basis of Explorer data. The size of most of the particles is ranged from one to five microns; their energies are so small that they should not penetrate the protective coating of the solar cells. There are also larger particles (250μ) with a collision rate of about 22 collisions/cm²/year. Other data were obtained with Pegasus spacecrafts.

3.1.2.2 *Study of Lighting Conditions.* The lighting conditions vary following the type of mission imposed on the satellite.

In effect, the mission defines the various parameters characterising the orbit and can impose a general attitude and configuration on the satellite. Thus circumterrestrial mission of scientific or technological research will require different reasoning than a mission of technical application (tele-communication, meteorology, navigation etc.) or again an extra terrestrial mission such as those belonging to the American solar system exploration programmes or more simply those of the moon.

For extraterrestrial missions, the solar energy received per unit surface perpendicular to the incident solar radiation varies in intensity as the inverse square of its distance to the sun, this distance being counted taking the distance earth-sun as unity; this radiation is usually always available, except when the space vehicle is in the shadow of the planets. In general, the photovoltaic system of space probes is formed from panels which are always oriented towards the sun (Mariner, Ranger).

For circumterrestrial missions, the solar energy received per unit surface perpendicular to the incident solar radiation has a constant intensity of about 1.400 W/m^2 , outside the atmosphere. Its spectral composition is constant and is given by Johnson's spectrum (see Section 1).

Duration of Lighting. Finally, circumterrestrial orbits are often characterised by an alternance of light and shade, and consequently a variable duration of lighting.

It is therefore necessary to study, for this important case, the variation of the lighting duration in the course of the satellite's journey around a definite orbit and its evolution in time (which can cover several months to several years) as a function of the change in space of the relative positions of the earth, the satellite, and the sun, and those of the initial orbital characteristics.

Lighting duration varies, with the angle the orbit makes with the earth sun axis, with the kind of orbit (elliptical or circular) and the altitude of the space vehicle.

It has a direct bearing on the charge and discharge time of the electrochemical battery.

3.1.2.2.1 *Aspect coefficient*

A. Definition. Consider a satellite turning around the earth and if its principal axis is always directed towards the centre of the earth (gravity gradient stabilised satellite) a perpendicular plane of this axis will intercept a varying flux as the inclination of the luminous rays changes with respect to this plane.

The real *active* surface is equal to the surface of this plane multiplied by a corrective factor called the *aspect coefficient* and which is equal to the cosine of the angle which the normal to the surface considered makes with the direction of the incident luminous rays. If the surface is always oriented towards the sun this angle is zero, and the aspect coefficient is equal to one: the solar generator is then formed from panels, the face of which is constantly in the sun (this carries the solar cells) and the other always in the shade.

When the satellite has a complex surface, or it is made from parts of surfaces, one is forced to consider the *average aspect coefficient* of all the solar generator. This is equal to the fraction of the active surface to the total exterior surface. By active surface should be understood the total exterior surface projected on a perpendicular plane to the sun's rays.

Consider a sphere of radius R . Its total exterior surface is equal to $4\pi R^2$. The active surface is constant whatever be the direction of the sun's rays and is equal to πR^2 . Thus the average aspect coefficient of the sphere is equal to $\frac{1}{4} = 0.25$.

The maximum power produced by a solar generator is roughly proportional to the active surface and consequently to the aspect coefficient.

This coefficient depends on the direction of the solar radiation and on the configuration of the solar generator (geometrical form, shadows) it has a prime importance in the conception of photovoltaic systems of gravity gradient or spin stabilised satellites, i.e. those which do not have a constant attitude with respect to the sun.

Such solar generators are formed from solar cells placed either on the skin of the satellite or on paddles formed from parts of planes. Contrary to the panels, paddles present their two faces alternately to the sun and consequently have solar cells recto and verso.

B. Different Types of Solar Generators

- *Cells mounted on the skin:* RELAY 1 - VANGUARD - FR-1 - ATS 1 - COURIER - TIROS - ESRO 1 and III etc.
- *Paddles:* EXPLORER XII - XIV - XV - XXXIII - OAO - D 1 - UK 1 and 2 etc.
- *Panels:* RANGER 6 and 7 - MARINER II IV and V - NIMBUS I and II - OGO etc.

C. Different Shapes of Solar Generators. The different shapes taken by the solar generators of the satellites of recent years has been both varied and numerous. One can however classify them into planes, cylinders, spheres, and polyhedrons of revolution. The most used are those of parts of planes in the form of paddles, or of cylinders paved with large plane bands forming the generator facets.

Purely spherical shapes are rare: COURIER - EXPLORER 32 - TELSTAR I.

The spherical shape, however attractive gives rise to serious difficulties in the reliability of the interconnections between the cells. Thus, although having constant aspect coefficient (in theory) the power per unit surface is very small.

The generators formed from paddles are numerous; and the form of the pattern, although generally plane, is very varied. These paddles are independant of the structure of the satellite; they are folded during the launching and deployed only after the placement in orbit.

D. Determination of the Aspect Coefficient of a Solar Generator. St. Jean has presented a study which allows for the average aspect coefficient of a solar generator of simple surface and having either paddles, or cells mounted to the skin of the satellite to be calculated. He considers the case of a sphere, the formulas for which are known, and which allows one to pass easily to the practical shapes of satellites: truncated cones, cylinders, or parts of planes (paddles).

For generators having paddles, the problem is similar but complicated by the shadow thrown by the paddles onto neighbouring paddles for certain values of the incident angle of the solar rays. We will see later the practical effect of shadows.

The number of paddles should be redundant; the orientation of the paddles should be studied in relationship to the average direction of the luminous rays. The position of the paddles with respect to the satellite will be adjusted so as to maximise the average aspect coefficient and at the same time minimise its variation as a function of the incident angle of the luminous rays and the rotation of the satellite around its axis.

The theoretical formulas established by St. Jean allow, for a given geometry, the prediction of the variation of the aspect coefficient as a function of the incidence angle of the luminous rays. A particular case is that of the cylinder and the plane, if the curves for different values of the apex angle of the cone are traced (Fig.31).

The power output of the solar array is roughly proportional to the aspect coefficient; it varies with the spacecraft attitude with respect to the Sun; it also varies with the spin angle of the spacecraft around its spin axis. In practice, the solar array shape should be designed so that its average aspect coefficient has a great value and a very small variation as a function of these two parameters. In particular, so that it is never zero; this is the case for the cylinder when the incident luminous rays are parallel to the generator axis of the cylinder; this is remedied simply by putting on the base of the cylinder a sufficient number of cells to obtain the desired power. Figure 32 shows an example of the calculation of an average aspect coefficient for one shape of satellite.

In conclusion, the minimum of the average aspect coefficient of the generator is determined in the worst lighting conditions without forgetting the influence of shadows on it. The desired power being known, the necessary active surface for a given type of cells is deduced from it and from this knowledge the shape of the solar generator necessary to attain this total surface.

3.1.2.2.2 *Effect of shadows thrown on the solar generator*

1. Origin of Shadows: Shadows are thrown on the solar generator from:

- aeriels or antennas,
- masts,
- paddles,
- parts of the satellite.

The most obvious result is a decrease in the power output. This loss of power depends on:

- size and shape of the shadow,
- the relative position of the shadow with respect to the solar generator,
- geometrical layout of the solar cells,
- the electrical connections between the solar cells.

2. Generalities. The shadow effect varies with time and depends on the lighting conditions. It depends equally on the type of solar generator considered; in the case of generators with paddles, the shadow thrown by the paddles onto neighbouring paddles results in a severe reduction of the aspect coefficient. In the case of a generator with panels, shadows are rare except for those of aeriels and masts. These are, however, long and thin and can intercept numerous rows of solar cells.

3. Effect of a Shadow on the Solar Cell Layout.

A. Consider a simple solar cell. Its equivalent network is represented by Figure 33 with:

R_s = The series resistance of the forward biased cell.

R_{sh} = The leakage resistance of the reversed biased cell.

The complete characteristics (I-V) of a solar cell vary with the material (Silicon, CdS, CdTe) and with each sample for a given material, except in the working region (generator) (Fig.34).

B. If one considers a string of "n" cells in series, of which only one is in shadow (Fig.35), the cell in shadow is then reversed biased and it is equivalent to a shunt resistance R_{sh} of high value; in these conditions, one must consider the region III of the characteristic (I-V) of the cell. As a first approximation one can say that the complete string is an open circuit.

C. Consider a row of "p" cells in parallel of which one is in shadow. In these conditions the shadowed cell is forward biased and allows a current I_D to pass offering a resistance R_s which is generally very small (Fig.36): this is the region II of the characteristic; as first approximation the row is on short circuit.

The complete characteristic of the cell, whether in shadow or illuminated, has thus a large influence on the way in which the considered circuit reacts, for in the final analysis, the *actual* loss of power will depend on the values of R_{sh} or R_s with respect to the total resistance of the circuit.

In general, a shadowed cell is not completely on open or short circuit; in the case of an open circuit, the resultant effect varies for each cell for when a reverse bias is applied to it, it behaves as a bad zener diode; the region III of the characteristics (I-V) should be considered and it is essentially variable with each sample (see Figure 37).

D. Ralph Sullivan has determined *experimentally* the influence of shadows on the characteristics (I-V) of a 48×8 series-parallel array, in particular conditions of illumination.

First, consider a sub-module of 8 shaded cells in parallel. A potential drop $V = V_s$ will appear which will vary according to the type of reverse characteristic (a), (b) or (c) of the solar cells considered (Fig.37).

For a module made from cells such as (a), V_s is very big and the available voltage for charging will be very small; one can say that practically all the array (48×8 cells) can be considered as on open circuit (Fig.38a).

On the other hand, for cells such as (c), there will again be a notable voltage drop, but the array is still able to provide some power (Fig.38b). The curves established by Sullivan give the family of characteristics obtained when a submodule is partially shaded in the considered array.

Then, in the case of a string of series connected solar cells, most of the power loss takes place in the first shaded cell. The degradation depends on the solar cells used. If photocells were ideal, i.e. without leakage current when the cell is reverse or forward biased in the dark, the theoretical power loss would be equal to n/N ("n" = number of shadowed cells, "N": total number of photocells in the array). In practice, the *silicon* solar cell has a very small series resistance when it is forward biased in the dark; therefore the power dissipated through the shaded cells must be added when these cells are connected in parallel with other illuminated cells (Fig.38c).

In the case of an array with 8 strings connected in parallel, each string including 48 cells connected in series, i.e. an array not interconnected, the power loss when one only photocell is shaded is equal to 12.5% of the initial power output; in the case of a fully interconnected array the same as Sullivan studied, the power loss is only equal to 6% (Fig.38d). When the whole string is shadowed, i.e. 48 cells, the fully interconnected array is less profitable than a non-interconnected array of which each string of solar cells connected in series is protected with a diode.

Figure 38d shows the effect of variable shadow conditions on a series-parallel array; this figure is only interesting insofar as it indicates the shape of the curves which vary essentially according to the type of photocells forming the network of the solar generator.

In conclusion, it must be remembered that the study of the effects of shadows thrown on a photovoltaic system is the same as the study of the influence of short circuits on a network using non-linear components (such as solar cells) and designed with a certain percentage only of interconnected cells.

A NON-INTERCONNECTED ARRAY

The study and the determination of the shape and of the size of shadows will give this percentage of interconnection and the module disposition on the spacecraft. In particular, it is very important in the case of, for example, gravity gradient or spin stabilised satellites. The satellite shape and the geometric layout of the solar cells will be optimised in order to minimise the shadows or that shadows intercept series sub-assemblies rather than those mounted in parallel.

4. Determination of Shadows. They can be determined by calculation, or by a descriptive geometrical test; but this task is tedious and in general little liked by designers. Also, it is unique to each satellite or series of satellites for a given mission.

In general, it is preferred to locate the shadows with the aid of a model, simulating a parallel lighting and determining the number of modules or sub-modules intercepted for different attitudes of the satellite. Which returns to the study of the variation of the aspect coefficient and the determination of its new minimal value, allowing this time for the shadows.

3.1.2.3 Influence of Space Environment

3.1.2.3.1 The reliability of solar cell arrays

A. Practical Considerations. The reliability of a photovoltaic system is a particular case of that of the power source serving the satellite. We have seen that the energy source comprises several components each of which have their failure probabilities.

As a general rule the reliability is estimated and calculated at every sub-assembly level.

This calculation has been made for Mariner II and IV; from it the end of mission reliability was estimated as 0.716 for Mariner II against 0.711 for IV although the mission of Mariner IV was 2.5 times longer and its number of components greater.

This result is obtained generally:

- in studying, sub-assembly by sub-assembly, the reliability of the system.
- in using for various sub-systems redundant connections, which necessitate, for example, duplication of the electrochemical battery, the current carrying cables, the electrical contacts on the cells, etc.
- in using "Hi-reliability" components.
- in minutely testing the finished system.

Two cases should be distinguished in the study of the reliability of a photovoltaic system:

1. The eventual power loss due to the solar cell and contacts reliability.
2. The power losses which result from the random interception of projectiles (micro-meteorites) coming from intersiderial space, to which solar cells are particularly exposed and sensitive.

In these two cases, the reliability of the system is augmented by completely inter-connecting different cells among themselves.

If the random interception of micrometeorites cannot be avoided the reliability of contacts can however be increased in improving solar cell technology, or again only using "space-proven" techniques.

B. Reliability Analysis. With some particular assumptions, W.A.Klein has computed the reliability of a solar generator, in flight. His assumptions are:

1. open circuits of mounted solar cells occur at random with a constant failure rate of 0.75×10^{-6} failures/hour.
2. the probability of having a solar cell on short circuit is zero.
3. the failure rate of the interconnections is zero.

Laboratory tests on solar generators justifies the assumption that the most probable failure is that of open circuitry. However, the failure rate of 0.75×10^{-6} /hour is only a rough approximation to the conditions in space. The author gives a comparison of the reliability of a solar cell assembly with and without interconnections for the case of a 96×7 cell module.

Several remarks should be made; firstly, a solar cell array is not completely run down if one or several cells are on open circuit. This should be borne in mind when estimating the reliability. Secondly, a theoretical determination of the reliability, like that outlined by Klein, is only practically useful if the failure rate measurement is made on as many units as possible, as well as on the solar cell mounted on its panel, and on the electrochemical battery. These tests are long and expensive.

For the case where these values have been experimentally determined, statistical analysis will determine how much the photovoltaic systems will need to be overdimensioned to allow for its statistical deterioration.

If the rates are such as they can only be estimated, statistical analysis will determine the degree of redundancy, i.e. at what level and in which groupment of solar cells in the array the interconnections should be made.

3.1.2.3.2 The influence of radiation effects. The effect of electron and proton bombardment from the Van Allen belts on the silicon solar cells is now quite well known, and we know that it manifests itself by an irreversible reduction of the electronic

performance. It is thus a very important problem because it effects everything equally, the life-time of the photovoltaic system amongst others.

It is impossible to give general information, valid in all cases, for a complete, array that is to say, to be able to state, *a priori*, what reduction of the solar cell array's output power will have occurred at the end of a certain number of days or years in orbit, without precisising a certain number of parameters characterising the orbit or the mission.

The power loss at the end of a given time depends essentially on the dosage and the nature of the particles encountered, the dosage and the type of particle will depend, in their turn, essentially on the position of the orbit with respect to the Van Allen belts or to the deeper space environment where more energetic particles are encountered.

The overall plan for an *a priori* calculation of the deterioration of a solar cell array in orbit, depends on the following facts:

- complete characterisation of the orbital parameters and their evolution in time and space.
- complete knowledge of the Van Allen belts circling the earth (nature, flux, and energy of the particles encountered) or of the region of space in which the satellite will evolve.
- evolution of the solar cell performances under the action of particle radiation as a function of the dosage for a flux of given particles, having a known energy.

The solution of such a problem is complex. At the beginning of space experiences the number of unknowns was such that the deterioration of solar generator performances in orbit was not determined. Today, without being complete, it is possible to approach the problem rigorously and thus attain the probable deterioration value.

The calculation consists then, in determining the energy, the type and the dose of radiation received as the orbit intersects the Van Allen belts or the regions of deeper space encountered. Allowing for the effects of these radiations on the solar cells, the permissible deterioration power can be deduced with a high probability. The maker of the generator should then:

- choose amongst all the available solar cells that which has the best performance.
- increase the number of cells so as to have, even under the worst conditions, the performance level demanded. This increases the price, the surface, and the weight of the generator as a consequence.
- increase the irradiation resistance of the solar cells, protecting them with the aid of a small slide of special glass (very often made by Corning Glass the different types of which will be found in the remainder of the course) in sapphire or in fused silica. It should be noted that the cell protection is greater, the greater the thickness of the glass. (cf. Figure 39).

This results again in an increase in price and weight of the received solar array.

Knowing the dose, the energy, and type of particles received in time, the maker can determine the overdimensionment necessary for the solar generator thanks to a good knowledge of photocell behaviour under irradiation.

This knowledge has been acquired by irradiation, on the ground, in the proton or electron accelerators (e.g. Van de Graff) and the experience of these later years confirms the similarity of solar cell behaviour under artificial irradiation.

Numerous experiments have been performed in flight. The series of American Explorers has studied in detail the cartography of the Van Allen belts and of space further out. Many things still remain to do and experiments are actually in preparation.

Numerous tests have equally been made to determine solar cell performances in orbit. We will cite the most recent work of Dr R.C. Waddel on ATS-1 which completes those already performed on Relay-I and II. Numerous other research workers have made experiments in this field. In France as well, results have been telemetered from FR-1.

It is actually freely admitted that the cells N/P of $1 \Omega \text{ cm}$, are more resistant than the cells P/N of $1 \Omega \text{ cm}$ (Figs. 39 and 40). The best results are actually obtained with these cells N/P having a base resistivity of $10 \Omega \text{ cm}$, covered with a glass slide which is more efficient the thicker it is, all things being equal, however, elsewhere; its thickness is greater than 150μ .

Conclusions - The importance of the radiation effect on the solar generator is far from being negligible. In every case where it has been possible, the expected deterioration has been noted for the systems detailed in Section 3.3.

Finally, Figures 39 and 40 give an idea of the time necessary to reduce by 25% the short circuit current as a function of the thickness of the protecting layer, on different satellites (comparison between N/P ($1 \Omega \text{ cm}$) and P/N ($1 \Omega \text{ cm}$)).

The newer research projects follow two lines; one tries to improve the performance of the protecting glass slide, which would allow it to be thinner; a thin layer of Si O_2 of 25μ seems actually to have been made.

The other line of research tries to improve the behaviour of the actual cell; promising projects in course of development are based on the application of a lithium doped silicon cell.

From the improvement of the cell will result *ipso facto*, an overall improvement of the solar generator. From this point of view, the application of thin film cells seems particularly promising.

3.1.2.4 Influence of the temperature

A. The conversion efficiency of a photovoltaic device depends on the temperature at which the solar cells function. It increases reasonably linearly when the temperature decreases between -100° and $+100^\circ\text{C}$. In every case it reaches a maximum which is situated between -80° and -100°C , and which varies with the type of cell considered (cf. Figure 41).

-In space, the heat exchanges between the satellite and space take place by radiation; they therefore follow the Stefan-Boltzmann law, space being taken as a black body at 0°K .

If the solar generator is considered more specially, it immediately appears necessary to define which type of generator is used; paddles, panels, or cells mounted on the "skin" of the satellite.

This last type is intimately related to the thermal stabilisation of the satellite itself. The electronic and scientific equipment, consumers of electricity, dissipate an energy in the form of heat and constitute a mass having a certain thermal inertia, which is very favourable in avoiding the thermal shocks brought about by the alternance of light and shade.

When the satellite is in the sun, the total received energy varies, according to the lighting duration and the orbital attitude of the space vehicle, proportionately to the average aspect coefficient, the equilibrium temperature of each facet or solar generator zone needs a certain time to establish itself, allowing for the speed of rotation of the satellite around its axis.

B. Calculation of the equilibrium temperature. In the case of generators with panels or paddles, the problem can be approached.

The energy balance will establish itself thus if:

- Kirchhoff's law is valid
- the incident solar radiation is normal to the entrance face
- the solar radiation reflected by the earth is neglected.

Incident solar energy Energy converted Energy radiated into
absorbed = into electricity + space by the panels

$$I\alpha_e S_e = W_u + \sigma(S_e \epsilon_e T_e^4 + S_s \epsilon_s T_s^4) . \quad (33)$$

Calling:

- I = incident luminous energy per unity of surface
- σ = Stefan's constant
- W_u = energy converted into electricity
- S_e = total surface of the entrance face
- S_s = total surface of the exit face
- T_e = temperature of the entrance face
- T_s = temperature of the exit face
- α_e = average energy absorption coefficient of the entrance face
- ϵ_e = average emissivity of the entrance face
- ϵ_s = average emissivity of the exit face.

Amongst other things α_e , ϵ_e , and ϵ_s are considered to be uniform over the whole surface considered.

This is never the case in practice especially on the entrance face; the solar cells only cover a part of the surface.

The exit face of the panel is generally homogeneous. This is realised in practice with the aid of black paints, of which Figure 42 gives an example of their characteristics.

In practice also, the panels are plane and the entrance surface is equal to the exit surface, ($S_e = S_s$). Finally, it is arranged that $T_s = T_e = T$.

Also if it is supposed that ρ is the conversion efficiency of the absorbed energy into electricity, it follows that

$$T = \left(\frac{I(1 - \rho)}{\sigma} \right)^{\frac{1}{4}} \left(\frac{\alpha_e}{\epsilon_e + \epsilon_s} \right)^{\frac{1}{4}} . \quad (34)$$

In what follows, to obtain the order of magnitude of the temperatures obtained, the panel will be supposed not to lose electricity and that consequently $W_u = 0$.

We will thus obtain an excessive value for the temperature; an error of 10% in the efficiency results in an error of approximately 4% of opposite sign in the equilibrium temperature, in supposing $\rho = 0.10$ and $\alpha_e = 0.70$.

C. Characteristics of solar cells. Figure 42 gives the temperature variation of the emissivity of a typical filtered solar cell, and of a black paint which is deposited on the reverse face of the panel.

The emissivity of a bare cell is very much weaker: 0.368 at 400°K (Ref. Hoffman Co). It can perhaps be increased by the method of deposition, transparent in the visible spectrum and opaque, with a high emissivity, in the near infra red: SiO film, quartz, or sapphire layer, organic deposition.

Figure 43 shows the influence of surface treatment on the spectral absorptivity of a silicon cell.

ϵ_s being given, a family of curves can be traced giving the equilibrium temperature of the cell for different values of α_e and of ϵ_e .

