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AUGUST 15, 1965

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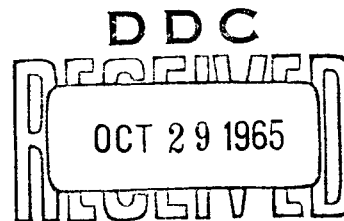
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RESEARCH AND DEVELOPMENT
OF OPEN-CYCLE FUEL CELLS

(Fourth Quarterly Progress Report)
(Under Modification 4,) Contract NAS 8-5392
(For The Period Ending August 15, 1965)

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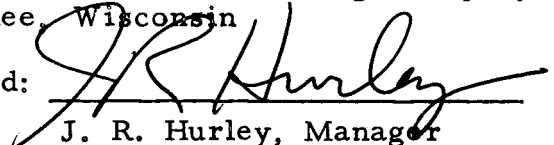
George C. Marshall Space Flight Center
Huntsville, Alabama

PREPARED BY

R. Desai, G. Monette, C. Williams

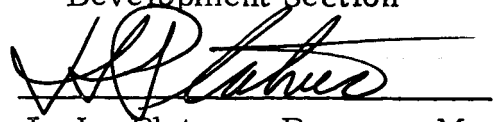
Research Division, Department 3341
Allis-Chalmers Manufacturing Company
Milwaukee, Wisconsin

Approved:



J. R. Hurley, Manager
Systems Research and
Development Section

Approved:



J. L. Platner, Program Manager

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	i
ABSTRACT	ii
SUMMARY	iii
1.0 COMPUTER PROGRAM FOR FUEL CELL PARAMETER OPTIMIZATION	1
1.1 Effects of Adding a Water Recovery Subsystem	1
1.2 Discussion	2
2.0 FUEL CELL STARTUP TECHNIQUES AND PRELAUNCH INSTRUMENTATION	3
2.1 System Evaluation Criteria	3
2.2 Instrumentation	3
2.3 System Startup	4
2.4 Sea Level Operation	5
3.0 MATHEMATICAL MODEL OF STATIC MOISTURE REMOVAL PROCESS	7
3.1 Discussion	7
4.0 RELIABILITY MODEL OF FUEL CELL SYSTEMS	8
4.1 A Study to Compare the Performance of Various Systems	8
5.0 CONCLUSIONS	10

INTRODUCTION

This report is the Fourth Quarterly Progress Report issued under Modification Number 4 to Contract NAS 8-5392. Progress during the period of May 16, 1965 through August 15, 1965 is covered herein.

ABSTRACT

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Modification and extension of the existing digital computer program for minimizing the weight of fuel cell power systems has been completed and design charts are presented. The study of prelaunch startup and instrumentation has been completed. The computer program for the mathematical representation of the static vapor pressure method of water removal has been debugged. The results of a study to compare the reliabilities of various series parallel fuel cell configurations are given in chart form. An analysis to compare the performance of series versus parallel systems is presented.

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SUMMARY

The digital computer program for fuel cell system parameter optimization has been modified and extended to include the use of batteries for supplying a portion of peak power. The subroutine for computing the properties of a radiator as functions of the system operating parameters was modified. The effects of including a water recovery subsystem are now considered by the expanded program.

The criteria for evaluating fuel cells at the launch area and the required instrumentation are listed. The methods of rapid startup and prelaunch operation are presented.

The results of a computer run made to simulate the transient operation of fuel cells at 200 ASF are presented.

The study to compare the reliabilities of various series-parallel fuel cell configurations has been completed. Reliabilities of various configurations producing 2 KW are presented. The results of an analysis to compare the performance of series versus parallel systems are also described.

1.0 COMPUTER PROGRAM FOR FUEL CELL PARAMETER OPTIMIZATION

The existing computer program (IBM 704) for fuel cell parameter optimization has been modified and extended to include the use of batteries for supplying a portion of peak power. Modification of the subroutine which computes the properties of the radiator as functions of the system operating parameters has been completed. The effects of collecting water are also considered by the expanded program.

A complete description of the program has been prepared for publication.

1.1 Effects of Adding a Water Recovery Subsystem

The effects of adding a water recovery device to the present fuel cell system are as follows:

- (1) The amount of heat to be dissipated will become greater and hence radiator weight will increase.
- (2) The weight of a water recovery device itself will have to be considered.

Since general information regarding the second effect is not available, detailed consideration has been given only to the first effect. The weight of the collection device itself can be included with the auxiliaries to the fuel cell.

Q_w is the control character in the program to determine the weight of a radiator. If Q_w is set equal to 1100 Btu/hour, the program will calculate the optimum system weight when no water is collected. If Q_w is zero, system weight will be calculated when the entire amount of generated water

is collected. If Q is $w(1100)$, then weight will be calculated for a system collecting $(1-w)100$ percent of generated water, where w is a fraction, so that $0 < w < 1$.

1.2 Discussion

This program calculates the minimum weight of alkaline hydrogen-oxygen fuel cell systems supplying power within set voltage limits. Nomograms for approximating the minimum system weight for various power levels are presented in Figures 1 and 2. The weights are determined on the basis of present Allis-Chalmers capabilities (January 1964 technology), a supercritical reactant storage, a radiator with a 0.999 probability of survival, and a voltage regulation requirement of 29 ± 2 volts.

Minimum system weight can be further reduced by using either primary or rechargeable batteries to supply a portion of peak power. The reduction in weight can be fifty percent or more if the peak power is four to five times the base load. Rechargeable batteries will provide the minimum weight system if the peaks occur repeatedly.