Taking for example $\epsilon_s = 0.800$ which we will suppose constant for a variation in temperature of $\pm 50^\circ\text{C}$ and considering a bare cell for which $\alpha_e = 0.935$ and $\epsilon_e = 0.368$ the ratio

$$\frac{\alpha}{\epsilon} = \frac{\alpha_e}{\epsilon_e + \epsilon_s}$$

is equal to 0.71 for 140 mW/cm²; from which is obtained: $T = 92^\circ\text{C}$ i.e. 73% of maximum output power at 28°C (Fig. 41).

If a cell is now considered for which $\alpha_e = 0.70$ and $\epsilon_e = 0.835$ that is to say, a cell of the type represented in the curve 4, the ratio α/ϵ equals 0.430. This gives $T = 49^\circ\text{C}$ and an output power equal to 93% of the power at 28°C.

The temperature will be lowered, all things equal elsewhere, if the emissivity of the substrate is increased; a cell with a blue-red filter is very suitable; however, its adoption results in a powering of the energy efficiency all things being equal elsewhere, which the preceding example has not taken into account; the reduction comes from a decrease in the absorption coefficient between 0.4 and 1.4 μ .

D. Thermal cinetics. The establishment of the temperature equilibrium depends on the lighting conditions (duration of the alternances light-shade, attitude of the solar array with respect to the sun, etc.), on the type, and on the construction of the solar generator. It is more particularly related to its thermal inertia.

In general, the temperature is well controlled in the case of skin-mounted solar cells. Paddles and panels have a small thermal inertia; they cool very rapidly when shaded. In the sun, paddles have a temperature smaller (+ 30° to + 40°C) than those of panels, the temperature of which can attain + 60° to + 80°C. After being shaded, a sudden fall of temperature is observed, which can attain -100°C, introducing enormous thermal strains (e.g. Nimbus).

As an example, Figure 44, shows the paddle temperature of D-1 in flight.

3.2 Solar Array Fabrication

3.2.1 Realisation of a Solar Array

3.2.1.1 Method of solar cell mounting. The cells are mounted on their panel by simply bonding. This is generally done in two stages:

- the cell is first soldered to the metallic face of a thin epoxy resin laminate of the integrated circuit type.
- the laminate is then bonded as lightly as possible to the metallic support of the structure, generally in the form of an aluminium honeycomb sandwiched between two thin foils of aluminium.

To protect the cell against the particle radiation of the Van Allen belts, a slide of special glass (frequently of fused silica) is bonded to the entrance face of the cell. It is rectangular, of dimensions slightly less than those of the photocell so as to allow contacts to be easily made. The entrance face of this window is provided with a blue filter which eliminates the ultraviolet component of the sun's radiation of wavelength smaller than $4,100 \text{ \AA}$. This avoids the premature decomposition of the adhesive. Sometimes the filter is more complex, for as well as allowing the useful radiation to pass, it eliminates the near infra-red radiation of wavelength greater than 1.2μ . This is then called a blue-red filter; it is made from a large number of optically suitable thin films, and it is very expensive (cf. Figure 43).

The adhesive should be stable under the working conditions (vacuum, temperature, radiations); as well it should assure a good thermal contact between the cell and the substrate. It is generally of a silicone base.

Finally, to avoid luminous energy losses through reflection, anti-reflection layers suitably adapted to the different materials, are deposited on the various entrance faces.

Figure 45 shows schematically how a silicon solar cell is mounted on the body of the satellite, or on paddles or on panels.

The thicknesses of the various layers vary with the fabrication processes and the projects considered; that of the substrate in particular is closely related to the width of the panels and to the stress that these will have to support.

Those given in the method schema correspond to the state of the art in 1965, that is to say, to Mariner IV, which numerous authors consider as being the most typical type.

It should be noted that the substrate represents an important fraction of the total weight of the assembly; according to Treble, at the present state of the art it represents 68% of the total weight per unit surface of the operational panel; against only 15% for the bare solar cell (see Table IX).

As the solar cell is too small producing as it does only very feeble voltages and currents (0.4 volt, 20 mA approximately), it is necessary to join them with others in series and in parallel to obtain the necessary power. This grouping is done in stages, which allows the consideration of sub-assemblies of the solar panel, which is itself a sub-assembly of the solar generator.

Firstly the cells are tested, matched and grouped by sub-module, then by module; several modules form a panel. The solar generator can comprise two, four, eight solar panels (oriented or not) and often more.

The sub-module generally has "n" cells connected in series and "p" in parallel; the series or parallel contacts are generally duplicated from the construction, the intercell contact is therefore *multiple*, but not being made from *independent* contacts, it is less reliable.

The sub-modules are *interconnected* so as to form a module. According to the size of the panel and the solar array the modules can be again grouped among themselves, and an interconnection study is made for each project. The size of the sub-assemblies varies with that of the generator; also, to facilitate the terminology we will designate as modules the smallest sub-assembly from which the total assembly can be made without needing direct soldering to cells themselves.

This modular grouping favours the interchangeability of the elements in the case of accidental damage on the ground. The size of the satellite, its shape, its degree of complexity will determine the size of the smallest grouping of operational cells which may be changed in case of accident, without the safety of the assembly being jeopardized.

3.2.1.2 *Realisation of Sub-Modules.* To form a sub-module the solar cells can be assembled in two ways:

- flat mounted
- shingle mounted.

There is a variation of this last method which is almost that of a flat mounting.

A. Flat Mounting. The figure below explains this method for both the series and parallel groupings.

Advantages

1. The independence of the cells allows the easy replacement of a broken cell, without the need to replace the whole module.
2. Robust.
3. On a supple support, with special connections, the module can be twisted without risk of damage.
4. Large freedom for the series-parallel interconnections.
5. The active surface of the cell is used under the best conditions.
6. A good resistance to the thermal and mechanical strains.

SERIES GROUPING

PARALLEL GROUPING

Inconveniences

1. The lost surface between the cells is important principally in the series grouping case.
2. Risks of damage to the solar cells before mounting and to the interconnections of the cells between themselves at the soldered joints.

B. Shingle Mounting. The cells are mounted similarly to tiles on a house roof; the rear electrode coming directly in contact with the electrode which is in the form of a comb in the entrance face; the soldering between the two electrodes is made at the level of the comb housing.

It is thus essentially a series mounting, allowing a high number of cells per unit surface and, in eliminating the straps, improves the weight ratio of an equal number of cells.

Inconveniences

1. Difficult replacement of a broken cell; generally the sub-module is changed.
2. Difficult to interconnect the cells among themselves.
3. Slight reduction in the active surface of the cell.
4. Not adapted to the fabrication of supple panels.
5. Poor resistance to thermal shocks and to mechanical and vibrational strains.

C. Mixed Mounting. Described by E.J.Stofel, it is a combination of the preceeding mountings: It is more compact than the shingle mounting, but lowers the active surface per cell.

Greater difficulties in mounting and repairs. Demands a very strict tolerance control. Better resistance to thermal shocks or mechanical strains.

D. Comparison Between the System A and B. This is made using the experimental values of Hoffman Electronics, between a sub-module of 5 cells mounted following one of the two systems (2×1 cm).

3.2.1.3 Module Fabrication. Module elaboration is a fundamental step in solar generator fabrication; it is at this stage in effect that the solar cells are realised; soldering of the connection straps or cells to each other.

It is a very delicate operation carried out in special conditioned rooms necessitating a large amount of care and mechanisation if the productivity and reproductability are to be increased.

Each maker has his own secrets of fabrication, to obtain good soldering without deteriorating the solar cell characteristics. He wants the highest performances possible and a high reliability for the lowest price.

The choice of metal for making the connections between cells is also very important. W.R.Cherry has made a list of the properties necessary. Among these are principally:

- an excellent thermal and electrical conductivity
- a large flexibility
- easy soldering.

The majority of metals are covered with a film of gold or tin to obtain easy soldering. Kovar is good from the point of view of expansion, but has to be plated with gold for soldering, and is perhaps preferable to copper.

Palladium does not need a supplementary coating; it can also be obtained in fine yet strong wire form; it would thus be very convenient if it were less expensive.

Finally, a large amount of manual work is necessary if the soldered joints are to be both strong and thermal and mechanically shockproof. In particular the gold coating should be very fine, for if not the excess gold forms with the tin of the solder a very fragile and easily broken eutectic (cf. E.J.Stoffel).

The soldering of the connections is made automatically. Several types of automatic soldering methods exist (by induction or resistance heating, tunnel furnace, oil baths).

Resistance soldering gives the best results; the heat is locally concentrated and easy to control; it is universally used, and consumes a minimum of solder. The tunnel furnace has been used for a long time, but it poses numerous problems of temperature regulation and the length of time needed at high temperature causes deterioration of the solar cell contacts.

Finally, the module elaboration stage is also important from the control point of view; the modules being generally of modest size, fastidious controls should be exercised. All the circuits and the contacts being redundant, it is extremely difficult to know from electrical measurements whether one or several parallel contacts are defective, if one is still good.

An attentive manual and visual examination is thus necessary before the mechanical and thermal qualification tests.

3.2.1.4 Solar Array Fabrication. This necessitates the assembly of modules among themselves to form a certain number of panels or facets; following the size of the array, the intermediary groupings can be made according to the final shape required.

But it can be considered at this stage of the fabrication the module is bonded to its final substrate forming the solar generator's structure. Here again, it is impossible to give precise details of the method because numerous various processes are used by the maker and are related to the way in which the modules are designed. We will note, however, three stages which are generally found in all fabrications:

- base-structure
- bonding of the module to the base
- interconnections between modules.

A. Base-Structure. It is made in a light metal, Al, Mg, Be; aluminium is the most used and the least expensive. It is made from two thin foils of aluminium sandwiching a honeycomb also of aluminium. This base is universally used. It is dimensioned according to the stresses it will have to support. Panels of 0.5 m^2 are currently being made.

The complete array forming the generator is formed from a certain number of panels encased in a rigid frame structure of aluminium which forms the exterior frame of the satellite or those of the panels or paddles attached to the satellite.

The aluminium honeycomb base has the following advantages and inconveniences:

Advantages

- great rigidity
- light weight
- ability to support large temperature variations.

Inconveniences

Poor thermal conductivity.

Numerous research projects are trying to improve the thermal conductivity of honeycomb bases which is particularly disadvantageous in the case of panels oriented towards the sun.

To obtain an excellent electrical isolation between the module and the base, a fine layer of fiberglass is deposited on it; on certain honeycombs, the aluminium foil has been replaced by a thick sheet of fiberglass; easier to make it can be used in the fabrication of curved panels. However, the thermal conductivity is even worse than for a honeycomb completely in aluminium.

The isolating layer on the aluminium should attain 50μ at least to be efficient. Break down voltage: 200 V. Insulation resistance sheet $10^{11} \Omega/\square$.

This results in a severe increase in the framework's weight 150 g/m^2 .

If the module is itself mounted on a thin sheet of epoxy resin (printed circuit type), this electrical insulation is obtained in an excellent way and it is sufficient to glue it with a silicone adhesive onto the bare framework.

B. Bonding of the Module. A silicone based elastomer adhesive, type RTV, gives excellent adhesion having good temperature and vacuum stability. It keeps also a certain elasticity, coupled with a large adherence, which points to a good resistance to thermal cycling ($-100^\circ + 100^\circ\text{C}$).

C. Interconnections between Modules. It is necessary to interconnect the modules between themselves. The same principles are applicable as in the elaboration of a module. It should be added in this case that the soldering is done by hand. An even greater care should be used in this operation or else the modules themselves will be damaged by excessive heating. During this operation it is essential to try and make the soldering only between the wires or the current conduction plates. It is out of the question to make the soldering onto the cells themselves. The current utilisation leads are duplicated or triplicated and teflon sleeved.

3.2.2 Solar Array Tests

3.2.2.1 Electrical Performances Tests. To determine the solar generator's performance in flight, it is necessary to measure its conversion efficiency at Air Mass 0 (AMO) under 140 mW/cm^2 for the case of missions close to the earth. For missions further away, or closer, to the sun, we only know that the solar constant varies as $1/d^2$ ("d" being the distance of the spacecraft to the sun, calculated taking as unity the distance earth-sun).

The measurement of the efficiency is extremely delicate, and has given rise to a lot of work, and certain specifications. It should be remembered finally, that the solar cell efficiency depends on the temperature and consequently, the exact orbital performances of the solar generator will depend on the equilibrium temperature of the solar generator.

3.2.2.1.1 *Air mass definition.* Cf. Section 1.2.1.

3.2.2.1.2 *Solar constant value.* Cf. Section 1.1.1.

3.2.2.1.3 *Efficiency determination.* (AMO - 140 mW/cm²).

For this, one can either artificially simulate the sun, by tungsten or xenon filament lamps, or samples can be measured in the sun, on the ground, that is to say in conditions of AM close to 1 and to 100 mW/cm² and with the aid of a standard cell determine the values at AMO - 140 mW/cm².

A. Measurements from Solar Simulator. Much progress has been made on solar simulators, they are very often adapted to the solar spectrum AMO for the working region of *silicon*. They are being used more and more.

For cells or modules, when the simulator is correctly calibrated, the cell to be tested is illuminated, its temperature being perfectly regulated. The characteristic I-V is obtained and the efficiency is deduced from it. The calibration of a solar simulator is a very delicate and important operation; some specifications have been established by the Solar Energy Work study group of the AIEE, defining the norms of construction.

However, it seems difficult for the users to find a luminous source answering these specifications and covering a surface greater than m². The quality of the source and the manner in which it changes must be often checked using calibrating cells.

Finally, if one wants to test solar panels of a reasonable size ($S \sim m^2$ or more), the use of such a simulator is, in practice, delicate; Measurements in the sun can be made.

B. Measurements in the Sun. The performance tests of the Ranger and Mariner II panels have been made in the sun, and have given rise to a certain number of experimental determinations on the ground, confirmed by the values telemetered during the flight of the satellite concerned.

In the United States, the experimental measurements in the sun have been made at Table Mountain in California (altitude 7,400 ft - 2,120 meters).

In France, Mont Louis has been chosen where a solar furnace has been built (altitude 1,565 m) in the Pyrénées Orientales.

The lighting conditions vary depending on the place where the measurements are made; they are usually situated around 100 mW/cm² and an Air Mass near to 1.

All the experimenters determine the efficiency value by measuring the short circuit current of the cell or panel.

In effect, I_{sc} is

1. very sensitive to the luminous intensity
2. little sensitive to the temperature.

From these measurements in the sun, on the ground, there are two ways to obtain the performances of photovoltaic systems in flight, for the same temperature.

1. The measurements are made on the ground for a certain solar radiation and Air Mass value.

These results are multiplied by a correction factor determined from a cell calibrated and tested under the same conditions.

2. The panel is tested for different Air Masses; the short circuit current value at AMO is obtained by extrapolation of the curve, $\log I_{sc} = f(m)$ (which is a straight line).

The principle of the first method is as follows:

The short circuit current of the panel is determined and the solar intensity is measured by a pyrheliometer, under the smallest Air Mass conditions as are possible. It is necessary to work in collimated solar light to eliminate the radiation of the sky (cf. determination of calibrated cells by J.Zoutendyk and K.Ray).

If W_m is the incident solar energy at Air Mass m , and I_{sc} the measured short circuit current, the value of I_{sc} at 140 mW/cm^2 ($m = 0$) will be equal to I_{sc1} such that:

$$I_{sc1} = I_{sc} \times \frac{140}{W_m} \quad (W_m = \text{mW/cm}^2) .$$

In fact, I_{sc1} is not the true value, because it is necessary to allow for the fact that the solar repartition spectrum at the earth (Air Mass = m) is different from that at $m = 0$ (AMO). It is thus necessary to correct the value obtained by a factor which allows for this phenomenon; it is called the "spectral correction factor".

This factor is determined either by calculation, or experiment, on a solar cell (cf. calibration of a cell at AMO 140 mW/cm^2) having the *same spectral sensitivity*.

The second method avoids the use of a calibrated cell. It is based on the following principle;

The total collimated short circuit current of a cell varies exponentially with Air Mass for an Air Mass below three.

Experiments are made at different Air Masses; a curve is drawn, giving $\log(I_{sc})$ versus Air Mass. A straight line is obtained statistically. By extending this line, I_{sc} for Air Mass 0 is obtained.

J.Zoutendyk has used this method for the measurements at Table Mountain for Air Masses greater than 0.8. He has thus tested the solar panels of Ranger III. He has compared the results obtained with the performances of the panels during flight, just after launching.

He found that attainable accuracies are about $\pm 2\%$ for short circuit currents and $\pm 3\%$ for efficiency extrapolations. Many precautions are necessary to obtain such precision, and J.Zoutendyk has catalogued them and has also given the detailed method.

However, important errors can occur due to the determination of the Air Mass, which is particularly imprecise for large values, and which is particularly sensitive to the atmospheric changes that occur frequently during the day. Also experiments have been made in order to work at Air Mass values less than 1 (Table Mountain only reaches 0.8).

H.Brandhorst has made some measurements in a plane, up to altitude of 13,000 meters; this allows Air Masses between 0.14 and 0.7 to be reached. This method should be more precise therefore, as the different points of measurement can be very close and the atmosphere is very pure.

It seems possible with this method to calibrate solar cells to $\pm 1\%$. More precise than the ground method, it still remains more expensive to carry out and less practical in the case of large panels.

3.2.2.2 *Various tests.* The solar generator should respond, above all, to the different qualification tests which are elsewhere imposed on the complete satellite.

The launch conditions are simulated on the ground (vibration tests, acceleration, noise). Different levels are defined based on the booster used; the resonance frequencies and the effects produced are determined. On the ground, in the large simulators, the solar generator's behaviour is studied under space conditions: vacuum, thermal cyclage, testing under vacuum at high and low temperatures, thermal shocks.

Vacuums are of the order of 10^{-6} torr. Thermal cycling and abrupt temperature variations simulate orbital thermal conditions.

The tested generators are identical to the flight models; mechanical strength tests are carried out for various positions in the three orthogonal directions.

3.3 Operating Photovoltaic Systems Examples

3.3.1 *Introduction*

This chapter describes briefly the operating photovoltaic systems used on recent operating satellites. Explorer 33 belongs to the Explorer family, with solar cells mounted in the same way as Explorer 14. The results are more recent and have been described by MacKenzie. D1 and OAO belong also to the same type.

ATS 1 has its solar cells mounted on the spacecraft skin, such as Relay 1, Fr 1, and many other satellites.

Nimbus II, OGO, Mariner IV, are also described. Their photovoltaic systems use panels. Panels are paddles which are always oriented to the sun. These three recent satellites are the most typical:

- Nimbus II : the largest weather satellite
- OGO : the biggest observatory satellite
- Mariner IV : the most sophisticated solar cell panel technology.

At least, in conclusion, some tables give data on the different satellites launched during these last years.

3.3.2 *French Satellites*

3.3.2.1 *D-1 Series.* This series includes the three satellites D-1A, D-1B and D-1C for operational flight.

D-1A or D-1: also called "Diapason". It was launched successfully on 17th February 1966, by the French booster "Diamant".

(a) The power source of the three satellites is the same. It includes 4 paddles with solar cells on both faces. The angle between the paddle plane and the spin-axis equals 145° .

Each face has 288 cells. 32 solar cells connected in series are grouped in a module. The modules are flat-mounted. On each face, there are 9 modules connected in parallel. There is one series-connected diode per module. The four paddles are connected in parallel with a diode per paddle (Fig.48).

2,304 silicon n/p solar cells (2×1 cm) whose resistivity is $10 \Omega \times \text{cm}$.

(b) Electrical characteristics of one paddle-face:

(100 mW/cm²) AM 1. Sun normal to the paddle. 28°C.

- open-circuit voltage	:	17 V	
- short-circuit current	:	470 mA	
- Maximum Power output	:	5.38 W at 12.5 volts	
- Panel weight breakdown	:		
Bar panel (honeycomb)	:	490 g	66.5%
Weight of cells including (coverslips, adhesives, connections)	:	250 g	33.5%
		<hr/>	<hr/>
		740 g	100%
		<hr/>	<hr/>
- Active area of each face	:	560 cm ²	
- Power density	:	96 W/m ²	
- Specific power	:	7.4 W/kg	
- Efficiency	:	9.6% (AM-1. 100 mW/cm ² . 28°C)	
		i.e.	
		8.2% (AM0.140 mW/cm ² . 28°C)	

(c) The complete characteristics of the solar cell array are given in Table XI and by the Figures 49 and 50.

3.3.2.2 Fr-1

- launched successfully on 6th December 1965, by a scout booster
- total spacecraft weight : 60 kg
- solar cells are body-skin mounted.

The solar generator has the same shape as the spacecraft. It is made up of three rings connected in parallel; each ring is made of 8 identical facets on which the modules are bonded (Fig.51).

There are 160 cells on each facet. Consequently there are 3,840 cells. The cells are grouped in modules: 4 for each rectangular facet and 7 for each trapezoidal facet.

All the modules are connected in series, and are composed of submodules with ten shingled cells for each rectangular facet. In the case of the trapezoidal facet the number of cells included in each submodule varies from 3 to 8. The submodules are connected in parallel (see Figure 52).

(a) Solar cell characteristics

- n/p. 1×2 cm silicon resistivity : $10 \Omega \times \text{cm}$
- coverslide anti-radiations : 150μ

(b) Facet characteristics

- AM-1.100 mW/cm² - 28°C sun normal to the facet
- Maximum output power : 3.07 watts at 16 volts

(c) Solar array characteristics

- see Table XI
- aspect ratio versus incident light is shown in Figure 53

(d) Flight performance

The spacecraft is still normally powered without the use of the second electrochemical Ag-Cd battery.

3.3.3 US Satellites

3.3.3.1 *Explorer XXXIII*. Called also Anchored Interplanetary Monitoring Platform (AIMP). It is a typical small Inter Planetary Monitoring Platform. It is used for the scientific exploration of inter planetary magnetic field and the study of the space environment in the vicinity of the earth and moon.

Shape of solar cell array (Fig. 54)

4 paddles positioned around the spacecraft 90° apart from each other; the angle between the paddles plane and the spar-spin axis plane is 25°.

Power level requirement

After one year in orbit and in the worst conditions of illumination, the power must be equalled at least to 35 watts with a peak of 39 watts during 10' every 12h.

The capability of each paddle face before degradation is at normal incidence (40°C) 42.8 watts at 19.8 volts.

After one year in orbit a degradation of 15% is expected; i.e. 6.4 watts. The result will be a maximum capability of 36.4 watt for each paddle face.

In the worst operating conditions, the average power will be 49.2 watt, for the total array at the end of its life; the minimum instantaneous power will be 40.5 watt in the same conditions.

Power system weight (from MacKenzie)

4 solar array paddles	:	110 kg	61.5%
battery	:	4.9	27.4
prime converter		1.8	10
solar array regulator	:	0.2	1.1
Total		<u>17.9 kg</u>	<u>100%</u>

The power to total array weight ratio of interest is obtained by considering the minimum power at the end of satellite mission. In this case, this ratio is 2.2 w/kg.

Solar generator design

1. Cell characteristics

- n/p silicon solar cell (2×2 cm)
- minimum efficiency : 10.5% (AMO. 140 mW/cm^2)
- thickness : 300μ
- solderless Ti-Ag contacts
- cover slides made of Corning 7,940 fused silica (150μ) with an UV filter (cut-off at $4,100 \text{ \AA}$) for maintaining the light transmission characteristics of the adhesive.

2. Paddles characteristics

- each paddle has 960 solar cells on each face. Thus there are 1,920 solar cells on each paddle.

SOLAR PADDLE SUBSTRATE STRUCTURE

- weight of a paddle = 2.4 kg.

Paddle weight breakdown

- Paddle structure	: 1.2 kg	50%
- 1920 silicon cells	: 0.6	25%
- 1920 coverslides	: 0.3	12.5
- silicon adhesive	: 0.3	12.5
Total	<u>2.4 kg</u>	<u>100%</u>

- an expanded metal silver conductor is mounted directly beneath the solar cell modules in order to provide a path for a sheet current return which cancels the stray magnetic field generated by the current in the solar cells (from MacKenzie).
- the adhesives used are made of silicones (thermal stability) type RTV 40 or RTV 602.

3. Solar cell layout

On each paddle, the cells are grouped into 4 modules which are each isolated electrically from the others by a parallel pair of diodes.

A module is made of 48×5 cells series-parallel layout; the interconnections are made of gold plated molybdenum bus bar.

We find again the principles of redundancy and reliability.

3.3.3.2 *ATS-1*. Launched successfully on 6th December, 1966.

ATS-1 belongs to the Applications Technology Spacecraft program which was created to advance spacecraft technology.

ATS-1 is the first of the series of five satellites. It weighs 700 kg. Cylindrical shape; diameter: 1.40 m; length = 1.50 m.

For *ATS* spacecrafts, three orbit configurations are chosen:

- (a) Spin-stabilized spacecraft with synchronous equatorial orbit (*ATS-1*).
- (b) Gravity-gradient stabilized spacecraft with an orbit inclined roughly by 28.5 degrees.
- (c) Same orbit as A and same stabilization as B.

This program is also the logical continuation of previous experiments made with *Tiros* and *Nimbus* for meteorological applications and with *Telstar*, *Relay* and *Syncom* for space communications.

Power requirements

- For the spacecraft minimum load : 10 watts
- With loads for all the experiments : 210 watts
- Average load depends upon ground programming of the experiments. It is fixed to 160 watts.

Power system weight

Solar array	28 kg	56.5%
Batteries (2)	16 kg	33%
Discharge controllers (2)	3.4 kg	7%
Voltage limiters (2)	1.2 kg	2.5%
TOTAL	<u>48.6 kg</u>	<u>100%</u>

Solar cell array design

1. Cell characteristics

- n/p 1×2 cm phosphorus doped silicon (base resistivity : $10 \Omega \times \text{cm}$)
- Each cell has a fused silica coverslide 750μ thick, with blue filter and anti-reflective coatings.

2. Solar array configuration

22,000 solar cells are mounted on the spacecraft (see Figure 55) which is cylindrical: the solar array can be divided in three sections:

- the aft array with 8 individual cylindrical portion panels. These panels are removed to allow the access inside the spacecraft, the whole array contains 187 strings arranged in parallel.
- the forward array with 66 parallel connected modules. Each module is composed with 3 parallel strings of 62 cells in series. Each module has 186 cells. The forward array: 12,276 cells.

- a small array made for battery charging. It is composed of 12 strings of 15 series-connected cells for each battery. The strings are symmetrically spaced on strips of one cell at 60° degree intervals around each solar array cylinder.

3. Solar array capability

Initial power : 187 watts at 26.9 volts

After 3 years orbit : 125 watt (expected) (see curve from MacKenzie, Figure 56)

The degradation expected is near 33% of the initial power for *three* years.

4. Flight performance

All the experiments are possible; the spacecraft is still completely powered.

3.3.3.3 *Nimbus II*. (Called "C" before launching)

- Launched successfully on 15 May, 1966.
- Nimbus satellites are the largest weather spacecrafts ever built by USA.
- Total spacecraft weight : 410 kg.
- It belongs to the Nimbus Program which uses satellites for meteorological purposes.
- The particular parameters of its orbit (sun synchronous near polar) give a special design of the solar array which is composed of two large panels which can be always oriented to the sun by turning around a single axis. These special conditions are very interesting in order to decrease the solar cell array size and weight.

Power level requirements

160 watts : minimum continuous power.

Lifetime : 6 months

An active control system is used to orient the spacecraft and the solar paddles (minimum power required continuously : 100 watts).

Power system weight : 85 kg

Solar generator design (See Figure 57)

1. Solar cells characteristics

- n/p 2 × 2 cm phosphorous doped silicon
- 150 μ fused silica coverslide with its blue-red filter
- The coverslides were cemented to the silicon slide with Furane 15-E.

2. Solar array configuration

Solar cells are mounted on two platforms: each platform has 5.472 cells on a mounting structure, and is composed of a mounting structure for mechanical rigidity and different accessories for their orientations.

3. Solar cells layout

Solar cells are mounted on one face of the aluminum honeycomb platform and they are series-parallel interconnected.

The platform is divided into 6 boards - boards are identical; each one is composed of 98 modules connected in series; each module consists of 10 cells connected in parallel. In addition, each platform contains a long board made of 6 cell and 3 cell modules in order to use all the available area. Each board is connected to the solar array bus through insulation diodes.

Capability of solar array

- maximum output : 460 watts AMO at the beginning of its life
- minimum output : 387 watts 39.45 volts at 40°C at the end of its life.

Flight performance

In spite of the opening of one series interconnection on one long board in orbit 1,066 the power requirement has always been obtained with a lifetime of one year.

3.3.3.4 *Orbiting Observatory Satellites.* OAO and OGO will be considered. OAO is the typical one of the Orbiting Astronomical Observatory serie. OGO belongs to the same program but this serie is used for Geophysical studies.

All these spacecrafts are typical because of their sizes particularly if the photo-voltaic systems are considered.

3.3.3.4.1 *OAO - Orbiting astronomical observatory.* A schematic view is given by Figure 58; it is the largest unmanned satellite created in order to have a standardized vehicle for many scientific missions with only minor changes.

Its total weight is 1,750 kg; it was successfully launched but it failed after two days in orbit because of the overheating of the primary battery. More than 80,000 solar silicon cells are arrayed on fixed four paddles, the largest ever used.

In the worst conditions of illumination and space environment they were able to generate 680 watts. When sunbeams are normal, the maximum initial power output was 1,000 watts at 28 volts unregulated.

- Power characteristics listed in Table XI.

3.3.3.4.2 *OGO.* OGO is an Orbiting Geophysical Observatory. It belongs to the family of large orbiting satellites used as observatories; the more recently launched one in 1967 was OGO-4. All the spacecrafts of OGO serie have the same shape and characteristics; a spacecraft design can be used repeatedly with only minor modifications for different combinations of experiments. An OGO schematic view is given by Figure 59.

Two particular points must be noted for this solar array:

1. The use of beryllium.
2. A practical solution for the thermal problem concerning this array.

The beryllium is used because of its light weight and its thermal expansion coefficient similar to that of silicon cells. This OGO individual cells are mounted on beryllium plates.

For the thermal problem, it must be considered that the total array receives an incident solar energy of about 10,000 watts, less than 10% is converted into electricity. A great quantity of the incident energy is used to increase the panel temperature; this temperature is limited by the energy loss radiated from the rear surfaces of the panels. It has been necessary to study this surface with caution in the case of OGO. In fact, a

potassium silicate coating were used, and kept the solar cell temperature below 85°C, roughly when the panels were fully illuminated (reported from George Ludwig). In addition, in order to avoid damage to the cells by thermal stresses during satellite night the beryllium substrate thickness was increased in order to have sufficient thermal mass which prevented cooling below -140°C after a night of 2 hours.

The complete array can supply an initial total electrical power of approximately 650 watts. In fact, an effective initial available power of 490 watts at 29.5 volts is obtained; i.e. 37% of losses due to the light transmission through coverslides and filters, orientation errors, and errors in measurement and cell matching.

After one year in orbit, a power output of 300 watts is expected namely about 40% of losses (these data are reported by G.Ludwig).

3.3.3.5 *Mariner IV*. It belongs to Mariner program for the exploration of Venus and Mars planets.

Mariner II launched on 27 August, 1962, successfully to Venus with a previous earlier attempt (22 July, 1962) which had failed. Mariner II obtained exceptional data from Venus, its mass, its magnetic field, its temperature etc.

The first attempt to Mars was Mariner III. It failed. Mariner IV is the first successful spacecraft launched on 28 November, 1964, to the planet Mars.

It flew by Mars 8.5 months later on 14 July, 1965.

- the design of the Mariner series of spacecraft began in 1961. It must produce spacecrafts able to operate missions to both Venus and Mars.
- all the Mariners use two celestial references for three axis stabilization. In their general shapes Mariner II is identical to Mariner IV, in detail Mariner IV is more elaborate, Mariner IV is larger and heavier than Mariner II; with solar panels expended and solar pressure vanes opened Mariner IV spans over 6.75 m, about 1.8 m more than Mariner II.

Mariner IV has 4 solar panels instead of two for Mariner II because the Mars mission carries the spacecraft away from the Sun (cf. Fig.60).

At least great improvements are studied in order to decrease structural weight.

- Spacecraft total weight : 200 kg (Mariner II) - 260 kg (Mariner IV).

Solar array design

1. Solar cell characteristics

- p/n (1 × 2 cm) Boron diffused (500 μ)
- electro-less nickel plated, solder-dipped ohmic contacts
- 22.8 mW at 28°C for the average *bare* solar cell under 100 mW/cm² 2,800°K tungsten illumination.
- a power loss of about 10% is obtained with the average filtered solar cell mounted on its substrate. This loss is broken down as follows:
 - 4% : losses through filter and cover glass
 - 6% : losses of matching, handling, and assembly.
- Coverslide with blue filter (e = 150 μ; cut-off 4,100 Å) bonded to silicon with silicone adhesive (RTV 602) the same technology used on Ranger and Mariner II.

2. Solar array configuration

- the photovoltaic systems is composed of *four* panels oriented toward the sun
- active area : 6.5 m^2
- each panel is divided into 4 electrically-isolated sections
- each section contains 12 modules connected in parallel
- the module is the smallest sub-assembly of solar cells, and was designed such that all soldering connections made directly to the cells would be accomplished before assembly of the module to the panel.
- the photovoltaic array contains 28.224 cells for Mariner vehicle.

Solar generator fabrication

The sections are harnessed to the panel connector with a bondable Teflon wire. The harness is routed along both edges of the substrate spars and is supported with teflon cable clamps. Connecting wires are branched from the main bundle attached to the spars and run across the panel and through these holes (reported by Dawson). All the wires are protected by Teflon.

To minimize the requirement for feed-through holes in the panel and reduce mechanical stress associated with the attachment of the harness cable directly to the modules, a circuit board concept consisting of flat copper ribbon and beryllium copper stand off encapsulated in epoxy fiberglass was developed. The circuit boards provided all the inter-module redundant wiring required and were bonded to the cell surface of the substrate with RTV-40 (reported by Dawson).

Panel substrate design

The design consisted of a 100μ aluminium skin reinforced with lateral 75 corrugations and this substrate matrix was supported over its entire length by two parallel box beam spars. Corrugation skin and spars were bonded together with Shell Epon 913 adhesive.

The entire back surface of the panel was coated with a high-emissivity gloss black paint.

The solar panel substrate weighed about 4.8 kg.

Interconnections

Because thermal shock rates greater than $25^\circ\text{C}/\text{minute}$ are possible (small thermal mass of the Mariner panels) Kovar was investigated and used for bus bar material.

3. Solar array power characteristics

They are given by the Figures 61 and 62. In particular, Figure 59 gives the different values of the output power in several space conditions from testing on Earth.

3.3.4 Conclusions

The tables on page 567 give several data obtained from different authors. In practice, it is more difficult to have data which can be compared one with another. However, the Cherry's list has been chosen and completed with French Operating satellites.

This Table XI shows the total array efficiencies obtained with panels, paddles and skin-mounted solar cells. We notice that the greatest efficiencies are obtained with panels.

The Table 12 gives a comparison between the various power systems of the 3 successfully launched Mariners. Great improvements have been obtained from Mariner II to Mariner IV. Mariner IV has a particularly interesting solar cell system from the view point of the design of a lightweight panel and of the technology of the solar cells assembly; the power density (maximum power to panel weight ratio) is the highest. It is the result of the development of a light weight structure combined with a sophisticated technology of solar cells mounting. Details of this technology are given in Table XIII with the different improvements which still can be expected in the future.

3.4 New Researchs and Developments on Photovoltaic Systems

3.4.1 Introduction

The rapid survey of the photovoltaic systems used has shown the progress which has been made and the present tendencies to reach powers of about a kilowatt, OAO, Mariner IV and several round the earth satellites of the USAF can supply between 600 and 1000 watts.

Many experiments of recent years have shown that it was possible for a power source drawing its energy from the conversion of solar radiation to supply all the range of proposed space experiments.

Powers superior to a kilowatt will be necessary for future uses and various space projects; telecommunications, propulsion, manned satellites and deep space exploration.

Consequently, the NASA has begun several studies in order to attain the objective of 50 kW. The United States has been interested in such systems since 1963. Kenneth Ray has studied numerous systems based on the deployment of a flexible structure on which the solar silicon cells, are mounted.

These systems, which are essentially intended to enlarge the active surface of the collecting system, take advantage of the improvements obtained by the adjustment of solar cells lighter or better adapted to such missions. We can therefore distinguish between the improvements to the solar cells themselves, and the new results which affect more especially the perfecting of light weight structures which can be deployed or inflated.

3.4.2 New Research on Solar Cells

The improvements which aim to increase the performances of the bare cell can be grouped under 2 main headings.

The first consists in using the actual operational cell which has proved its worth, and in increasing its power to weight rates or its active surface.

In order to do so, the thickness of the base is reduced and solar cells, carried out on dendritic silicon which can be up to several centimeters long (1×30 cm) are adjusted.

The second consists in making another type of solar cell, lighter, bigger and less expensive than the present silicon solar cells.

3.4.2.1 Silicon solar cells improvements. The increase in the power to weight ratio of the actual silicon solar cell can result in the increased conversion production or a reduction in the thickness of the cell and its accessories (adhesive, soldered joints, anti-radiation glass, etc.).

The increased conversion production on an industrial scale can hardly be considered without a severe penalization on the landed price. The improvement in the present technology of mounting cells on their substrate will have only poor results and can only be brought about to the detriment of the final quality of the generator and in consequence of its

reliability. However, an interesting improvement for the present conventional cells is the replacement of the glass window by a thin film ($25\ \mu$) which serves the same protective purpose. The actual windows which play an effective role have a thickness of at least $150\ \mu$.

The improvement which promises the best results, consists in reducing the thickness of the silicon plate. Thickness of $200\ \mu$ and $100\ \mu$ are contemplated and Table XIII shows the improvements, taking as a base the technology of Mariner IV which the specialists all agree in considering as the most representative.

In theory and in practice the thickness of the cell cannot be reduced without bringing about a deterioration of the conversion production. For thicknesses of $200\ \mu$ the experimental values obtained are worse than those expected after the calculations.

The thinning down of present cells by a simple reduction of the silicon plate, leads, everything else being equal, to a reduction of 10% in the values of I_{sc} for $200\ \mu$ and of almost 30% for $100\ \mu$ (from Ralph).

Some progress will be made to palliate such disadvantages, but for this type of cell, which is much more delicate and more complicated to manufacture and has a lower performance than the actual thick cells ($500\ \mu$) the landed price will probably be much higher.

3.4.2.2 Thin film solar cells. Another line of research to obtain a power-to-weight ratio and large active area, consists in making photocells of thin films with a suitable active material.

3 materials have been studied and compared and cells have been made, GaAs, CdTe, CdS. At present, the most brilliant results have been obtained with the CdS, thanks to a technique of deposit by thermal evaporation in a vacuum on a plastic substrate (cf. Section 2.4).

Although they have a weaker efficiency than the conventional silicon cells, the CdS cells can normally attain 6% on $55\ \text{cm}^2$ in development manufacture with power-to-weight ratios of 200 watt/kg.

Superior efficiencies have recently been given by Reynolds (8% in standard measurement conditions) who has tested these cells in flight. The samples tested worked very well.

There were 2 panels of 8 cells connected in series. The area of the cells was only $2\ \text{cm}^2$.

Other tests on satellites are in view for October 1967.

3.4.3 New Research on Lightweight Structures

In order to attain powers of a nominal value of 50 kW, the necessary active area will be superior to $350\ \text{m}^2$ for a solar constant of $1.4\ \text{kW/m}^2$ and solar cell efficiencies better than 10%.

With cells which have half this efficiency (the present state of the production of thin film cells) $700\ \text{m}^2$ should be allowed.

This is therefore a very ambitious aim and poses certain problems of deployment and stabilization in space.

The surface should be turned towards the sun to maximize the received energy and to cut down the aspect ratio.

3.4.3.1 *Inflatable structures.* A spherical system may appear attractive; its aspect ratio is constant. However it must be noted that the relation between the useful power and the total available power is 0.25.

In this case a generator of 700 m² with thin cells would have the form of a balloon with a diameter of 30 m. Its interest lies in the fact that mylar could be used as an envelope in which an internal gas pressure of 0.5 torr would be sufficient. This is the internal pressure of Echo 1.

It is interesting to note that:

- the weight of the gas can be disregarded (N₂ used)
- 95% of the weight of the generator is caused by thin film solar cells
- 3% to 5% is the weight of the mylar.

L.D. Massie who studied this possibility in 1963, envisaged average specific powers of 21 watt/kg for a generator of about 50 kW, manufactured with cells of CdS having a 5% efficiency.

At present, CdS cells have made great progress; they attain 5% to 6% with power-to-weight ratios of 175 watt/kg (bare cells). We can therefore affirm that the power-to-weight ratio has doubled in respect of Massie's and a specific power of nearly 40 watt/kg can be expected for the proposed generator.

There are still a certain number of difficulties: its deployment in flight - and problems of folding and interconnections reduce its reliability.

It does not appear that this system has given rise to concrete designs.

3.4.3.2 *Folding Structures.* Considering the present state-of-the-art, it seems difficult in the limits of this paper, to make a comparative study of the various options considered by the different nations who are interested in Space questions.

The aim of 50 kW is, in the long run, useful and interesting; in the present state of our knowledge we must envisage it in order to assure the continuation of the success achieved by photovoltaic devices compared with other autonomous power supplies (nuclear or radio-isotopic reactors etc.).

This aim has the merit of setting the problem of structures, of mechanical deployment systems and the advisability of storage solar energy converted into electricity,

In the United States table models already exist and are submitted to different space environment tests and mechanical and thermal stresses. The 20 kW step is well advanced and is studied either with silicon or with film cells CdS and CdTe.

The designs belong to 2 main types differing in the idea of the deployment system.

A. Folding structures with rigid panels

The first consists of a certain number of strongly made rigid panels, folded during the launching and which spread out in flight so as to form a wing; the panels fixed to the body of the satellite are assembled to supply the total power desired.

Example: The system studied by Boeing Co. under the direction of J.P.L.* (Fig.63).

* Jet Propulsion Laboratories.

The aim is to attain a power of 50 kW in standard measurement conditions. For that, we have 4 panels on 2 perpendicular axes, each panel representing 12.5 kW. This study is well advanced and the problems of conception and technology are practically solved.

According to D.W.Ritchie, there are no further difficulties for the construction of the total system.

The characteristics will then be as follows:

- 46 kW at 1 A.V.
- active solar cell area : 425 m^2 (that is, about 108 W/m^2)
- total weight of panels : 860 kg
- power-to-weight ratio : 53.5 W/kg
- silicon solar cells (thickness : 200μ)
Number > 1 million ($2 \times 2 \text{ cm}$). $\rho = 9 - 10\%$ AMO 28°C with a special arrangement on the electrodes.

The structure is made of beryllium and many problems have had to be solved in order to machine this metal and to assemble it so as to minimize the weight.

Problems of assembly and mounting of the cells together and of the resistance of the material in dynamics are not really acute and will soon be solved.

B. Roll-up systems

The second system uses a flexible substrate which is rolled on a cylinder and afterwards unrolled in flight. This principle has been realized in two different ways.

One method has been studied by the Ryan Aeronautical Co. with J.P.L. and the other by K.Ray at Hughes Aircraft Co.

(a) Ryan - J.P.L. system

The first system seeks to obtain a power of about one kilowatt with the help of 4 panels of 50 sq. ft each; the assembly and the detail of the panel is shown in Figure 64.

The size of the total generator is 200 sq. ft (18.5 m^2); this will shortly be increased to 800 sq. ft (74 m^2) after a detailed study of a structure with 4 panels of 200 sq. ft each.

The characteristics of the actual design are as follows:

- panel 50 sq. ft (4.65 m^2)
- weight 11.3 kg (with solar cells and interconnections)
- power-to-weight ratio : 28 W/kg .

The deployment system requires the use of an electric motor which by means of a magnesium gear-wheel meshes a drum, with a diameter of 30 cm, on which is rolled the solar cells array. The extendable masts are made of titanium of 150μ calibrated thickness which allows it to be rolled on the drum; each drum spreads only one array of cells.

In future we hope to increase the power-to-weight ratio, by improving the materials used (substrate, solar cells, machinery).

(b) Fisca (Flexible Integrated Solar Cells Array, Figure 65)

The second realization is called Fisca, it will show the feasibility of a folding device supplying high power levels with the greatest possible, power-to-weight ratios.

The following table sums up the ratios expected for the various power levels:

Expected Weight Breakdown

<i>Power Level</i>	<i>Total Weight kg</i>	<i>Panel Weight / Total Weight</i>	<i>Dimensions Panels</i>	<i>No. Panels</i>	<i>Watt/kg</i>
1 kW	14.7	34%	0.37 × 1.5m	2	68.0
10 kW	107	52.5%	0.74 × 5.8m	2	93.5
20 kW	214	47%	0.74 × 5.8m	4	93.5

These powers by weight units result from the improvements which will be made to new models and obtained from the manufacture of a prototype of 500 watts which has been submitted to environment tests.

The form of this 500 watts model is very close to the previously described with the slight difference that its conception allows two solar cell arrays to be spread out in 2 diametrically opposite directions from the same roll.

This deployment is realized by means of 4 systems manufactured by De Havilland (two for each panel). These systems, called "De Havilland masts" are made up of 6 steel blades which are rolled flat inside a box. At the moment of deployment they are pulled out by a motor and rolled on themselves to form a rigid tube. Kenneth Ray has described how the dendritic silicon cells of 1 × 30 cm used are interconnected. He has also described the different mechanisms making up the system and the results of the various ground tests to which the prototype was submitted.

In the light of these very encouraging results which confirm the analytic predictions, it would appear possible to look forward with optimism to the realization in the near future of 20 kW systems which give the expected performances.

3.4.4 Conclusions

Many other possible ways exist of realizing photovoltaic systems which have powers of several tens of kW.

The problems set by the structures and the solar cells which are to be fixed on them seem to have been correctly solved on medium powered prototypes (500 watts).

The systems which fold up on themselves have the advantage of compactness and are very useful for storing in the rocket. The systems with rigid panels are more cumbersome.

Finally we must consider the prospects offered by these systems and the values which characterize their expected performance, often predicted from the characteristics of the actual prototypes which have powers nearing the kilowatt.

As soon as powers nearing 50 kW or higher are envisaged, the servitudes inherent in the exploitation of solar energy, examined in the first chapter, become of the highest importance.

The increase in the panel area provokes new problems concerning the thermal control of the panels which receive an enormous incident energy (more than 500 kW in the case of systems at 50 kW electric) become preponderant and take on an importance which is hardly ever met in the case of systems using lesser powers, although OGO, OAO or Mariner IV are already very well finished and perfected compared with systems using weaker powers. It should be remembered that the cells are sensitive to temperature, the upper limit of which is situated for the thin film cells at 125°C for CdS ($\rho = 6\%$ at 28°C; $\rho = 2.5\%$ at 125°C), from F. Shirland.

A last equally important point is the collection of the current produced by the panels, since these high powers require a large intensity current. (1250^A at 40 volts for 50 kW).

In the present state of technique, these deployable systems are made by using silicon cells.

Silicon cells are efficient, stable and proven in space environment in respect of thin film solar cells. However the recent attempts which are reported by Reynolds give good results in the case of CdS cells made on the roll-up array studied by Hughes Aircraft, in order to obtain a 15 m² deployable solar array (Lewis Research Center).

At least, the cost of a high power array will be decreased by the use of thin film cells; at the present time its cost is estimated to be \$20 millions (100 millions of francs) by A.E. Potter for a 50 kW silicon array.

Deployable High-Power Solar Arrays Under Study

(From A. Potter)

<i>Nominal Power (kW)</i>	<i>Nominal Area (m²)</i>	<i>Solar Cell Type</i>	<i>Company</i>	<i>Construction Style</i>
50	465	Silicon 200 μ thick	Boeing	Folding
20	186	Silicon conventional	R.C.A.	Folding
0.5	4.6	Dendritic silicon Conventional cell Thin film Cds	Hughes Ryan Lewis	Roll-up flexible Roll-up flexible Roll-up flexible
0.2	1.8	Conventional	Fairchild	Roll-up

REFERENCES FOR SECTION 1

- Solar radiation, ed. N. Robinson (Elsevier 1966).
- Space Radiation, in Space Radiation effects on materials, ASTM Special Technical Publication 330 (Amer. Soc. for testing and materials). 1962.
- B.J. O'Brien. Review of studies of trapped radiation with satellite-borne apparatus. Space Science Reviews, I, No.3, 1963, pp.415-484.
- A.E. Mann, F.N. Benning. Reaching for the sun (a series of articles on solar simulation), Environmental Quarterly, September 1963 to September 1964.

REFERENCES FOR SECTION 2.1

- J.J. Loferski. Theoretical Considerations Governing the Choice of the Optimum Semiconductor for Photovoltaic Solar Energy Conversion, J. Appl. Phys. 27, 1956, p.777.
- M. Wolf. Limitations and possibilities for improvement of photovoltaic energy converters. Proc. I.R.E. 48, 1960, pp.1246-63.
- T.S. Moss. Solid State Electr. 2, 1961, p.222.
- H. Valdmann, M. Rodot, H. Rodot. Comm. Coll. Int. Dispositifs Semi-Conducteurs (Paris 1961).
- R.C.A. Review, Vol.22, 1961, No.1.
- E.S. Rittner. Photoconductivity Conference, Wiley, 1956, p.215.
- J. Tauc. Photo-and thermoelectric effects in semiconductors (Pergamon Press 1962).

REFERENCES FOR SECTION 2.2

- M. Rodot. Les matériaux semiconducteurs (Dunod 1965).
- R.A. Smith, Semiconductors (Cambridge Univ. Press, 1959).
- T.S. Moss. Optical properties of semiconductors (Butterworths 1959).
- I.S. Blakemore. Semiconductor statistics (Pergamon 1962).
- F.A. Kröger. The chemistry of imperfect crystals (North Holland, Amsterdam 1964) translated from Russian.
- Coll. sur les effets de rayonnements sur les semiconducteurs, Royaumont 1964 (Dunod, 1965).
- V.S. Vavilov. Effects of radiation on semiconductors (Consultant Bureau 1965), translated from Russian.
- Compt. Rend. Conf. Int. sur les Photopiles en Couches Minces (Marseille 1966). Rev. Phys. Appl. 1, No.3, 1966.

REFERENCES FOR SECTION 2.3

- W.Shockley, J.Queisser. Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. J. Appl. Phys. 32, 1961, p.510.
- J.Tauc. Photo and thermoelectric effects in semiconductors. (Pergamon Press 1962).
- Compt. Rend. Conf. Int. sur les Photopiles en Couches Minces (Marseille 1966), Rev. Phys. Appl. 1, No.3, 1966.

REFERENCES FOR SECTION 2.4

- Solar Cells for Space Craft Power System (edited by Hoffman, Electr. Corp. El Monte, California, USA).
- F.C.Treble. Recent Developments in Silicon Solar Cells, Comm. Meet. Prop. and Energ. Panel, AGARD (Liège 1967).
- M.Rodot. Les Photopiles au CdTe, Comm. Meet. Prop. and Energ. Panel, AGARD (Liège 1967).
- J.Tavernier, P.Sibillot, E. Le Grives. Comm. Meet. Prop. and Energ. Panel, AGARD (Liège 1967).
- F.A.Shirland. The History, Design, Fabrication and Performance of CdS Thin Film Solar Cells, Adv. Energy Conv. 6, No.4, 1966, p.201.
- D.C.Reynolds. Cadmium Sulfide Solar Cells. Comm. Meet. Prop. and Energ. Panel, AGARD (Liège 1967).

REFERENCES FOR SECTION 3.1

- S.H.Winkler. Optimum design of a space vehicle storage system. 14th Annual Proceedings Power Sources Conference.
- C.C.Osgood and S.H.Winkler. Optimizing the design of a solar power supply systems. American Astronautical Society. Meeting January 18-20, 1960.
- Bernard St.Jean. (NASA TND-1904).
- Ralph M.Sullivan (N 65 29814). Shadow effects on a series-parallel array of solar cells.
- N.A.Goyette. Series-parallel interconnections for solar arrays. S.T.L. 8949-0007-NU-000.
- P.R.Dennis and S.Seshu. Reliability and redundant circuitry. (NASA CR-128).
- W.A.Klein and S.N.Lehr. Reliability of solar arrays. Vol.RQC - 11. No.3, October 1962.
- Kirk M.Dawson and G. Curtis Cleven (JPL). Design and reliability considerations for the Mariner Mars 1964 spacecraft power system.

- P.S.Nekrasov. Protecting solar array output against individual cell failures.
- Ramond C. Waddel, X-711-67-176. Early results from the solar cell radiation damage experiment on ATS-1.
- W.Cooley and R.J.Janda, NASA SP-3003. Handbook of space-radiation effects on solar-cell power systems.
- W.R.Cherry and J.A.Zoutendik. State of the Art in solar cell arrays for space electrical power. Space Power Systems Engineering. Progress in Astronautics and Aeronautics. Vol. No.16.
- W.H.Evans, A.E.Mann, et al. Solar panel design considerations. Space Power Systems. Progress in Astronautics and Rocketry. Vol. No.4.
- J.Douglas Sailor. Advances in Astronautical Sciences. Vol. No.5.
- Alfred Thelen. The use of vacuum deposited to improve the conversion efficiency of silicon solar cells in space. Energy Conversion for Space Power. Progress in Astronautics and Rocketry. Vol. No.3.
- Hoffman Electronics Corporation. Solar cells for spacecraft power systems.

REFERENCES FOR SECTION 3.2

- F.C.Treble. Recent Developments in Silicon Solar Cells. Preprint AGARD Liège June 1967.
- D.W.Ritchie and J.D.Sandstrom (JPL). Multikilowatt Solar Arrays. 6th Photovoltaic Specialists Conference. Cocoa Beach, March 1967.
- E.J.Stofel. Solar Cell Power Systems for Air Force Satellites. 6th Photovoltaic Specialists Conference.
- W.R.Cherry and J.A.Zoutendyk. State of the Art in solar cell arrays for space electrical power. Space Power Systems Engineering.
- O.C.Butcher et al. Development Status of Solar Generators based on silicon, photovoltaic cells. Preprint AGARD Liège, June 1967.
- John A. Zoutendyk. 1. A method for predicting the efficiency of solar cell power systems outside the earth's atmosphere. JPL - TR No. 32.259. 2. Solar - cell power systems testing. JPL - TR No. 32.250.
- Henry W.Brandhorst Hr. (N 65 - 29.447). Air Plane Testing of solar cells.
- K.A.Ray. Design parameters for photovoltaic power conversion in space. May 1963.

REFERENCES FOR SECTION 3.3

- André Lebeau. Le Programme Spatial français. Sciences et industries spatiales 3/4, 1967.

Charles M. Mackenzie. Solar power systems for satellites in near-earth orbits. 6th Photovoltaics Specialists Conference. Cocoa Beach, March 1967.

K.M. Dawson and J.V. Goldsmith. Mariner Mars 1964 power-systems design and flight performance.

Dan Schneiderman et al. Recent mariner spacecraft-design and flight. Advances in the Astronautical Sciences, Vol.19.

W.R. Cherry and J.A. Zoutendyk, see References Section 3.1 or 3.2.

George H. Ludwig (NASA TN-D 2646). The orbiting geophysical observatories.

REFERENCES FOR SECTION 3.4

Kenneth A. Ray. 1. Flexible solar cell arrays for increased space power. IEEE Transactions on aerospace and electronic systems, Vol. No.1, January 1967. 2. The development of a flexible deployable solar array. 6th Photovoltaics Specialists Conference, March 1967.

L.D. Massie. Thin film photovoltaic cells for solar energy conversion. IEEE Vol. AS No.3, December 1963.

P. Vasseur. Perspectives offertes par les cellules solaires en couches minces pour les applications spatiales. Revue de Physique Appliquée September 1966, No.3.

D.W. Ritchie and J.D. Sandstrom. Multikilowatt solar arrays. Cocoa Beach, March 1967.

George S. Hunter. Requirements for Solar Arrays Spurring New Techniques. Aviation Week and Space Technology, August 14, 1967.

P. Rappaport. Photovoltaic Power. J. Spacecraft, July 1967.

Andrew E. Potter Jr (NASA SP-131). Conventional and thin-film solar cells.

TABLE I
Fraction of Solar Electromagnetic Energy
Radiated in Various Wavelengths

<i>Wavelength (Å)</i>	<i>Radiation</i>	<i>% of Solar Electromagnetic Energy</i>
1 – 2000	far ultraviolet	0.2
2000 – 3800	near ultraviolet	7.5
3800 – 7000	visible	41.0
7000 – 10000	short infrared	22.0
10000 – 20000	medium infrared	23.0
20000 – 100000	long infrared	6.0

TABLE II
Solar Energy Received by 1 cm² at
Normal Incidence on Different Planets

Mercury	6.5 G ₀
Venus	1.9 G ₀
Earth	G ₀ = 139.5 mW/cm ²
Mars	0.4 G ₀

TABLE III
Minimal Thickness *l* for Different Materials
with Direct or Indirect Transitions
(after Rappaport)

<i>Material</i>	<i>E₀ (eV)</i>	<i>Transitions</i>	<i>Thickness <i>l</i> (μ) Needed to Absorb 90% of radiations $h\nu > E_0$</i>
Si	1.11	indirect	150
InP	1.25	direct	0.8
GaAs	1.40	direct	2
CdTe	1.45	direct	10
GaP	2.23	indirect	10 to 100 ?
CdS	2.4	dir. (+ imp.level)	1

TABLE IV
Properties of Some Semiconductors at 300°K

<i>Material</i>	E_0 (eV)	χ (eV)	qV_D (eV)	μ_n (cm ² /V.s) for n :		μ_p (cm ² /V.s) for p :		τ_p (s)
				10 ¹⁵ cm ⁻³	10 ¹⁸ cm ⁻³	10 ¹⁵ cm ⁻³	10 ¹⁸ cm ⁻³	
Si	1.1	4.01		1300	800	500	250	10 ⁻⁷ – 10 ⁻⁴
InP	1.25			4600		150		
GaAs	1.40	4.07		9000	4500	450	150	10 ⁻⁸ – 10 ⁻⁶
CdTe	1.45	4.28	0.33	1200		50		10 ⁻¹⁰ – 10 ⁻⁸
ZnTe	2.3	3.53	0.18			100		
CdS	2.4	4.79	0.07	295		(15)		10 ⁻¹⁴ – 10 ⁻⁹

TABLE V
Heights of Semiconductor-to-Metal Barrier
(after Mead)

<i>Semiconductor</i>	<i>Metal</i>	E_B (eV)
n-CdS (vacuum-cleaved)	Au	0.78 – 0.80
	Pt	0.85 – 0.86
	Ag	0.56 – 0.58
	Cu	0.35 – 0.36
	Ni	0.45
n-CdS (chemically deposited)	Au	0.66 – 0.68
	Pt	1.1 – 1.2
	Pd	0.59 – 0.62
	Ag	0.35
	Cu	0.41 – 0.50
n-CdSe (vacuum-cleaved)	Au	0.49
	Pt	0.37
	Ag	0.43
	Cu	0.33
n-CdTe (vacuum-cleaved)	Au	0.60 – 0.71
	Pt	0.58 – 0.76
	Ag	0.66 – 0.81
	Al	0.76

TABLE VI

Short-Circuit Current J_{sc} and Open-Circuit Voltage V_{oc} for a Junction
Between Two Materials 1 and 2, Either Photoconductors
(PC: $n_{inj.} \gg n_{eq.}$) or Semiconductors (SC: $n_{inj.} \ll n_{eq.}$)
(after Keating)

Mat. 1	Mat. 2	Expressions of V_{oc} and J_{sc}	Observations
PC	PC	$qV_{oc} = \Phi_0 - \frac{kT}{2} \log_e \frac{\tau_{n1}\tau_{p2}}{\tau_{n2}\tau_{p1}}$ $J_{sc} = qg \frac{L_{a1} + L_{a2}}{\beta}$	
PC	SC (p-type)	$qV_{oc} = \Phi_0 - \frac{kT}{2} \log_e \frac{p_{02}\tau_{n1}(L_{n2} + \tau_{n1}S_n)}{g\tau_{p1}\tau_{n2}(L_{a1} + L_{n2})}$ $J_{sc} = qg \frac{L_{a1} + L_{n2}}{\beta'}$	if $\frac{L_{a1}}{L_{a2}} \ll$ $\frac{\tau_{n1}}{\tau_{n2}} \exp\left(-\frac{\Phi_n}{kT}\right)$
PC	SC (p-type)	$qV_{oc} = \Phi_0 - kT \log_e \frac{L_{a1} p_{02}}{g\tau_{p1}(L_{a1} + L_{n2})}$ $J_{sc} = qg \frac{L_{a1} + L_{n2}}{\beta'}$	if $\frac{L_{a1}}{L_{a2}} \gg$ $\frac{\tau_{n1}}{\tau_{n2}} \exp\left(-\frac{\Phi_n}{kT}\right)$
SC (n-type)	SC (p-type)	$qV_{oc} = \Phi_0 - kT \log_e \frac{p_{02}L_{p1}\tau_{p1}^{-1} + n_{01}L_{n2}\tau_{n2}^{-1}}{g(L_{n2} + L_{p1})}$ $J_{sc} = qg(L_{p1} + L_{n2})$	

NOTATION

g = injection rate

Φ_0 = barrier in the dark

L_n, L_p = diffusion lengths of electron and holes

L_a = ambipolar diffusion length (formula (25))

n_0, p_0 = carrier densities in the dark

τ_n, τ_p = carrier lifetimes, assumed to be independent of g

$$\beta = \frac{L_{a1}^2}{2L_{p1}^2} - \frac{L_{a2}^2}{2L_{p2}^2}; \quad \beta' = \frac{L_{a1}^2}{2L_{p1}^2} - 1$$

S_n = electron recombination rate at the interface

TABLE VII
Performances of Photocells

<i>Material</i>	<i>Photovoltaic Structure</i>	<i>Efficiency (%)</i>		<i>Specific Power (W/kg)</i>	<i>Stability</i>	
		<i>Laboratory</i>	<i>Industry</i>		<i>without irradiation</i>	<i>under irradiation</i>
Si crystal	p-n junction	11-15	10-12	60	excellent	poor
GaAs	{ crystal p-n junction	11				
	{ film Pt contact	4		200	good	
CdTe	{ crystal {CdTe-Cu ₂ Te	9				
	{ film {see Section 2.3.3.1}	5		165	mean	good
CdS	{ crystal {CdS-Cu ₂ S	9				
	{ film {see Section 2.3.3.2}	6-8	4-7	240	good	good

TABLE VIII

<i>Material</i>	<i>Year</i>	$\eta(\%)$	<i>Specific Weight*</i> (kg/kW)	<i>Specific Area</i> (m ² /kW)	<i>Cost*</i> (10 ⁴ F/kW)
Si single crystal	1964	12	60	10	250
	1967	12	50	10	180
	1970	(12)	(25)	(10)	(150)
CdTe thin-film	1964	3	—	—	—
	1967	5	9	24	—
	1970	(6)	(7)	(20)	(20)
CdS thin-film	1964	4	—	—	—
	1967	6	6	20	50
	1970	(7)	(5)	(17)	(10)

* Including substrate

TABLE IX
State-of-the-Art Weight Breakdown

<i>Component</i>	<i>Material</i>	<i>Weight Per Unit of Cell Area, kg/m²</i>	<i>% of Total Weight</i>
1. Cover slides	special glass (150 μ)	0.318	6.8
2. Solar cells	silicon (350 μ)	0.850	15.2
3. Connectors	copper foil (50 μ)	0.175	3.1
4. Solders		0.030	0.5
5. Busbars		0.070	1.2
6. Cements	total thickness (5 μ)	0.084	1.5
7. Insulating sheet	laminate (100 μ)	0.193	3.4
8. Panel with support	Al. honeycomb 6.2 mm cells in 25 μ foil with 250 μ skins.	3.820	68.3
	Panel 37 mm thick tape- ring to 12.5 at edges, supported on tubular booms	—	—
	TOTAL	5.6 kg/m²	100%

from F.C. Treble

TABLE X

	<i>Flat Mounting</i>	<i>Shingle Mounting</i>
Active area (per cell)	1.9 cm ²	1.8 cm ²
Cells/ft ² (max.)	415	455
Packing factor (%)*	85%	88%
Watts/m ² (cell efficiency 10%) AMO. 140 mW/cm ²	118 watts	122 watts
Efficiency	8.45%	8.7%

* Packing factor = Total active area per unit panel area

TABLE XI
Spacecraft Power System Characteristics

	<i>Ranger 6 and 7</i>	<i>Mariner Mars 64</i>	<i>Nimbus II</i>	<i>OAQ</i>	<i>Explorer XII</i>	<i>Tiros $\theta = 45^\circ$</i>	<i>Relay 1</i>	<i>D-1</i>	<i>FR-1 ($\theta = 160^\circ$)</i>
Array attitude versus sun.0: oriented or no (N.O.)	0	0	0	NO	NO	NO	NO	NO	NO
Number and size solar cells	Si (1 × 2) 9.792	Si (1 × 2) 28.224	Si (2 × 2) 11.000	Si (1 × 2) 80.000	Si (1 × 2) 5.600	Si (1 × 2) 9.120	Si (1 × 2) 8.400	Si (1 × 2) 2.304	Si (1 × 2) 3.840
Mounting	Panels	Panels	Panels	Paddles	Paddles	Body	Body	Paddles	Body
Weight for array (kg)	18.6	32		124	4.95	11	11.6	2.96	6.5
Weight of storage (kg)	24	15		76	2.85	18	12.6	2	4.8
Total weight of power systems (kg)	42.6	47	85	200	7.80	29	24.2	4.96	11.3
Area of array (m ²)	2.3	6.5	4.5	22	1.4	1.65	1.6	0.8	0.77
Array weight per unit area (kg/m ²)	8	4.9		5.6	3.5	7.2	7.3	3.7	8.4
Maximum power (watt) AMO.140 mW/cm ² :	226*	680*	460*	980*	20.4	51	35	14	17
- Per unit array weight (W/kg)	12	21.3		7.9	4.1	4.6	3	4.7	2.8
- Per unit array area (W/m ²)	100	105	102	45	14.5	31	22	17.5	22.6
- Per unit system weight (W/kg)	5.3	14.5	5.4	4.9	2.6	1.75	1.45	2.8	1.54
TOTAL ARRAY EFFICIENCY %	7.1*	7.5*	7.3*	3.2*	1.0	2.2	1.55	1.25	1.6

* At 55°C.

** The paddles normal to sun line.

TABLE XII

Comparison Between the 3 Mariners Power Systems

<i>Satellite Name :</i> <i>Flight to :</i> <i>Launch day :</i>	<i>Mariner II*</i> <i>Venus</i> <i>August 26, 1962</i>	<i>Mariner IV**</i> <i>Mars</i> <i>November 28, 1964</i>	<i>Mariner V</i> <i>Venus</i> <i>June 1967</i>
Number of panels	2	4	4
Total number of solar cells (1 × 2)	10,710 P/N	28,224 P/N	17,640 P/N
Total active area (m ²)	2.5	6.5	4.1
Battery weight (kg)	15.3	15	15
Panel weight (kg)	19.5	32	33
Total power system weight (kg)	34.8	47	48
Maximum power: AMO. 140 mW/cm ² . (watt)	209	680	370
Power to panel weight (W/kg)	10.7	21.3	11.2
Specific power (W/kg)	6	14.5	7.7
Power density (W/m ²)	84	105	90
Total array efficiency (%)	6	7.5	6.4

* Data from J. Zoutendyk

** Data from W. Cherry

TABLE XIII

Comparison of Solar Cell Stack Weights
and Power Density

from D. W. Ritchie

<i>Materials</i>	<i>Technology</i> <i>Mariner IV</i> <i>500 μ Thick Cell</i>	<i>Improvements</i> <i>Developmental</i> <i>200 μ Thick Cell</i>	<i>Improvements</i> <i>Developmental</i> <i>100 μ Thick Cell</i>
Cell	1.00 kg/m ² 52.6%	0.34 kg/m ² 35%	0.24 kg/m ² 34.1%
Filter	0.30 kg/m ² 15.8%	0.16 kg/m ² 16.5%	0.05*kg/m ² 7%
Filter Adhesive	0.05 kg/m ² 2.7%	0.05 kg/m ² 5.5%	
Bus Bar	0.12 kg/m ² 6.3%	0.12 kg/m ² 12.5%	0.12 kg/m ² 17.3%
Dielectric	0.10 kg/m ² 5.3%		
Interconnections	0.12 kg/m ² 6.3%	0.12 kg/m ² 12.5%	0.12 kg/m ² 17.3%
Thermal coatings	0.12 kg/m ² 6.3%	0.12 kg/m ² 12.5%	0.12 kg/m ² 17.3%
Adhesive	0.09 kg/m ² 4.7%	0.05 kg/m ² 5.5%	0.05 kg/m ² 7%
TOTAL STACK	1.90 kg/m ² 100%	0.96 kg/m ² 100%	0.70 kg/m ² 100%
Power density 140 mW/cm ² - 55°C	105 w/m ²	108 w/m ²	100 w/m ²
Specific power	55 w/kg	113 w/kg	143 w/kg
Array energy conversion efficiency %	7.5%	7.7%	7.15%

* This point can be improved by the use of an integral coverslip which is under development. 25 μ thick SiO₂ integral coating can be applied. This coating is not "space proven".

Fig. 1 Solar spectrum in outer space (earth orbit, A.M. zero) (doc. Smithsonian Inst.)

Fig. 2 Solar spectrum on earth (air mass number m): (after Robinson, Solar Radiation, Elsevier, 1966)

Fig.3 Variation of the intensity of solar flux, with air-mass number m , different wavelengths. Curve M is a mean valid for the whole spectrum.
(After Robinson, Solar Radiation, Elsevier 1966)

Fig.4 Spectrum of a solar simulator (doc. Spectrolab)

Fig.5 Band scheme illustrating (a) absorption of photons, (b) collection of photo-carriers, by a silicon solar cell

Fig.6 Equivalent circuit of a solar cell

Fig.7 Band scheme of a p-n junction: (a) in the dark; (b) under illumination - in the space-charge region, a Fermi level is no more defined, and quasi-Fermi levels for electrons and holes, satisfying Equations (11) and (12) respectively, are shown

Fig.8 Current-voltage characteristic and load-time

Fig.9 Maximum theoretical efficiency of a photocell for different materials, plotted versus their bandgap E_0 (after R.E.Halsted, J. Appl. Phys. 28, 1957, p.1131)

Fig. 10 Absorption coefficient of various semiconductors versus wavelength
(after P. Rappaport, Rev. Phys. Appl. 1, 1966, pp.154-9)

Fig. 11 Band scheme at a vacuum-semiconductor interface

Fig. 12 Localized level due to imperfections in CdTe.

(a) non-identified defect obtained by short heating under Cd pressure or by electron bombardment;

(b) doubly ionized vacancy V_{Cd} or vacancy-impurity complex

(The ionization states of the centers are indicated when their electron is bound to the centers; the figures give the distance of the levels to the nearest (valence or conduction) band, in eV)

Fig. 13 (a) Electron and (b) proton-damage coefficient K as a function of particle energy ϵ , for p-type silicon (after Cooley and Janda, NASA SP-3003)

Fig. 14 Band scheme of a metal-to-semiconductor contact in the dark

Fig. 15 Barrier energy of different metals on ZnS (electronegativity dependent) and on GaAs (Surface state dependent) (after C. A. Mead, Solid State Electr. 9, 1966, p. 1023)

Fig. 16 Band scheme of a heterojunction: (a) in the dark, (b) under illumination

Fig. 17 Load characteristics of a photovoltaic cell for two different light flux:
(a) high injection conditions, (b) low injection conditions

Fig. 18 Band scheme of a CdTe photocell (a) after Cusano = steep heterojunction,
(b) after Bernard et al. = progressive homojunction

Fig. 19 Band scheme of a CdS photocell, after Reynolds (Meet. of Prop. and Energ. Panel AGARD, Liège 1967)

Fig. 20 I-V characteristic of a Si-photocell (AM zero) at different temperatures (doc. S.A.T.)

Fig. 21 Relative variation of a Si-cell characteristic with intensity of light flux (doc. Hoffman)

Fig. 22 Spectral response of a blue-shifted and a red-shifted Si-cell, and mean response of a cell devised for AM zero use (doc. Hoffman)

Fig. 23 Current voltage characteristic for Bell Tel. Lab. blue-shifted n/p 1Ω cm Si solar cell under 9.5 MeV proton irradiation (after Cooley and Janda, NASA SP. 3003)

Fig. 24 Time for 25% reduction in short circuit current for n/p 1Ω cm Si cells in circular equatorial orbits of various altitudes (after Cooley and Janda, NASA, SP. 3003)

A = vacuum-deposited gold grid
 B = p- Cu_{2-x}Te (100 Å)
 C = n- CdTe (10 μ)
 D = n- CdS (1 μ)
 E = Mo foil (50 μ)

Fig. 25 Structure of a CdTe solar cell

Fig. 26 Load characteristics of a good, large area CdTe thin-film solar cell (after Cusano, Rev. Phys. Appl. 1, 1966, p.195)

Fig. 27 Spectral variation of I_{sc} for constant incident energy, for a CdTe solar cell (after Cusano, Rev. Phys. Appl. 1, 1966, p.195)

- A = plastic cover
- B = embedded gold grid
- C = p-Cu₂S
- D = n-CdS
- E = metallization
- F = polyimide substrate

Fig. 28 Structure of a CdS solar cell

Fig. 29 I-V characteristic of a CdS thin-film solar cell (after Shirland, Adv. Energy Conv. 6, No. 4, 1966, pp. 201-22)

Fig. 30 Spectral response of a CdS solar cell: (a) without, and (b) with a superimposed white light (after Shirland, Adv. Energy Conv. 6, No. 4, 1966, pp. 201-22)

Fig.31 Theoretical aspect ratio of a plane, a cylinder and a cone
(with $\phi = 30^\circ$ and $\phi = 60^\circ$)

Fig.32 Average aspect ratio of a satellite shape

FIGURE 33

FIGURE 35

FIGURE 36

FIGURE 34

FIGURE 37

Fig. 38a

Fig. 38b

Effects on shadowing of one complete row of parallel cells. I-V characteristics (two cells shadowed at a time) for two particular submodules

(From Ralph SULLIVAN)

Fig. 38c

Fig. 38d

Effects on total array characteristics of shadowing several different strings of 16 series cells

Effects of a shadow covering:

A = 1	series cells shadowed	× 1 parallel	cell shad.
B = 1	"	"	"
C = 2	"	"	"
D = 16	"	"	"

* Percent power output at $15.5 < V < 20$

Fig. 38 Shadow effects on a 48×8 series-parallel array of solar cells

Fig.39 Flight data on silicon solar cell life radiation damage. p/n 1 $\Omega \times \text{cm}$.
(from Cooley and Janda.)

Fig.40 Flight data on silicon solar cell life radiation damage. n/p 1 $\Omega \times \text{cm}$.
(from Cooley and Janda.)

Fig.41 Typical silicon solar cell. P_0 = maximum power output at 28°C,
 P = maximum power output at $\theta^\circ\text{C}$

Fig.42 Emissivity characteristics

Fig.43 Silicon solar cell absortivity characteristics. (From Hoffman Inc.)

Fig.44 Solar cell temperature evolution versus time for diapason typical orbit.
Spin-speed: 22.8 r.p.m.

Fig. 45 General principles for solar cell mounting on its substrate

5- Cell shingle submodule

5 - "Flat mounted" submodule.

Fig. 46 Sub-module fabrication

Fig. 47 Another connection cell design, from Ferranti Inc.

Fig. 48 D-1. Paddle

Fig.49 D-1. Influence of the aspect ratio

Fig.50 D-1. Influence of spin angle on I_{sc} . (AMO 140 mW/cm^2 , 28°C.)

Fig.51 FR-1. Schematic view

Fig.52 FR-1. Facets interconnections

A = Without antennas shadows

B = With shadows

Fig. 53 FR-1. Aspect ratio versus incident light

SCHEMATIC VIEW OF EXPLORER AIMP Solar

ARRAYS

SIZE OF ONE PADDLE

Fig. 54 Explorer 33

Fig. 55 ATS-1 schematic view; solar array

Fig. 56 ATS-1 I-V characteristics. Solar arrays

Fig.57 Nimbus II. Solar panels

Fig.58 OAO solar paddles. Schematic view

Fig.59 OGO solar array

Fig.60 Mariner IV

Fig.61 Mariner IV. Power versus voltage for different space conditions

Fig. 62 Mariner IV. Solar array characteristics

Fig. 63 Conceptual design of folding solar cell array. 50 kW. (From J.P.L.)

Fig.64 Conceptual design of roll-up solar cell array 1.25 kW - 440 kg from D.W.Ritchie

Fig.65 Deployed mechanical demonstration model. 500 FISCA W. (From Kenneth Ray.)

French satellite DIAPASON. Solar cell paddles are folded

French satellite DIAPASON. Unfolded solar cell paddles

French satellite FR.1. Solar cell array

APPENDIX I

OPTIMIZATION OF ENERGY STORAGE FOR SOLAR SPACE POWER

by

G.C.Szego and B.Paiewonsky

Institute for Defense Analyses, Arlington, Virginia, USA

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APPENDIX I

OPTIMIZATION OF ENERGY STORAGE FOR SOLAR SPACE POWER

G.C. Szego and B. Paiewonsky

Our Sun represents the only significant extra-vehicle energy source for powering satellite and space vehicle power systems. In the vicinity of the Earth, the total radiant energy available is about 1.35 kW/m^2 , or 0.126 kW/ft^2 , or 1.13 kW/yd^2 , $428 \text{ Btu/ft}^2 \text{ hr}$. These figures are subject to a ± 0.60 per cent diurnal and $\pm [0.40 - 2.5]$ per cent short-term variations. The latter are due to perturbations such as solar flares, prominences, spots, etc.

There are basically three different conversion concepts which may be considered for the conversion of solar incident to electrical energy: photovoltaic, photoemission and thermal. Because an Earth satellite usually has an orbit which is primarily dictated by its mission, it is generally true that an Earth satellite spends a substantial fraction of time in the solar shadow of the Earth. During this period of time, the power requirements of the satellite may well continue to be substantial or might in fact even exceed the requirement during the illuminated portion of its flight. For mission-oriented reasons, even a long-distance space vehicle or a satellite in extremely high orbit may still find it difficult to orient even portions of its equipment toward the Sun. Consequently, it is generally necessary for an energy storage system to be provided so that power output can be maintained during the non-illuminated portions of the flight. For photovoltaic solar energy conversion, this storage can take only the form of electrical storage, that is, storage batteries. In this system, the batteries are floated across the load and when the power generation rate exceeds the load consumption rate, there is a surplus of electrical power with which to charge the batteries. When this condition is reversed, power flows from the batteries to the load.

In the area of thermal conversion of solar energy, it has heretofore been conventional, in fact universal, to assume that the energy storage should be carried out by floating a thermal storage system which stores heat energy usually in the form of latent heat of phase change, which operates in such a way as to provide thermal energy to the conversion system from storage during periods of non-illumination by the Sun. It is the purpose of this paper to point out that there are commonly obtainable conditions under which on a mass minimization basis it becomes appropriate either to store the energy during illuminated periods in the form of electrical energy or, in fact, even to combine thermal energy storage with electrical energy storage. This paper will present an analysis on the basis of which the optimal system or combination can be predicted.

In order to make the results general and useful for preliminary design, a number of simplifying assumptions have been made. The parameter variation limits have been so chosen so that virtually all conceivable conditions of operation and performance of the conversion and storage elements will be covered in this span. The functional block diagram shown in Figure 1 indicates the relationship of the major system components.

Table I indicates the definition of symbols and terms used.

It is appropriate to point out that the mass of the collector includes the orientation system associated with that collector, and the mass of any electrical device includes its controls and necessary conditioning equipment.

The next point which needs examination is the power histogram or the duty cycle. Figure 2 indicates the power vs. time for a given orbit. In order to make this the worst possible case, we assume that the peak power demand occurs during the dark period of the orbit. In case the peak demand occurs in the illuminated portion of the orbital period, this can easily be treated by the method developed here.

Let W_i be the power demanded by the load during the i^{th} interval of duration Δt_i of the dark part of the orbit. The total energy supplied to the load while the satellite is in the shade, is $E_{L_{\text{shade}}}$

$$\left(E_{L_{\text{shade}}} = \int_{(1-\gamma)\theta}^{\theta} W_L dt \right).$$

Let W_{el_i} be the power supplied from electric storage during the i^{th} interval. Now define

$$\alpha_i = \frac{W_{el_i}}{W_i}$$

as the fraction of power supplied from electrical storage in the i^{th} interval, and define

$$\begin{aligned} \beta &= \frac{\sum \alpha_i W_i \Delta t_i}{\sum W_i \Delta t_i} \\ &= \frac{\text{energy drawn from electrical storage}}{\text{total energy delivered to load while in the shade}}. \end{aligned}$$

The electric storage unit supplies $(\beta E_{L_{\text{shade}}})$ kWhr of electrical energy to the load during the dark part of the orbital cycle.

ANALYSIS

The power sub-system mass can be estimated by using an energy balance and then calculating the masses of the major individual components in terms of the component efficiencies and specific weights. The energy gathered by the solar collector during the illuminated portion of the orbit is $(1-\gamma)\theta W_G$ where W_G is the gross solar radiated power captured by the collector. This energy is used to satisfy the demand during both the illuminated period and the dark period:

$$(1-\gamma)\theta W_G = \frac{1}{\eta_c} \int_0^{(1-\gamma)\theta} W_L dt + \frac{1}{\eta_c} \int_{(1-\gamma)\theta}^{\theta} \frac{\beta W_L}{\eta_{es}} dt + (1-\beta) \int_{(1-\gamma)\theta}^{\theta} \frac{W_L}{\eta_{ts}\eta_c} dt. \quad (1a)$$

[load requirement] [elect.storage] + [thermal storage]

Carrying out the integration and using the notation previously defined we obtain the energy balance statement in a briefer form.

$$(1-\gamma)\theta W_G = \frac{1}{\eta_c} E_{L_{\text{sun}}} + \frac{1}{\eta_c} \left(\frac{\beta}{\eta_{es}} + \frac{1+\beta}{\eta_{ts}} \right) E_{L_{\text{shade}}}. \quad (1b)$$

The total system mass is the sum of the masses of the solar collector, the thermal storage device, the electrical storage device and the thermal-electric converter. The mass build-up is given in Equation (2) where the physical source of each term can be identified by the subscripts.

$$M_{\text{tot}} = m_{\text{sc}} W_G + m_{\text{ts}} E_{\text{ts}} + m_{\text{es}} E_{\text{es}} + m_c \max W_{\text{converter}}. \quad (2)$$

This equation may be expanded by substituting the appropriate expressions for the individual components of power and energy.

$$\begin{aligned} M_{\text{tot}} = & m_{\text{sc}} \frac{1}{\theta(1-\gamma)\eta_c} E_{\text{Lsun}} + \frac{m_{\text{sc}}}{\theta(1-\gamma)\eta_c} \left(\frac{\beta}{\eta_{\text{es}}} + \frac{1-\beta}{\eta_{\text{ts}}} \right) E_{\text{Lshade}} + \\ & + m_{\text{ts}} \frac{(1-\beta)}{\eta_c} E_{\text{Lshade}} + m_{\text{es}} \beta E_{\text{Lshade}} + \\ & + m_c \max \left(W_{\text{sun}} + \frac{\beta E_{\text{Lshade}}}{\eta_{\text{es}}(1-\gamma)\theta}; (1-\alpha_1)W_1, \dots, (1-\alpha_n)W_n \right). \quad (3) \end{aligned}$$

[Peak output in sun] [Peak output in shade]

The mass of the thermal-electric converter is specified by the maximum value of the power which it must pass. During the illuminated portion of the orbit the converter must provide electric power for the load and for electric storage. During the dark portion of the orbit the converter processes thermal energy drawn from storage.

The relation between thermal and electric storage and the peak load during the lighted portion of the orbit determines the maximum power capacity of the converter. The last term of Equation (3) shows that the converter mass is determined by the peak power it must supply.

The total power sub-system mass depends explicitly on the division of energy storage. We can see this more clearly if we replace βE_{Lshade} by $\sum_i \alpha_i W_i \Delta t_i$ in Equation (3).

$$\begin{aligned} M_{\text{tot}} = & m_{\text{sc}} \left\{ \frac{E_{\text{Lsun}}}{\theta(1-\gamma)\eta_c} + \frac{1}{\theta(1-\gamma)\eta_c} \times \left[\frac{\sum_i \alpha_i W_i \Delta t_i}{\eta_{\text{es}}} + \frac{1 - \sum_i \alpha_i W_i \Delta t_i}{\eta_{\text{ts}}} \right] E_{\text{Lshade}} \right\} + \\ & + m_{\text{es}} \sum_i \alpha_i W_i \Delta t_i + \frac{m_{\text{ts}}}{\eta_c} \left(1 - \sum_i \alpha_i W_i \Delta t_i \right) + m_c \max \left\{ W_{\text{sun}} + \frac{\sum_i \alpha_i W_i \Delta t_i}{\eta_{\text{es}}(1-\gamma)\theta}; \right. \\ & \left. (1-\alpha_1)W_1, (1-\alpha_2)W_2, \dots, (1-\alpha_n)W_n \right\}. \quad (4) \end{aligned}$$

The task from here on is to explore the dependence of the total mass on the α 's and find minima, if any exist. It is clear from physical considerations that a high peak power demand of short duration may be satisfied by electric storage; perhaps giving a reduction in converter weight.

We will present a numerical example based on a special class of problems. To solve the optimization problem posed in the previous section it is necessary to divide the duty cycle into segments and examine the dependence of the total system mass on the division of power obtained from electrical and thermal energy storage devices during each interval. Implementation of the optimized system requires a detailed knowledge of the duty cycle as well as a power conditioning system capable of assigning varying fractions of electrically

and thermally stored energy as a function of time. To simplify matters, for the purpose of illustration, we assume that a constant fraction of the power, α , will be supplied from electrical storage to the load during the dark period. Using the notation of the previous section this means that $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_n$. We emphasize that it might be possible to obtain a lower total sub-system mass by treating the set of α 's collectively as N variables and searching for a minimum. If the constant value of α in the example is zero then no electrical storage is used. If $\alpha = 1$, then no thermal storage is used. An intermediate value of α gives the ratio of electrically stored energy to thermally stored energy. The example will show that intermediate values of α do in fact produce sub-systems with lower total mass than sub-systems using pure electrical or thermal storage.

Example:

$$\alpha_1 \equiv \alpha_2 \equiv \alpha_n.$$

We assume that an isolated power peak W_1 in the duty cycle occurs in the shape and this peak exceeds the maximum demand in the sunlit portion by a large amount. The average power demand in sun is W_{sun} . No stored energy is used to accommodate minor peaks in the sunlit part of the cycle.

The α 's are all equal. Consequently,

$$\alpha = \beta = \frac{W_{el}}{W_L} = \frac{\text{power supplied by electric storage}}{\text{total power demanded by load}},$$

where

$$\beta = \frac{\text{energy delivered from electric storage in shade}}{\text{total energy delivered in shade}}.$$

If we rewrite Equation (3), under the conditions specified for this example we obtain Equation (5) below:

$$\begin{aligned} M_{\text{tot}} = m_{sc} & \left[\frac{E_{L_{\text{sun}}}}{\eta_c \theta (1-\gamma)} + \frac{1}{\eta_c} \left(\frac{\alpha}{\eta_{es}} + \frac{1-\alpha}{\eta_{ts}} \right) \frac{E_{L_{\text{shade}}}}{(1-\gamma)\theta} \right] + \left[m_{ts} \frac{(1-\alpha)}{\eta_c} E_{L_{\text{shade}}} \right] + [m_{es} \alpha E_{L_{\text{shade}}}] + \\ & + m_c \max \left[W_{\text{sun}} \quad + \frac{\alpha E_{L_{\text{shade}}}}{\eta_{es} (1-\gamma)\theta}; (1-\alpha)W_1 \right]. \end{aligned} \quad (5)$$

[Peak output in sun] [Peak output in shade]

Observe that sum of the first three terms, (m_{sc} , m_{ts} and m_{es}) is linear to α but the m_c term is piecewise linear in α .

To minimize M_{tot} we must test the extremizing values of α : these are 0, 1, and an intermediate value corresponding to a "corner" in the graph of

$$m_c \{\max W_{\text{con}}\} \text{ vs } \alpha.$$

The intermediate value is found from the condition that the peak output in the sun is equal to the peak output in the shade, i.e.

$$(1-\alpha^*)W_1 = W_{\text{sun}} + \frac{\alpha^* E_{L_{\text{shade}}}}{\eta_{es} (1-\gamma)\theta} \quad (6)$$

or

$$\alpha^* = \frac{W_i - W_{\text{sun}}}{W_i + \frac{E_{L\text{shade}}}{\eta_{es}(1-\gamma)\theta}} \quad (7)$$

Figure 3 shows the α dependence of the first three bracketed terms in Equation (5).

Figure 4 shows the two sets of converter peak power levels plotted against α .

The graph of $\max(W_{\text{con}})$ to be used in computing the converter mass is the cross-hatched broken line.

The dependence of the total system mass on α is obtained by taking the sum of these two graphs. This is illustrated by Figure 5.

To find the minimum total system mass it is necessary to test the intermediate point α^* as well as the ends of the interval, i.e. $\alpha = 0$, $\alpha = 1$.

It is interesting to observe that the intermediate point, α^* , is independent of m_c although the location of the minimum, i.e. $(0,1,\alpha^*)$ does depend on m_c .

A digital computer program was developed which computes total sub-system mass and minimum sub-system mass over a specified range of parameters.

Figure 6 through 25 show the total sub-system mass plotted against converter specific mass (lb/kW). The system mass with electrical storage is about 50 lb lighter than the combined thermal-electric system over the range of m_c examined. Figure 7, however, shows that improving η_c from 0.01 to 0.07 makes the combined system lighter in mass for values of m_c greater than 60 lb/kW. These examples show that under certain conditions there are combined thermal-electric sub-systems which are optimal from the standpoint of minimum weight. The sub-system *minimum* masses are shown in Figure 8 for values of η_c between 0.02 and 0.22, and m_c from 5 to 105 lb/kW. The central region between the heavy lines is the area where the combined system is optimal.

CONCLUSIONS

It has been shown that in typical cases electrical or combined electrical-thermal energy storage can provide solar thermal space power systems of least mass. Therefore such systems should be designed by analysis for the input parameters specified, without assuming purely thermal energy storage alone, as has heretofore been the exclusive case with systems under consideration.

TABLE I
Definition of Symbols and Terms Used

η_c , converter efficiency	= $\frac{\text{energy (electrical) produced, net}}{\text{energy (thermal) input, gross}}$
	= $\frac{\text{net electrical power out}}{\text{gross thermal power in}}$
η_{ts} , efficiency of thermal storage	= $\frac{\text{thermal energy delivered on discharge}}{\text{thermal energy supplied on charge}}$
η_{es} , efficiency of electrical storage	= $\frac{\text{electrical energy delivered on discharge}}{\text{electrical energy supplied on charge}}$
θ	= orbital period, hr
γ	= fraction of orbital period spent in the dark, dimensionless
m_{sc}	= collector specific mass based on delivered power, lb/kW _t
m_c	= converter specific mass based on delivered electrical power, lb/kW _e
m_{es}	= electrical storage specific mass based on delivered energy, lb/kWh _e
m_{ts}	= thermal storage system specific mass based upon delivered energy, lb/kWh _t
$\max W_e$	= maximum power output of converter, kW _e
Δt_i	= duration of i^{th} interval of duty cycle
α_i	= fraction of power obtained from electrical energy storage in i^{th} interval
β	= $\frac{\text{energy in electric storage}}{\text{total energy delivered to load in shade}}$

TABLE II
Range of Relevant Parameters

Parameter	Lower Limit	Likely value	Upper Limit	Dimensions
η_c	0.005	0.15	0.85	dimensionless
η_{ts}	0.2	0.70	0.95	dimensionless
η_{es}	0.1	0.70	0.95	dimensionless
m_{sc}	0.05	2.5	5	lb/kW _t delivered
m_c	4	50	300	lb/kW _e delivered
m_{es}	1	70-200	300	lb/kWh _e delivered
m_{ts}	0.5	7	20	lb/kWh _t delivered

Fig.1 System block diagram

W_1 = Peak load (occurs in shade)

$$W_3 = \left[\frac{\int W_2 dt}{\Delta t} \right]_{\text{shade}}$$

Fig.2 Power histogram

Fig.3 Slope and intercept as a function of the efficiencies

Fig.4 Two sets of converter peak power levels as a function of α

Fig.5 The dependence of total mass on α

Fig. 6 Minimum power system mass vs m_c , converter specific mass

Fig. 7 Minimum power system mass vs m_c , converter specific mass

Fig. 8 Minimum power system mass vs m_c , converter specific mass

Fig. 9 Minimum power system mass vs m_c , converter specific mass

Composite Fig.6-7-8-9: Minimum power system mass vs m_c , converter specific mass, $\theta = 1.50$, $\gamma = 0.40$

Fig.10 Minimum power system mass vs m_c , converter specific mass

Fig.11 Minimum power system mass vs m_c , converter specific mass

Fig.12 Minimum power system mass vs m_c , converter specific mass

Fig. 13 Minimum power system mass vs m_c , converter specific mass

Composite Fig. 10-11-12-13: Minimum power system mass vs m_c , converter specific mass, $\theta = 2.00$ hr, $\gamma = 0.32$

Fig. 14 Minimum power system mass vs m_c , converter specific mass

Fig. 15 Minimum power system mass vs m_c , converter specific mass

Fig.16 Minimum power system mass vs m_c , converter specific mass

Fig.17 Minimum power system mass vs m_c , converter specific mass

Composite Fig.14-15-16-17: Minimum power system mass vs m_c , converter specific mass, $\theta = 5.00$ hr, $\gamma = 0.13$

Fig.18 Minimum power system mass vs m_c , converter specific mass

Fig. 19 Minimum power system mass vs m_c , converter specific mass

Fig. 20 Minimum power system mass vs m_c , converter specific mass

Fig. 21 Minimum power system mass vs m_c , converter specific mass

Composite Fig. 18-19-20-21: Minimum power system mass vs m_c , converter specific mass, $\theta = 10.00$ hr, $\gamma = 0.08$

Fig. 22 Minimum power system mass vs m_c ,
converter specific mass

Fig. 23 Minimum power system mass vs m_c ,
converter specific mass

Fig. 24 Minimum power system mass vs m_c ,
converter specific mass

Fig. 25 Minimum power system mass vs m_c ,
converter specific mass

Composite Fig.22-23-24-25: Minimum power system mass vs m_c , converter specific mass, $\theta = 24.00$ hr, $\gamma = 0.05$

APPENDIX II

PANEL DISCUSSION ON SPACE POWER SOURCES

by

Dr George C.Szego, Chairman

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APPENDIX II

PANEL DISCUSSION ON SPACE POWER SOURCES

Dr. George C. Szego, Chairman

I. GENERAL QUESTIONS SUBMITTED TO PANEL

1. Can you give a more detailed list of missions, planned or envisaged, above an energy of 50 kW electrical? (H. Gross, Brown-Boveri Company).

Szego:

(a) *Bases in Space.* There are only a few things that could possibly qualify for a power size beyond 50 kW. One of these, of course, is electric propulsion. (You have seen the data for estimating amount of thrust provided, what specific impulse is possible depending upon the propellant, etc.) A mission which relatively early could require more than 50 kW electrical is some kind of a base (orbital, lunar, etc.). The moment you have four to six people or more you will need powers of the level of tens of kilowatts - there's no point in having people in space unless you have something for them to accomplish. Therefore, it is the ancillary equipment more than the life support equipment which will demand such power (it takes about 1 to 1½ kW electrical/person, depending upon the size of the space vehicle population, to handle all the life support features).

I'm not going to discuss such sophistications as chemical, physical, and nuclear reprocessing of solid and liquid wastes into food, propellants, breathable atmosphere, etc. However, we certainly will need a regenerative system if the duration is extensive, and this can become very expensive in terms of energy, for we are under pressure to conserve mass while we reprocess used materials. This is energy-costly.

(b) *Massive Communications Satellite.* Another class of vehicles which will require large powers is a massive communications satellite - a total communications system (telephone, radio, television) where, in effect, the householder in contact with and through his local dialing center is in immediate relay contact with the satellite in order to make, let's say, an overseas call. That aspect is commercially closer than one might think.

(c) *Economics of US Space Operations.* The economics of telecommunications has hardly been scratched. Today, for example, in my own home state of Virginia (with a diagonal length of 600 or 700 km) I can make an evening call anywhere in the state for 25 Belgian francs - which is really quite cheap. Now the moment that it becomes feasible* routinely to direct dial calls all over the world at modest cost, you begin to tamper with the economics of the existing communications systems. For example, privately leased telephone and teletype wires are very commonly used commercially to connect offices on different continents. On a monthly rental basis these tielines are quite expensive, but they are justified in that direct dialing over the public lines (toll calls) would cost more. If we don't have to maintain sub-marine cables and radio relay (repeater) stations, using satellite repeater telecommunications instead, I think 50-kW electrical satellites will be run of the mill. This is one of the few commercial applications of space that seems to make sense.

* C & P Call. The C & P Telephone Company of Virginia, January 1968.

In doing things from space one should exercise the kind of caution expressed by Ben Jonson in the 17th century when informed that a woman was preaching as a Presbyterian minister. His comment was that such a phenomenon could be compared to a dog walking on its hind legs, i.e., you don't have to ask if it's done well - the fact that it is done is novelty alone. Jonson's opinion of female ministers points up an error into which many of us tend to fall. That is, if it's done through space, by space, in space, or has some link with space, it is a very good thing. That attitude, of course, will soon vanish. Space operations will have to survive (at least for other than say national defense reasons) strictly on an economic basis. If a telephone or television repeater is cheaper and more effective - more "lucrative" - from space, that's the way it will be done. If it's cheaper terrestrially, that is how it will be done.

Unfortunately, I cannot give you a time schedule, particularly for these base stations, because we ourselves aren't too clear as to what is next. You know, of course, that the US space program is under fire from Congress. The argument is that we have so many involvements at home and abroad that have higher priority. Our foreign aid program, for instance, has been a very large chunk of money since long before World War II, now of the order of 5 or 6 billion dollars every year. The foreign aid program has also been under fire - why have it when the disadvantaged portion of our own population is in need of housing, employment, training, etc? Or when we have all kinds of urban problems such as traffic congestion and air, land, and water pollution? How can we possibly justify going to the moon for 6 or 10 billion dollars when we could so well use this money on earth?

This is a question which is very hard to resolve in the political arena. And whether we like it or not, many of the answers to the questions that will doubtless be asked in this conference lie not in the scientific or technical realm but in the political arena of what is acceptable to the taxpayer. We know how expensive space operations can be. It used to cost a kilodollar per pound to orbit a moderate size payload; today it costs about half of a kilodollar per pound. It's still of the same order, so we have not yet made a sharp cut there.

In regard to the question of reusable space vehicles, this will have much influence on space power systems. If the traffic density becomes such that reusable launch vehicles and spacecraft begin to make economic sense, there will be a greater need for space power systems than if we have to launch each payload with its own disposable \$25 million launch vehicle.

Finally, 50 kW electrical is a peculiarly awkward size. It's pretty straightforward as to how to generate 2, 3, 4, 5, or 10 kW, or how to generate 100, 200, 300 kW, or a megawatt, but it's not entirely clear how you would go about generating 50 kW, for it falls in between.

(d) *Near-earth Observation.* Another area (which I find awkward to describe because it is very circumscribed by security considerations) deals with near-earth observation. There are concepts virtually within our grasp now that could easily consume of the order of 30 kW, if not 50 kW. However, the only amplification I can make relates to the post-Apollo follow-on program (What are we going to do after we land a man on the moon?). We are supposedly looking into using that same hardware for near-earth satellite operations involving all sorts of geological and geophysical experiments which may ultimately have commercial value.

There are also visionaries who say we will control weather. Well, a tropical hurricane has more energy in it than a large handful of H-bombs, and how you are going to control *that* is just a little unclear to me - from space or anyplace else. But certainly our knowledge of weather and its prediction, if not its control, has benefitted considerably from our space operations.

2. What power system and power levels should be used for the 24-hour satellite (for Europe or US) for both black and white and color television? (E.Knoernschild and W.Peschka).

Szego:

I think at the moment if one had to orbit a 24-hour satellite and the necessary power required was such that you would not try to communicate with each home television antenna but instead would use ground repeater concepts, you would certainly use a solar photovoltaic system and batteries. At the moment there is really no other system ready or nearly ready to fly with the life capability inherent in a 24-hour satellite. You just can't afford to orbit a 24-hour satellite for only 3 days of operation. So I think it is clear that the power system would have to be photovoltaic. Is there any disagreement on that score for a 24-hour satellite?

3. Why is the bandwidth of the transmission from satellite proportional to the power required? (Knoernschild/Peschka).

Szego:

I would say that it is a matter of signal to noise ratio and antenna sensitivity. A signal to noise ratio of 2 to 1, or better than 2 to 1, is necessary with some signal processing to discriminate satisfactorily to get an intelligible signal; so the question of keeping the signal to noise ratio greater than 2 is the issue. Part of this is geometry - the inverse square law of any radiating source - and part is the focusing capability which has inherent variation from one frequency to another. Ground antenna size has, of course, an inverse effect on bandwidth requirements.

4. Why is SNAP-2 (System for Nuclear Auxiliary Power) no longer of interest? It produced 3 kW and worked well. (Knoernschild/Peschka).

Dieckamp:

(a) *Cessation of the SNAP-2 Program.* I would like to thank those gentlemen for that fine expression of support for the SNAP-2 program. I think it is true that SNAP-2 worked fairly well. During the last few years there were integrated a total of some 30,000 hours of testing with the CRU-5 (Combined Rotating Unit) which was the fifth evolutionary model of the rotating machine built during the development effort. One of those machines ran for almost 5000 hours and three ran for a time in excess of 3000 hours.

The program had progressed to the point where it was technically clear that there was no reason to suspect that the rotating machine or a mercury Rankine cycle could not be made to work successfully in space, with adequate reliability and lifetime. Mockup systems had even reached the point of turbine startup by blowdown, condenser operation in a simulated zero g configuration (all the condenser tubes in a horizontal plane), and the cycle itself closing the loop, priming the pump, and reaching a self-sustaining operation in a matter of minutes.

The program is dead now, I think, because after a period of almost ten years (about \$40 million was spent on development of the rotating machine alone) the people in charge grew weary of it. And under budget pressures to support new programs or ideas in the absence of a specific expression of interest, application, or impending application, the decision was finally made to cease the effort with the concluding remark that the technology had been brought along adequately to assure everyone that it was possible and that there was no need therefore to go further until application for it arose.

(b) *Justification for the SNAP-2 Mercury Rankine Cycle*

Szego:

We might add the postscript that really SNAP-2 must be classed purely as a demonstration system. This nuclear reactor has a capability of hundreds of thermal kilowatts; harnessing it to a CRU that puts out 2 to 3 kW must be viewed as a demonstration.

Dieckamp:

I'm not sure I understand the logic of that. Even if the reactor had produced a million kW, if you wanted x kW in space and SNAP-2 could provide it at the required weight and other constraints, what difference does it make whether the reactor put out a lot of power or not? The reactor, as a matter of fact, was probably at the size limited by criticality rather than by heat transfer or energy density.

Also it should not be overlooked that the application of that machinery today would probably be with a radioisotope source rather than with a reactor.

The real issue is whether or not one can develop a 5-kW Brayton cycle CRU for less money and in shorter time and end up with higher reliability, starting from where you are today, or whether you would be better off following the mercury cycle. I think that is the real issue - which is being ducked by dropping the mercury cycle and going to the Brayton cycle. (*Szego:* I don't think the 5-kW Brayton was the issue when they cancelled SNAP-2.)

Dieckamp: As a system development, SNAP-2 was cancelled three years ago. The rotating machinery as a technology program, though, has only been "killed dead" within the last six months.

5. Give a critical evaluation comparing isotopes, reactors, and solar energy. (Knoernschild/Peschka).

(a) *Radioisotope Source Versus the Nuclear Reactor for Extended Manned Applications*

Rasor:

Mr Dieckamp stated that it would make more sense to use a radioisotope source than a reactor. Why is that? the reactor is developed and has an infinite life. What's the big isotope push here?

Dieckamp:

I think the reason for using an isotope source instead of a reactor when the reactor is already developed, relates to the assessment of the potential missions or requirements that may come into being in the next five to ten years. And in this few kilowatt power range I feel fairly safe in predicting that there will be a hard requirement for a 5-kW power source in the greater than 90-day lifetime regime for use in manned spacecraft - probably early manned orbiting laboratories (MOL's), etc.

When one goes into this region beyond 50 or 100 kW-days of energy requirement the fuel cells become quite heavy, making the radioisotope systems look advantageous. As I mentioned in my lecture, the radioisotope systems are preferred for manned applications because of the low shielding requirements for alpha-emitting isotopes, which allow those heat sources to be integrated into existing or slightly modified spacecraft with a minimum of complexity. To integrate a reactor powerplant into a manned spacecraft would be a completely different problem and the weight situation would be such that you probably would never do it.

(b) *Solar Photovoltaic Compared to Radioisotope Systems*

Rodot:

I think that 5 kW for photocells is not far from the maxima now desired. The situation for radioisotopes seems to be such that the maximum is 60 watts. In the case of solar arrays it is about 1 kW, so solar cells seem to be nearer qualified for a 5-kW program.

Daspet:

To draw an exhaustive comparison between the respective possibilities offered by photocells and radioisotope sources, the satellite mission has primarily to be considered.

As a general and brief statement, I may say that such a comparison appears valuable to me only in the case of powers lower than a few kilowatts.

The main drawbacks of radioisotope sources become serious penalties at high power levels; the high price of radioisotopes, and their shortage on the national and international markets lead to selecting high efficiency conversion systems. It is almost certain that, for such powers, the greatest possibilities in this field are offered by thermodynamic cycles. Although they have a low conversion efficiency, thermoelements can remain in continuous operation for several years. The mass power of radioisotope, thermoelectric conversion generators is comparable to that of the solar generators in association with electrochemical batteries which would equip satellites orbiting around the earth at low altitude. Life time of such generators will be greatly shorter than radioisotope thermoelectric generators of equivalent power. The limitation is ascribable not to photocells, but to electricity storing batteries.

Solar generators of a few kilowatts will require large surface displays in space: several scores of square metres. Thin film photocells are quite suitable for such systems, as they can be displayed in large arrays, are not sensitive to space particle radiations, and have a low cost. Such advantages counterbalance to a great extent their low initial conversion efficiency.

Such generators will be particularly light and require little space if they are oriented towards the sun; nuclear energy systems will be more compact and will hardly affect the general satellite design, but they will be markedly heavier and, therefore, not competitive.

Therefore, solar generators appear very suitable for certain missions to be performed by geostationary satellites when sunning time amounts to approximately 99% of the whole orbiting duration, if the mission is interrupted during eclipses, as it is likely for the retransmission of televised information.

If this is not the case, or if satellites orbiting around the earth at low altitude have to be supplied in power, the weight and lifetime of the solar generator will be highly influenced by the existence of electrochemical batteries which are indispensable for supplying the satellite with the necessary power during eclipses.

The choice of the power source (solar or radioisotope generator) will depend essentially on the specifications of the satellite mission.

As regards missions oriented towards civil applications, such considerations as cost and, from a more technical viewpoint, long orbit lifetime and excellent reliability, seem to be determining factors. Although it is not yet largely used, radioisotope nuclear energy holds high future prospects, especially if radioelements become available in sufficient quantities and at low cost. To achieve this aim, high financial investments are now required.

Dieckamp:

In the case of the long-lived radioisotope sources the most likely material to be used is plutonium at a potential cost of the order of \$1000.00 per thermal watt, i.e., \$5 million per electrical kilowatt if you were using a 20 percent efficient Brayton cycle power conversion system.

In regard to the question of isotopes versus solar cells for extended MOL applications, I don't think the issue is simply one of weight. There are estimates in the literature on solar arrays for manned spacecraft ranging from a few hundred pounds per kilowatt up to a few thousand pounds per kilowatt. Perhaps the latter number is surprising to you. However, when you have to restrict the manned spacecraft to a low altitude in order to stay below the Van Allen Belt radiations, you find you are in a region of significant drag where the subtended area of a large multikilowatt solar array becomes a significant penalty in terms of propellant requirement. But even then, again I'm not sure that the simple weight difference is the most important matter.

Perhaps one of the most significant factors in many of the studies of solar arrays for manned spacecraft is potential degree of mission interference. These rather large arrays located around the spacecraft may obscure the observation angles or require extra perturbations of the spacecraft in order to maintain solar orientation.

(c) Solar Dynamic Systems Versus Reactors

Zwick:

I would just like to point out that in this choice of energy sources one of those mentioned was solar. And of course solar dynamic systems have from time to time been considered and worked on. The SUNFLOWER system (essentially a SNAP-2 CRU and a 30-ft mirror) was cut to a so-called technology program about 5 years ago, primarily because of the difficulties associated with the development of the machinery and materials - but also because these problems were essentially the same as those of SNAP-2. Now SNAP-2 has solved many of those problems and demonstrated technology which certainly should be applicable to SUNFLOWER. The mirror, as I recall, was developed and demonstrated with little difficulty, although it was not tested outside the laboratory. (It's specific weight can be found in the summary from Dr Szego's paper.)

The advantage of solar dynamic systems as compared to reactor systems (the power source keeps decreasing as you go to lower and lower power levels and there isn't any shielding problem but there is obviously an orientation problem) is that SUNFLOWER would turn out to be a lighter system than any comparable solar cell system. I don't know how it compares with the isotope system but certainly if you could stand the orientation problem... I suspect that the availability of metal for mirrors...

Dieckamp:

Well, I'm very surprised. Because, again, if I postulate correctly that the principal weight component is related to drag compensation for a solar array, and if I recognize that a Rankine cycle is going to have about the same net efficiency of a solar array, I find that I have the same amount of subtended area hanging out, and therefore I have the same amount of drag propellant. So why fool around with all that rotating machinery? Why not just have the solar cells?

Rasor:

I think it ought to be mentioned too that to my knowledge there has been no test of a mirror in space. Whether or not there is erosion, whether any of these concentrator-based things, whether it's thermionic or Rankine, etc., raises a feasibility question that is still outstanding.

Szego:

I'm not sure that is valid. But in any case, I think the issue of solar dynamic systems has not really been closed. The issue of drag is also invalid in part in that you don't always orient the radiator or the solar cells perpendicularly to the flight path. There's a vast difference between the perpendicular drag and the laminar or one-edge drag. Furthermore, this drag (if you do it on edge) can be made up, using an electric thruster at very high specific impulse, at fairly economical power. In other words, it's just like another parasite on the system, or it might be considered as a lesser efficiency.

Zwick:

Well, drag is kind of a red herring anyway, because it depends upon what orbit you are in. If you want to prove that they're worthless, you put them into low orbit, and if you want to prove that they are good, you put them into high orbit.

Dieckamp:

We're talking in the context of a manned application, which will be restricted to low orbits by radiation.

6. What are the thermodynamic reasons that fuel cells are superior to batteries? Is it volume reduction by cryogenics? (Knoernschild/Peschka).

(a) Fuel Cells Versus Batteries for Long and Short Term Missions

Cohn:

Thermodynamically the efficiencies of fuel cells and batteries are the same. I don't quite understand the question.

Knoernschild/Peschka:

Why is it that fuel cells are better in the long range period than the other one? Because somehow there is the material which has to be chemically disposed? But you could do the same with a battery. *What is so much heavier by ten times?*

Cohn:

Now I understand, There is no simple answer to which is better. It depends upon the length of the mission, assuming that you want to use electrochemical power. For a short mission it pays to store your energy in metal and metal oxide. As the length of the mission increases from hours to days or weeks, or to perhaps at most three months or so, and you still want to store all of your chemical energy in the vehicle, you find that *per pound* of reactant you can store more chemical energy in hydrogen and oxygen as liquids, including the package and everything else, than you can store in metal and metal oxide.

Knoernschild/Peschka:

In other words then, in order to take care of the chemical energy per pound of reactants you have to get hydrogen cryogenically cooled; otherwise your tank weight would probably offset completely what you would gain from a fuel cell.

Szego:

That's right. For short missions there's no use using cryogenic material. But just compare the molecular mass involved in one equivalent of iron to iron oxide as compared to hydrogen to hydrogen oxide. The metals store less energy per unit mass.

Knoernschild/Peschka:

Then the difference between those systems is the difference in the energy contained between a metal to oxide and hydrogen to oxygen.

Szego:

Plus the grid structure it takes to store the paste or whatever form you have the battery reactants in.

Cohn:

Plus all of the auxiliaries that go with the fuel cell system which you do not need with a battery system. But essentially, in a rough way, that's the difference.

(b) *Energy Storage for Regenerative Systems*

Huybrechts:

I assume, Mr Cohn, that you are talking about primary energy sources when you discuss the batteries. Now, for regenerative systems do you see the same picture?

Cohn:

Yes, exactly the same in that for a short orbit time the battery stores the energy quite adequately. If on the other hand you want to consider storage of chemical energy during the lunar night (two weeks or a fortnight) then during that period again you can store energy at lighter weight by storing it in gases. We are just now starting a study on storage of hydrogen and oxygen - this time not cryogenically (or perhaps cryogenically, perhaps as gases) for a lunar base on the lunar surface. Because there again it doesn't make sense to store chemical energy in batteries, i.e., in metal and metal oxide, for two weeks.

(c) *Electrolytic Regeneration*

Szego:

I would like to repeat an earlier observation that if you use an electrochemical device as a recycling converter, i.e., run the water through and then in some other way thermally or nuclearly decompose it back into hydrogen and oxygen and run it through again, then you have a heat engine - which could never be as good as a once-through cryo system because the fuel cell is not 100 percent efficient.

Cohn:

I hate to disagree with you, but there is one case in which you do not have a heat engine. If you regenerate electrolytically it is the same as recharging a secondary battery, which is precisely what we're considering. (Of course this is not thermal, but for hydrogen and oxygen in water we do not ever seriously consider a thermal regeneration.)

Szego:

If you use electrolytic regeneration, then you're talking about roughly 50 percent efficiency at best in the electrolyzer and perhaps 80 percent efficiency in the fuel cell, which combine as 40 percent. You can do that with a diesel engine.

7. (Unidentified Questioner) What about reliability in failure modes of the multiplicity of thermocouples or thermionic devices versus the turbine?

Zwick:

(a) *Failure Modes in Turbomachinery.* Turbomachinery which has been proposed for use in space has really a very limited number of failure modes. Most of these are predictable by good engineering design techniques. However, the problem with most of the turbomachinery for space has been that the materials used in the systems really didn't permit the intrinsic reliability of the turbomachinery to come through because corrosion was going on all the time.

If you consider a Brayton cycle machine (an inert working fluid and gas lubricated bearings), for example, there is really nothing touching. And if you look at the temperatures and the rates of rotation of the turbomachinery (the stresses, etc.) the only real limitation on the rotating parts is that at some point you could get into creep limitations. But these are things you can design for, and by limiting your design a little you can design for 10,000 hours, or 100,000 hours, in terms of creep.

The liquid metal systems have some other problems, but these are material problems of a sort: cavitation, impingement of particles, and especially mass transfer. And whether or not we will ever reach the day when we can say that the liquid metal systems have the same reliability that a gas system has - that the materials are, for all practical purposes, insoluble and that there is no mass transfer - I don't know. We're certainly not there now.

I think essentially we're there in the organic loops. I don't believe there is a real problem in the organic loops except high temperature degradation of the organic material. And here again you just reduce your sights and instead of working at 700°F and living with the degradation problem, or perhaps failing because of it, you reduce your temperature to 600°F and then you can go for a year or two without any problems.

As far as I know, once you get the dynamic system going and have the right materials available, you find that the system will probably fail because of some static regulating device someplace.

Rasor:

(b) *The Redundancy Issue - Static Versus Dynamic.* I think Mr Zwick is beating a dead horse. Granted that there might be more failure modes of a static device (which I think is inherently the other way around, as a matter of fact) the really important issue here is redundancy, i.e., you can have a large number of individual units which are in themselves complete in that the failure of one of these does not lead to the failure of others. Furthermore, they are connected in a redundant circuit, i.e., they are series parallel connected such that if you have 1000 units and lose one, you only lose about 1/1000 of the performance of the system.

In fact, I think I can illustrate this right on your home base ("Turbomachinery USA"). The turbomachinery that runs turbojet aircraft is indeed extremely reliable and has been brought to a very high level. However, notice that there are four turbomachines on each aircraft. As a matter of fact, there have been new aircraft (longrange) posed (I think by a European group) with two engines, which were rejected by the US airlines because they require fourfold redundancy.

Even though these turbomachines must be fourfold redundant, they are used for perhaps only six hours at a time before a failed unit *could* be replaced. Now that is pretty short compared with the times we're talking about (for space). And even though the overhaul period on commercial American aircraft is currently 600 hours, I have personally seen an engine go out on two different jet flights, which is enough for you to be concerned with the fact that at the end of six hours the engine *can* be replaced if necessary.

My point here is to illustrate the redundancy, *even* in the case of turbomachinery where there is a high degree of reliability and incidentally where you could get to higher efficiency by going to single units (or at least double since it would be rather difficult to integrate a single engine into the aircraft).

The point relative to thermionics and thermoelectrics is that you can easily make the system 1000 units (as has been done with SNAP-10A) or 10,000 units. Furthermore, before this you can have a test program in which you can accumulate many tens of thousands of module hours and get very good failure statistics. Therefore, you can draw a graph of the power output of the system versus time and have the expectation that the performance of the system will follow very closely. In the case of turbomachinery, if you have *only* one turboalternator, this curve (although perhaps slowly degrading) has a tremendous possible discontinuity in it at any stage of the life of the system. Now, if you have four of these you compromise the effectiveness of the system quite a bit, but it's a far cry from 4000.

If I remember correctly, when the AEC and the NASA were about severely to cut back the SNAP-50 and SNAP-8 turbomachinery programs, they issued a White Paper (Summer 1962) emphasizing this redundancy problem. This was one of the big justifications for the cut-back of the engineering hardware development in the dynamic machinery area and for putting a fraction of these funds into seeing at least how far the static systems could go.

Szego:

I think you gentlemen can appreciate why we have separated static camp from the dynamic by three people. We want to remain friends.

Dieckamp:

(c) *Reliability of Failure Modes in Accelerated Testing for Static Devices.* I think there is no question but that rotating machinery can be built, and can be built with reliability and long life. The place where I have difficulty though, and where I see a significant difference between a dynamic converter and a static converter is in one's ability to understand the basic failure modes and intelligently to test under accelerated conditions such that the failure modes can be discovered more quickly, more readily in shorter periods of time, etc., thus making the development cycle much shorter. I know that in the case of the SNAP-2 program we thought long and hard to try to find out how to rub the machine to accelerate its potential failure modes. No one could decide that just running the shaft faster was the right thing to do because it affects the bearings differently from the turbine; or no one could decide to just run the machine hotter, because that also didn't stress everything in some reasonably proportional way.

In the case of most of the static devices where the failure modes are a simple result of materials interactions one can with a high degree of confidence run accelerated tests and greatly enhance development efficiency. And to me that's a very important practical fact.

Rasor:

(d) *Cost Factor in Obtaining Failure Statistics for Turbomachinery.* May I ask how many thermocouple (module) hours you accumulated on SNAP-10A before launch? (Ans. Millions of module hours.) They obviously made thousands of couples, but I think the important thing right here is to realize that you can easily test 100 such modules (for a year, in fact) and get good failure statistics. You can't take 100 turbomachines and test them for a year and get good failure statistics. First of all, because of the cost of such a complete system... I shouldn't have just said the turbomachinery. I mean it's so intimately tied in with the rest of the system in this case, that you must test the whole system - making 100 systems and testing them.

(e) *Question of Reliability for the Manned Application*

Zwick:

I would like to point out that this question of reliability for a manned application is particularly important. But on the other hand the presence of the man affects the reliability. In the case of the work done for the Manned Orbiting Research Laboratory (MORL) program, Douglas worked up an ingenious concept (presented in the 1966 version of this thing). There are two 5½-kW Brayton cycle machines fitted around a fuel block in such a way that when one of the machines fails (assuming that this impossible event occurs) it's a trivial matter to extend a boom, pull the entire failed system out of place, and slide in another system. I think they estimate an hour for this change which includes access, dismantling, etc.

They plan for two working units and two spares on board. They decided they would design the rotating machine for a year, and at the end of the year they would replace it. If I had something that would run all right for a year I would be very loath to replace it. But nevertheless the question of redundancy is an obvious approach and one which yields the same beautiful looking numbers for four or five dynamic systems as it does for a few thousand static systems - probably because the reliability has that many more "nine's" for the dynamic system.

Rasor:

You have somehow or other hit the manned thing again and in that case, of course, the man can go in with a wrench and a torch and cut the system off. I recently attended a meeting where the manned lunar base system was considered, and there they did indeed have men going in and replacing heat exchangers, cutting in lines, etc. This was the result of a study on what was going to be done with SNAP-8. (*Zwick:* But this is removal of the whole system?) *Rasor:* Okay. I'll accept even that. But the question is: Which one of these astronauts (the biomedical man, the astronomer, etc.) is going to be the mechanic that works on this engine. Time is important in space.

Zwick:

Ned (*Rasor*), the people at Douglas are so clever that even *you* could have done it! (laughter).

8. The issue of why plutonium has never been mentioned as a possible fuel for space reactors despite the low critical mass. Is this a matter of safety consideration or are there other reasons? (*Contzen.*)

Dieckamp:

The situation is changing very rapidly. Five or ten years ago, plutonium was kind of a hush hush quantity because of its weapons use, etc., so there was no serious consideration of using it for space reactors. (By the way, its critical mass is only best in a fast not a thermal reactor.) But now with the large number of commercial reactors throughout the world, plutonium is a more readily available quantity than uranium 235 (you don't have to have an isotopic separation plant in order to make it), so I would not be a bit surprised to see plutonium 239 become "popular" as a reactor fuel for space power plants. Also, I think that when you consider that in the next 15 or 20 years we will be moving into an economy where there are many, many fast breeder reactors, plutonium will be no higher in cost really than uranium. So I would expect to see plutonium used in space reactors.

9. What about the terrestrial use of thermionics?

Rasor:

(a) *Central Station Application of Thermionics.* I'd hate to invest my career in this area even though the thermionic converter has advantages of exceptionally high power density and high heat rejection temperature (for a static device). On the other hand, if your question is in the context of looking off far enough in the future then one area that definitely should be considered is, believe it or not, the topping of central station power plants - not necessarily of nuclear but possibly of flame heated ones.

Although this sounds wild, if you use the same rules of the game that the MHD people are using to justify their efforts (the same capital costs, same degree of building liquid oxygen plants to supplement the MHD, etc.), then actually the thermionics looks better.

I had a fellow look into this and make a study of a thermionic topped fossil fuel power plant. You can make it look just as attractive as or more so than the MHD plant with demonstrated device efficiencies and capabilities. Although I personally believe this is a long way off, all I'm saying is that if you want to use the same degree of optimism that the MHD people use, this is still something you should consider. I personally don't like to do it.

The point is that thermionics can substantially increase the efficiency of even a terrestrial based plant, especially when you top another power plant such as a thermoelectric converter. On the other hand, the unit cost is increased. In addition there is a lifetime limitation which even in the present state of the art of thermionics is shorter than for thermoelectrics. These few things have to be balanced against each other. I don't see thermionics being able to pay its way in this area in the near future, but it is one of the possibilities as far as terrestrial uses are concerned.

(b) *Thermionic Conversion for Commercial Applications.* Now believe it or not, there is a series of civilian commercial uses in which thermionics may play the dominant role (as a matter of fact within the next two years). I'll just have to leave it up to you to guess what these are - which is not a security problem but a proprietary one.

Zwick:

May I guess? In the United States and perhaps elsewhere in the world there are two forms of energy generally available - electrical and natural gas. In most of the states and large cities the distributors of natural gas are prohibited by public utilities commissions from distributing electricity. The result of this is that the natural gas industry is very anxious to increase its market for gas. They have a favorable price ratio for BTU's (or calories) of from 3 to 1 to 15 to 1, depending on the cost of electricity and the proximity to the natural gas field.

At any rate, in the United States there is a great deal of discussion frequently about "total energy". The idea of total energy is that you use the heat first to generate electricity and then use the leftover to air-condition the house, heat the rooms, warm the swimming pool, etc. And whatever is left you put through a small device and you do get the "squeal" out of it too.

Along this line one of the things that the natural gas industry would like very much to do (they can't do this in the middle of town and send it out because that would make them a public utility distributing electricity) is to have alongside each home a device which converts gas into electricity and at the same time permits all the other functions of the home to be taken care of. The American Gas Association annually spends literally millions of dollars, some of it on foolish ideas, some not so foolish, trying to find a way to do this. I would think that thermionic conversion would be one of the less foolish approaches that one might take to a combination of local electricity generation and heating the home, etc. There is a problem in getting the electrical power and the rest of the heat all to work out at the same time. They also have done a lot of work on fuel cells for the same application.

Rasor:

I thoroughly agree with you. The only trouble is that there are extremely severe capital requirements - lifetime and load factor problems.

I would rather put that off as being in the same kind of future as the central station application of thermionics. It is a possibility. It may not be thermionics that does it, but something of the sort sometime in the future.

Szego:

We also might mention that there is a multimillion dollar per annum program called TARGET which is sponsored by various gas transmission companies and is being carried out by the Pratt & Whitney Aircraft Company. It is a fuel cell approach to this problem in which a fuel cell in the home would provide a modest amount of electricity for those things that just won't be done conveniently by gas.

Rasor:

Yes, I would more subscribe to that approach for the near future. I should have mentioned, for the information of the questioner, the fact that there has been a contract given recently to the Consolidated Controls Corporation by the Coal Institute (both in the United States) for a demonstration coal-to-thermionic power system. They are actually going to build one of these. These people, like the American Gas Association, are trying to find things to do with coal because they are being put out of business by gas and oil.

II. QUESTIONS SUBMITTED TO MR ZWICK.

1. Are two-phase flow problems in zero-g environment a problem area? (Berger).

Zwick:

(a) *Condensing and Boiling.* Yes, it's a problem area but it's not a limiting factor. It's a problem area which required attention but which now has contributed to the literature and has essentially been solved.

In zero-g environment there are two types of problems: boiling and condensing. (That takes care of two-phase flow, doesn't it?) The boiling problem is generally solved by the fact that you have usually once-through systems in which the dynamic forces are normally on the order of hundreds of g's. In fact, in order to get a really high heat transfer coefficient for boiling way out into the missed flow area where you are at 80 or 90 percent quality, twisted tapes and things of this type which artificially introduce g fields, spinning the flow, are used. These dynamic forces are so great compared to what you would normally think of as g forces that I would say that zero-g is not really significant for boiling.

Zero-g is significant for condensing for a different reason. When you condense you are extracting heat from a fluid. In extracting heat from a fluid there is a tendency for the pressure to go up, just as in adding heat there is a tendency for the pressure to go down. As a result, in condensing flow if you didn't have any viscous losses the pressure would be rising - which tends to lead to flow instability. The way around this, of course, has been that by increasing the velocity of the flow so that the static pressure doesn't change, you can accommodate the increase in the total pressure. So, condensing systems with narrowing tubes (and thereby slightly increasing velocities) and sufficient pressure drop have been stable. Whereas constant bore tubes with very low pressure drops turn out to be very unstable in zero-g.

*(b) Selection of a Third Fluid in SNAP-8**Berger:*

I assume this is the basic reason for assembling the SNAP-8 configuration and incorporating a separate heat rejection loop?

Zwick:

No, I think the reason for incorporating a separate heat rejection loop, at least in part, is that the mercury is very heavy. And the weight of the mercury in the radiator is enormous compared to the weight of an organic heat transfer material. So it would be more than that.

Dieckamp:

I think the motivating force for going to a third fluid or indirect condenser in SNAP-8 is vehicle integration flexibility. It also makes a lot of sense when you stop to think about the problem of testing the integral system in any kind of a facility. If you can decouple the radiator, you end up with a much smaller package that has to be tested and subjected to the simulated environment. So in my opinion whether or not you use a third loop to the radiator is the consideration that there's some size where this becomes just a common sense thing to do in terms of power plant development and in terms of integration into the spacecraft.

Zwick:

The question of indirect versus direct condensing (which is really what you're getting to) relates to all sorts of power system and vehicle integration problems. You pay the penalty and the temperature drops, but then you could have smaller tubes; you gain some redundancy because you can have multiple cooling loops. I don't think it had anything to do with two-phase flow.

2. Has the mercury turbine of SNAP-8 been tested in vacuum? If so, what lifetime has been achieved under normal conditions and how many machines have been tested? (H.Gross, Brown-Boveri).

Zwick:

I'm not sure I know what you mean by "tested in vacuum". In the most recent Intersociety Energy Conversion Engineering Conference in August 1967 in Miami, there is an article summarizing the current status of SNAP-8. Although 300 hours of complete system testing has been accomplished, there is very little information as to what was accomplished in the way of sustained operation during those 300 hours. I really don't know from any outside source how long continuously the system has run. However it was started up and run, and put out the rated 35 kW (in fact, it put out 38 kW).

There were some differences between the manner in which the test was run and true space simulation. For example, they had the lubricating pumps going already, etc. In fact, it says:

"The basic shortcoming at startup was at the pumps. Primary NaK loop, heat rejection loop, and lubricant coolant were not started by an inverter at low speed. Rather, the pumps were operated at full speed on auxiliary power, and the turbine alternator assembly was not required to accelerate the pumps."

Now, aside from that I think it was essentially a space startup simulation, but I don't know how many machines were tested or what the longest duration was.

III. QUESTIONS SUBMITTED TO MR COHN.

1. What is the physical meaning of the efficiency of an electrochemical system being greater than one? (Cazeneuve).

Cohn:

The physical meaning very simply is that the entropy is negative instead of positive (This can happen occasionally, e.g., hydrazine and carbon monoxide) in which case the efficiency as calculated by simple thermodynamic calculation comes out greater than one.

Cazeneuve:

The reason why I asked this question is that, most of the time, I have heard the answer which you have just given me.

From a physical viewpoint, I think it means that the system borrows heat from outside to turn it into electricity.

I read in a periodical - I believe it was Brown-Boveri's - that this process actually takes place when the carbon, in solid form, is combined with oxygen to produce carbon monoxide (CO). In this case, the gas phase goes from 11.2 litres to 22.4 litres; an expansion occurs. In fact, the system acts like a heat pump, is that correct?

Cohn:

Yes, I believe theoretically that can be done.

Szego:

I think the basic answer to the question is one of definition. We define efficiency for a heat engine in such a way that a fuel cell *appears* to have a greater than one efficiency, and we simply go along with the convention so that we can more easily, more conveniently, compare fuel cell performance with diesel engine performance, thermionic devices, Carnot devices, etc. (If you use the fuel cell as a heat pump, as Mr Cazeneuve suggests, you can draw the heat from outside if the signs of the thermionic functions are proper, and sort of make use of this extra "boost".)

Cazeneuve:

Thank you. Now, I have got the information. Anyway, this is a limited phenomenon. It might be useful to write a note on this to clear this paradox.

2. As you remarked with regard to efficiencies, isn't there a requirement for life testing conditions to be defined for fuel cells? (Dr Goudot, CNES).

Cohn:

Very definitely there have to be life tests for which the conditions must be defined.

3. Do you think that the voltage of the element for a given category of cell is sufficient to characterize the test? (Goudot).

Cohn:

The voltage is sufficient if all other conditions in running the cell are constant, e.g., constant temperature, constant current density, constant purge intervals, etc. Normally, however, you don't want to run your life tests at a constant level because they are usually less indicative than tests which include varying levels.

4. In the example of the Allis-Chalmers cell you quoted as having operated for 2500 hours, what was the element voltage?

Cohn:

I cannot answer your question because the voltage varied with time. The Allis-Chalmers unit was tested to a very uneven power profile of so many minutes at one level and so many other minutes at another level, going up and down for short periods. For long periods it averaged out at 1.1 kW, but it was never run for any length of time at that power. And, of course, the voltage of an electrochemical device is a function of the current drain: the faster you draw current - the more load you draw - the lower is the voltage per cell. Roughly, the current density must be varied somewhere between 30 ma/cm² and about 200 or 250 ma/cm², and the voltage varied inversely accordingly.

5. Was the test continuous and could you report on any incidents that occurred during this time?

Cohn:

I'm not sure but I think this particular test has been continuous. In some cases we have deliberately shut down every weekend and in some for a particular holiday but I believe this test was continuous. Actually, this particular system behaves better if it is shut down from time to time. Other systems behave worse.

Although there have been many incidents I do not know of any during this particular test.

6. In regard to the problem of life testing batteries under satellite type cycling, do you have any suggestions for a more rapid, more energetic method than usual which would give a fairly accurate idea of the life?

Cohn:

We had a meeting on that particular problem about six months ago and distributed a report exclusively to the participants of the meeting for the particular purpose of getting ideas for accelerated life testing. There has been some accelerated life testing for lead acid batteries, but no one knows whether these same conditions are applicable and meaningful for alkaline batteries. We are considering starting a program this year on accelerated life testing for nickel cadmium batteries. However, we don't know whether we should increase the temperature, increase the depth of discharge, increase the rate of charge or the rate of discharge. Chances are that we will have to do a bootstrap operation doing a little bit of everything on different samples and at the same time run unstressed tests and by hindsight see what correlates and how well.

7. What at present is the effective number of cycles on a secondary silver zinc battery and at what depth of discharge?

Cohn:

I think the number of cycles on secondary silver zinc batteries is something like 500 cycles at somewhere between 30 to perhaps 50 percent depth of discharge. We have tested the silver zinc cell with an inorganic separator and have had about 2000 cycles at room temperature at 30 percent depth of discharge, and something like 500 cycles at 100°C at 30 percent depth of discharge. I don't know whether these tests were to the end of life or whether these were just the numbers I got at the time which could have continued beyond that.

8. Would you further elucidate your test method which you call "pattern recognition"? (von Dohren).

Cohn:

Incidentally, I said that pattern recognition was one of 18 different names that I have seen for this type of thing. I'm afraid it's not called engineering. One of my problems is to make engineers understand the difference between this and the normal methods.

9. What type of battery was chosen for the tests?

Cohn:

This was done with nickel cadmium batteries.

10. What was the population as compared with that chosen for a conventional approach?

Cohn:

We still don't know the size of the population that we have to use. We started our nickel cadmium battery tests with 1000 cells, and through a slight error we lost 340 of them. Thus, before we even started the life tests we were left with 660 cells, some of which are still running after almost 3 years. I think that 660 cells were too much. I think one should be able to do it with a fraction of that, but I have not yet gotten a good answer from a statistician as to how to set up these tests in the right way with a minimum number of cells.

11. What parameters did you employ in your investigation (cycle mode and temperature)?

Cohn:

I don't remember all the cycle mode and temperature parameters we employed off-hand, but the three temperatures were 0°C, 20°C, and 40°C. We started actually at 50°C but found we couldn't operate because the batteries would no longer accept charge. Therefore we had to go down from 50°C to 40°C. We had a 90 minute cycle (60 minutes charge and 30 minutes discharge), a 180 minute cycle (also 2 to 1 charge to discharge time), and a longer cycle which I don't remember.

12. What data did you list for your final evaluation?

Cohn:

Well, we kept the temperature constant and measured voltages. I'm reasonably sure that this is not as good as it could be done, but it was all we did so all we had available was voltages. We threw away the data for every 29 cycles, taking only the data for every 30th cycle, and we took data every five minutes instead of every five seconds.

These are grave mistakes. I recommend that you do not repeat them because much of what we have now is not nearly as valuable as it would have been had we had better data acquisition and had we taken more data more frequently and not thrown any away.

13. Please reference the paper referred to in your lecture on the structure of nickel oxides and hydroxides, respectively, occurring in nickel cadmium batteries.

Cohn:

I referred to a series of papers that appeared from about 1964 through this year (1967) in the Journal of the Electrochemical Society (American). The authors, both working at the General Telephone and Electronics Laboratories, Bayside, New York are Dr. Aria and Dr Kober.

14. Contribution for the Record by Dr von Dohren re Hydrazine Fuel Cells.

It is well known that usually hydrazine is introduced into the cell via the electrolyte, i.e., hydrazine is mixed with the electrolyte and pumped in. This direct reaction, however, contributes some difficulties, of which two important ones will be mentioned:

(a) The introduction via the electrolyte will have a detrimental effect on the performance of the cathode. Provision has to be made for preventing the hydrazine from coming into contact with the cathode, for instance, by separation of the anolyte and catholyte.

(b) Depending upon the temperature, considerable quantities of ammonia are formed by some side reactions, i.e., by chemical disproportionation. This ammonia cannot be utilized in low temperature cells. We were able at Varta to overcome these shortcomings by introducing a relatively small decomposer, working at temperatures slightly above room temperature. The catalyst developed for this purpose is a nonprecious metal type. Very little ammonia is formed in this decomposer. In order completely to utilize the hydrogen in the gas mixture, we have used successfully the well known Janus (double-faced) electrodes according to Justi and Lindsell.

15. Comments on the Future Direction of Energy Conversion for Civilian Application.

Rodot:

Although this subject has not been broached, it is worthwhile to point out the possibilities of solar cells, a source of space energy which is already operational. How far can they be used for applications of the ground? Contrary to the thermionic devices already mentioned, these are low power sources. However, low sources of electric energy are required in many instances, in particular in barren countries. For the sake of example, let us quote the problems of lighting, radio receivers, small water pumping engines. In many countries, these requirements will become critical long before any complete electric supply network is provided (India, Senegal).

This is an economic problem. Silicon solar cells are, and will remain unable to meet these requirements at reasonable prices. However, the development of thin layer solar cells may completely modify the situation in this respect.

Should any technical questions be raised concerning solar cells, we have among us Prof. Loferski who was one of the pioneers in this field, and who will be able to give answers.

Szego:

There are some studies being made of how one can proceed by taking a perfectly arid area (presumably littoral) and bringing a large source of very cheap energy to bear on the problem. By "large" I mean the many megawatts necessary to create an entire agroindustrial complex. Unfortunately, the studies being made by the Atomic Energy Commission don't concern photovoltaic energy conversion but rather nuclear energy converted in conventional thermodynamic fashion. The fact of the matter is that we seem to be a long way from economic feasibility. For irrigation water to be of economic value it must cost substantially less than let's say 10 or 20 cents per 1000 gallons, (one French franc for 4000 litres). This is already more than one can afford to pay for irrigation water - even though this water is used over and over again in greenhouses. By having hundreds of hectares under cultivation surrounding it, this large nuclear reactor (which also synthesizes ammonia fertilizer from the nitrogen in the air) provides energy as well as raw materials for synthesis by and for all kinds of industry. Unfortunately, the economic prospect is not too bright.

I think perhaps you are all aware that after 25 years of promise, during which the music has started many times, somehow nuclear energy is never invited to dance. Now it finally turns out that one can generate electric power for somewhere between 2 and 4 mills (0.2 to 0.4 American cents) per kilowatt hour electrical from large future nuclear power plants. At least we can say - economics being the hard cold facts of life - that right now more than 50 percent of all the power plants under construction in the world are nuclear. And those that are projected for early construction commencement are perhaps 80 or 90 percent nuclear. So there is *this* transformation.

As you probably know, central station electric generating plants have long lifetimes. They are depreciated in reality at the rate of about 25 to 40 years - perhaps longer (even though there are certain technological innovations that *do* cost money). So it looks like in about 30 to 40 years virtually all the power plants in the world, except for the hydroelectrics and the tidal plants, will be nuclear. And I would venture to say that a large part of those will be fast breeder reactors, if their safety aspects are satisfactorily developed. I don't know how the photovoltaic will fit into this economic picture but perhaps there is a place where small power will do the job of keeping a light burning in an Indian village or providing communication with remote areas - very important things for people who are totally without electric power. A few watts doesn't seem like much to you but it could be a large difference not only in the standard of living but in the quality of life.

Perhaps Dr Loferski has some comments on photovoltaics and their economics.

Loferski:

Well, not very much. This is a direction, of course, in which the present research on photovoltaic conversion is moving. The big requirement, as you pointed out this morning, is that the photovoltaic cell still costs quite a bit. I guess back in the days of the early invention of the photovoltaic cell, around 1956 or so, it was realized that we needed two orders of magnitude decrease in the price of the cells. This still hasn't been realized. The price has remained fairly stable over the years. The hope is, of course, that in thin film photovoltaic cells this decrease in price will occur.

There are serious problems as far as the research is concerned on such thin film cells and there is hope that if these problems are solved, these economic problems will fall along with them. That's all I would like to say on that score.

It's nice to come back every so often and see what kinds of troubles the competition is having. It seems like the problems are the same ones that they have been having since the inception of the space program. And I guess one should be complacent as far as photovoltaic conversion is concerned, but it seems like it is going to be here to stay for quite some time.

Szego:

Ten years ago, in a little town called Americus, Georgia, they put a solar photovoltaic cell with a battery on top of a telephone pole. From that day to this the local telephone line there has been operating largely from that power. However, since the telephone company in America has not installed this apparatus nationwide I judge that it was merely a demonstration device which doesn't yet appear to have economic feasibility.

IV. QUESTIONS SUBMITTED TO MR RASOR

1. Please discuss the transient behavior of thermionic reactors in case of diode failures. (K.Einfeld).

Rasor:

Unfortunately, studies of this question in the United States are extremely design-dependent, i.e., whether the effect of the diode failure has a great deal to do with the system configuration, interconnection between diodes, etc. And as a rule of thumb, anything strongly design-dependent in thermionics will be classified. As a result, the only study I know in the open literature is Bill Holland's paper (London Conference, 1966) in which he examines open and short circuit failures in a series parallel array.

2. What about series parallel connections of thermionic diodes to give minimum power loss in case of diode failure? Do practical solutions exist?

Rasor:

I refer you directly to Holland's paper in which he shows a real solution to the problem. That is, with an optimum interconnection in such an array (the network), the percentage decrease in output would only be the percentage of the number of diodes that fail. On the other hand, I want to emphasize that this requires access to the terminals of all the diodes. In the in-core reactor, typically there are 10 to 20 diodes that are series connected in a string in one of the elements, thus making access difficult. Although there are different designs for in-core thermionic reactors in which this may be possible, I cannot describe them here.

3. What about in-pile test data of thermionic fuel elements?

Rasor:

Across the board in the United States, in-pile test data for thermionic fuel elements are classified. On the other hand, the Brown-Boveri Corporation in Heidelberg describe the in-pile tests of their fuel elements in a publication called "B.B.Nachrichten". They carried some of the type which I briefly flashed on the screen to two percent burnup of the fuel, but these are uranium oxide in molybdenum elements. Furthermore, at the London Conference there was a whole session on nuclear fuels for thermionics which included the French and English contributions. However, there is no US contribution as far as in-pile testing is concerned. (The out-of-pile results on the compatibility of the fuels are described in my Ref.13 to Kaznoff and Weidenbaum.)

4. In regard to out-of-pile applications, if you want to make a design you will have to know on what efficiencies, and on what power densities you can base your design. I mean, quite a number of data were presented during this meeting which showed a general

trend but which were rather old, so I'm just wondering whether there is a possibility to base an estimate on the present day data on what potential still is available to achieve during the next three year period.

Rasor:

I think the design charts in my reprint summarize all the existing experimental data quite adequately. It may be that these charts are not highly precise over all the region they cover, but I think they are as precise as the variation in data among various groups (among various treatments of the surface, for example) which are still not 100 percent under control. Furthermore, most of these differences can be covered merely by a few degrees centigrade change in the cesium reservoir temperature, for example.

I think if you use those charts you are able to make a good estimate of present performance. I do not see any great advantages beyond this because we can now operate near optimum in the ignited mode. We have the materials for this. Rhenium, say, is almost optimum in the extinguished mode. This is a wave of the future in thermionics; however, we don't know yet exactly how to do it.

4. (a) I would like to make an addition to the answer you gave for my first two questions concerning the parallel and series connections of thermionic diodes. In my opinion, the Holland paper is purely theoretical. If you look at the designs of thermionic in-core reactors which you can envision, it is awfully difficult to make parallel connections of the diodes.

Rasor:

I'm sorry but I can't describe anything further than the designs that have been published.

Koskinen (Brown-Boveri):

We don't classify our work. Mr Jester here is developing several methods by which the cross connection can be used. And they appear to be quite practical.

Rasor:

I have two designs in my paper which are not being actively pursued in the United States, so I was able to include them. The point is that both of them, the thermionic version of Rumoshka and this double diode device, have the terminals of all cells accessible. So you are able to hook them up into a series parallel net such as Holland postulated. I believe that the in-core multiple cell thermionic fuel element (TFE) (20 cells) is a very advanced design - sort of the ultimate. Remember I said that it's the Cadillac of the thermionic business. I would rather see us evolve into that by an evolutionary process than by a revolutionary process. This is my personal opinion; it obviously is not reflected in what is being done in the United States.

5. What is the efficiency of DC/DC converters for thermionic reactors?

Zwick:

It's around 90 percent, or more.

6. What is the argument for a fast or thermal in-core reactor at 100 kW from the engineering point of view?

Rasor:

First of all, from the standpoint of weight you are near the breakeven point. This is an extremely design dependent quantity again, but somewhere in the region of 100 kW both sides can win. However, uncertainties in the calculations allow them to overlap here, so from a weight standpoint you can't tell.

From an efficiency standpoint alone probably the fast reactor can do better since you can probably use a higher power density. You can use more cells, better material such as rhenium, etc. But of course efficiency isn't the primary consideration. I'm afraid it's a rather broad question.

7. How about possible development of thermoelectric elements for temperatures greater than 1000°C.

Rasor:

There have been programs in the United States. At Gulf-General Atomics, for instance, cerium sulfide and a series of such compounds were investigated for high temperature use. The Monsanto Chemical Company worked on doped graphite derivatives for high-temperature thermal elements. Even though they were working for 2000°C, they were able to get ZT substantially higher than one at these higher temperatures.

On the other hand, there is the old problem of mechanical and thermal stability for these things. It's a whole new subject. We can't do it, except I would like to point that Monsanto is now out of the thermoelectric materials business, as is largely General Atomics. This may give you an idea of how important these developments were.

8. Discuss the degree of flattening necessary in a fast or in-core thermionic reactor in relation to diode performance and configuration.

Rasor:

Since this is an extremely design dependent thing, again I can't give you any numbers. However, flattening introduces more complexity into this system but it can be solved by fuel distribution or by changing the cell size.

There is less flattening required in the fast reactor system. The local perturbations aren't as bad. In the thermal system, especially as the control elements change their position during life, you can have very severe local flux depression. And you really need a distributed control of some kind. This again has been studied in great detail. I don't think I've seen much in the open literature on it.

9. What do you think about cesium fluoride additives? (Cazeneuve).

Rasor:

This is probably the best approach to the extinguished mode operation and therefore an important advance in thermionic converter technology. Although not conclusive, all the indications are that all of the additive work up to date has been a result of oxygen contamination. Again I refer you to the "B.B.Nachrichten" in which an article describes these results using cesium oxide. Probably the previous results on cesium fluoride were due to an oxygen contamination. Nevertheless, the results of this have been encouraging and regardless of what the impurity is that is causing the good effects, they are indeed good.

10. What is the best solution: separate cesium chambers or a common chamber?

Rasor:

Unfortunately, I didn't go into this. If you have two reservoirs - one with the additive in it and one with the cesium - they have two different temperatures to get the vapor pressures that you want. One will just condense in the other unless you have an orifice. You can't put them together or else you would have to have one temperature for both. So if you are going to have separate compounds, you are going to have separate reservoirs.

However, there are two things to be considered here. One is the integral reservoir (the graphite crystal or absorption reservoir that I described) where you can have any temperature you want. If you take this and put it into the converter - connect it to the cesium reservoir and optimize the diode, but at the same time connect it to the additive reservoir and optimize the diode - this same integral absorption reservoir will absorb the impurity (the additive) as well and will stay at optimum for a long period of time.

Cazeneuve:

This is not a second question. I asked you this question regardless of any assumption of additive or dope, but as regards the general case of the use of cesium alone.

Rasor:

Oh! I thought this was related to the additives.

I would say that the best solution would be to have, if possible, an integral reservoir in each cell and have them cross connected. Because the loss of cesium from the cell is one of the worst kinds of failures that you encounter. If you have a common cesium reservoir for say 20 cells, such as in the TFE, you lose all of them. So I would prefer them to be separate chambers, each with an integral reservoir. But you must have your design able to handle this.

I would like to amplify my comment about the additives, however. Thermoelectron Engineering Corporation (which has done a lot of the additive work, as well as Brown-Boveri) has found recently, modifying their previous discoveries, that having a cesium oxide reservoir alone is apparently not good enough. You must put the oxide directly on the collector, and then you don't need the reservoir. And if you have the reservoir, that's not good enough - you must oxidize the cesium on the collector. In other words, it is still an open subject. The good results are obtained. Why you get them is uncertain.

11. What is the optimum power output if the total power of the reactor is 50 kW or 500 kW? (Cazeneuve).

Cazeneuve:

I asked you the question of the optimum power of a diode adapted to the operation of a 50 - 500 kW jet-engine. I mean that there are, maybe, different sizes to be selected according to the size of the jet-engine in which the diodes have to be integrated - perhaps a few hundreds of watts, or even perhaps one kilowatt per unit. Do you have any opinion on this subject?

Rasor:

This is what I was leading to. The point is that the diameter of the cell tends to decrease as you increase the total power output of the reactor. This is just because you are trying to introduce more surface area into the reactor.

For example, a 50-kW reactor perhaps would have a 20-cm² cell, which would be something like a 200-watt cell. How many cells you have in series, now, depends on how well you can optimize the lead connections to conserve space and how thick the electrodes can be to minimize loss. But typically a 20-cm² cell - for instance, something like a 1½-cm diameter by say 5 cm long - might be typical for a 50-kW reactor. That would be something like a 200-watt cell. For a reactor up into the megawatt range, they get down to perhaps something like 2/3 cm (¼ in.) in diameter and something like perhaps 2 or 3 cm long. Now these were to operate at a higher power density but it would still only be about a 50-watt cell.

V. QUESTIONS SUBMITTED TO MR DIECKAMP

1. Lubrication for the bearing on SNAP-8. (R.Pruschek).

Dieckamp:

The bearings in general are dry lubricated with something like molybdenum disulfide burnished into the surfaces. There is not a large amount of material present - just a very light film. In general the materials combinations are hard materials against hard materials such as titanium carbide or aluminum oxide flame sprayed on shafts and things of that sort.

2. Power of the stepper motors.

Dieckamp:

I think the average power of the stepper motors for SNAP-8 is 15 watts. Again, those stepper motors are stepping only once every 100 sec or so, at which time the peak power is of the order of 100 watts for perhaps 10 milliseconds.

3. What is the estimated change in reactivity due to hydrogen loss in SNAP 10A or 8, and is it more or less than all the other changes in reactivity including variable poisons?

Dieckamp:

In the case of SNAP 10A the hydrogen loss over a year's life was about enough to result in 100° or so drop in temperature. Hydrogen loss was less than for such things as xenon and samarium. We do use samarium prepoisoning in the reactors, and as you go to higher temperatures and higher power levels. Hydrogen loss does tend to become the more dominant term in the reactivity loss mechanisms. I'm not able to quote those numbers in any greater detail, but I think we've also said in the open literature that in the case of something like SNAP-8 we expect to have about 5 percent of the hydrogen leak out of the system during its one year lifetime.

4. Has there been a program to investigate yttrium hydride?

Dieckamp:

Yttrium hydride is somewhat more stable than zirconium hydride at higher temperatures. However, at intermediate or lower temperatures, Yttrium hydride has a lower hydrogen density than does zirconium hydride.

I think perhaps the simplest way to put this in context is to say that in general we want the maximum hydrogen density that we can have at any given temperature in order to minimize the reactor size. So if I look at the hydrogen density as a function of temperature for constant dissociation pressure of zirconium and yttrium hydride, I will find that below about 1500°F I will have a higher hydrogen density with zirconium hydride. Above 1500°F or so I will have a higher allowable hydrogen density with yttrium hydride.

5. Discuss fast versus thermal reactors.

Dieckamp:

Some people have the opinion that a high-temperature reactor should be a fast one as far as space power's concerned.

I think my feeling on that is that the current capabilities of the hydride reactor are quite consistent with thermoelectric power conversion, the mercury Rankine cycle, and for some utilization of the Brayton cycle if you are not too concerned about radiator area. But the radiator area can be about the same as it is for a thermoelectric system in terms of watts of power output per square foot of radiator area.

So what this really means then is that if you can have these radiator areas perhaps of the order of 2000 sq ft per 30 or 40 kW electrical (at which point I'm beginning to sound like my solar cell colleagues), the advantage of a Brayton cycle with a hydride reactor is its higher efficiency in extending the power output capability of the energy limited SNAP-8 reactor, up to about 100 kW electrical.

In effect, you find you are trading off reactor development for power conversion development when you get into the regime where the reactor is energy content limited. Low efficiency conversion means I have to build a bigger reactor or put more development into the reactor. Higher efficiency conversion means I can use the small reactor but need to put the effort into the conversion cycle.

So, again, I think for high performance Brayton one needs to go to a different reactor concept than the hydride reactor. There are just no suitable materials choices for moderators for reasonable size reactors, so it becomes a fast reactor. There is just not much choice.

6. In regard to shielding, how are experiments done on the ground?

Dieckamp:

It is very difficult to perform meaningful shielding experiments on the ground either because of (1) air scattering, which allows neutrons effectively to bypass the shield and obscure the radiation effectiveness of the shield itself, or (2) it is very difficult to perform meaningful measurements inside a vacuum chamber (because now the walls of the container act as scatterers which allow neutrons to by-pass the shield). The only approach which has really been used (and depending upon the enthusiasm of the researcher, they claim it is adequate) is highly to collimate the receiver-detector so that you can select only those neutrons which have traversed the thickness of the shield rather than those coming from some other angle.

There are other shielding questions concerning the fact that the shield is heated during operation. In the case of SNAP 10A the shield ran at a temperature of the order of 700° F. In the case of SNAP-8 the maximum shield temperatures were of the order of 1000° F. As one goes higher in power, let's say to a megawatt or beyond (thermal) then I think one has to become quite concerned about cooling of the shield and maintaining it cold enough that you do not lose the hydrogen (which is the material slowing down the neutrons that is making the shield effective).

7. Do you use any heavy metal such as tungsten or depleted uranium?

Dieckamp:

For an instrument rated shield, in general you will find that by the time you have achieved the required neutron attenuation you will also have an adequate amount of gamma attenuation with lithium hydride only. However, in the case of a man shield it definitely must be a two region heavy metal and lithium hydride shield.

VI. CONCLUSIONS OF MEETING - R. A. WILLAUME

On behalf of all participants, I think it is indispensable that I extend my very sincere thanks to the speakers for their excellent papers, prepared with such care, and presented with such competence. We are all aware of the time required by the preparation of their work, and are very appreciative of the fact that, in spite of their heavy daily schedule, they have found it possible to bring their notes up to date to provide us with the latest results available.

I also wish to express thanks to Prof. Haus, who, in his capacity as Belgian National Delegate to AGARD, has made possible the organization of this Lecture Series in Brussels, and to Prof. Jaumotte to whom we are indebted for the necessary material arrangements made in the University of Brussels. I also wish to stress that Prof. Jaumotte represents the AGARD Propulsion and Energetics Panel, which selected and recommended this program.

I would like to point out that this Lecture Series and its organization represent, for AGARD, an experiment which may be improved. Therefore, the comments which you could formulate would help us in raising the level of the Lecture Series which we sponsor each year, and in improving their efficiency.

As you have been able to note, the attendance has been considerable, and the questions raised enable us to evaluate the program presented, its drawbacks, its advantages, and to give a new orientation to the organization of additional lectures.

I am quite conscious that the area covered this week is very broad and that we have only touched the subject; however, I believe that, in your future work, you will be able to derive some benefit from the information exchanged during these Lectures.

To conclude, I would also like to express my most sincere thanks to the interpreters who have performed such a delicate task, and who have succeeded in translating all the lectures in a remarkable manner in spite of the rapid elocution of some speakers.

Dr Szego, I wish to thank you for the technical implementation of the program. I believe you will be pleased to hear that we have all appreciated your efforts, and your careful preparation. For the result achieved, we are indebted to your high competence and to the interest you have devoted to this event. Thank you again.

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