2.0 FUEL CELL STARTUP TECHNIQUES AND REQUIRED PRELAUNCH INSTRUMENTATION

The specific criteria for evaluating a fuel cell system at the launch area have been developed, and the required instrumentation for this purpose is listed. Also considered are problems associated with the rapid startup and ground (or sea level) operation of a system.

2.1 System Evaluation Criteria

The criteria for evaluating a fuel cell system are:

- (1) Leakage Rates - There should be negligible leakage of any reactant or coolant.
- (2) Control System Operation - The control system of a typical fuel cell system consists of sensors, valves, and a master control. Each part of the system should operate within specified limits.
- (3) Stack Operation - The fuel cell stack should produce required power within specified voltage limits.

2.2 Instrumentation

A list of measuring devices needed to establish the criteria developed in the previous paragraph is given below.

To measure leakage from each subsystem and leakage between subsystems, the following devices will be needed:

- (a) Pressure Measuring Device

- (b) A clock
- (c) A source of inert gas (e. g. Helium)

Since the volume of each portion of the system is known, leakage rates could be inferred from pressure decline with time for each closed off portion of the system.

The sensors can be checked by testing their output for a known condition. For example, the temperature measuring devices can be checked if the module is known to be at ambient temperature. The master control can be checked by supplying a set of input signals simulating the output of the sensing transducers and observing the command signals which are sent to the valves. The valves can be tested by observing, via supervisory contacts, their reaction to these same signals.

For checking the satisfactory operation of the stack, voltage and current measuring devices will be needed. Several voltage measurements at pre-determined currents would establish the performance against the known V-A characteristics of a normally functioning system.

2.3 System Startup

The heat required to bring a fuel cell system up to its normal operating temperature can be supplied by any of the following sources. Approximately 20 Btu per ° F is required to heat the typical 2 KW system.

- (a) Electrical energy:
 - (1) Applied within the coolant duct by resistance heaters

(2) Applied to the outer wall of the canister by electrical resistance heaters

(b) The heat of chemical reaction inside the fuel cell, i.e., to operate the fuel cell and not allow the excess heat to escape. Preliminary data indicates that typical Allis-Chalmers cells can sustain current densities of 30 ma/cm^2 at temperatures down to 0° F .

Of these sources, electrical energy applied to the coolant duct has been chosen for the present Allis-Chalmers centerline module. This heating method tends to induce a temperature gradient within the fuel cell stack, which gives rise to a KOH concentration gradient. An analysis performed to study this problem indicated that the predicted gradients fall within the acceptable operating limits of the stack.

2.4 Sea Level Operation

Sea level operation of a fuel cell system requires that a method of water removal be provided. If the system has its own water recovery device, a small vacuum pump will be needed to remove non-condensables from the water vapor cavities, otherwise a vacuum pump with sufficient capacity to handle the produced water vapor will have to be provided.

It is possible to operate a fuel cell for a short period with no provision for removing the product water. Figure 3 shows the dilution of the electrolyte which results for various loads and durations. The capacity of a typical cell is such that a dilution to 25% concentration from 40% will cause flooding.

Other possibilities for water removal exist, such as operation at elevated temperature, with product water vapor being exhausted above ambient pressure; continuous purging of reactants, etc., but these were not studied.

At present the use of a vacuum pump is considered to be the most desirable method for water removal since the stack would operate in the normal range of temperature and pressure.

3.0 MATHEMATICAL MODEL OF STATIC MOISTURE REMOVAL PROCESS

The mathematical model of static moisture removal was completed and the computer program for it has been debugged. It is now possible to determine the transient and equilibrium water concentration throughout the cell for any temperature, gas pressure, vacuum cavity pressure, current, cell dimensions, and initial conditions. Any current distribution and temperature distribution in the hydrogen, oxygen, and vacuum cavities may be assumed.

3.1 Discussion

A computer run was made to simulate transient operation of a 0.2 ft^2 cell at 200 ASF. Figures 4 and 5 show the concentration gradients that developed in the gas cavities, electrolyte, and water removal capillary matrix after the cell had reached an equilibrium condition. Elements $i = 1$ to $i = 10$ represent the length of cell in the direction of gas flow and elements $j = 1$ to $j = 12$ represent the distance between the oxygen cavity and the vacuum cavity. Relatively drier and wetter elements near the reactant inlet and outlet, respectively, are caused, primarily, by the dry inlet gas, which evaporates water from the matrix at the inlet end and then deposits this water near the outlet end.

The concentration gradient in the electrolyte is due to the chemical reaction which results in production of water at the hydrogen electrode and consumption of water at the oxygen electrode. The gradient in the water removal matrix is necessary for removing water from the cell. The steps in the concentration gradients show the effect of temperature on concentration. The assumed temperature distribution is listed in Figure 4.

4.0 RELIABILITY MODEL OF FUEL CELL SYSTEMS

The reliability study of various series, parallel and series-parallel fuel cell configurations has been completed. The reliabilities were compared for two types of systems as shown in Figure 6. Type I systems are designed to produce 2 KW at 27 volts, and 0.8 KW at 31 volts. Type II systems are designed to produce 2 KW at any voltage. A voltage converter must be used in conjunction with Type II systems if specified voltage limits are to be met. In both cases, the power requirements were met by considering 1, 2, and 3 parallel strings and also by cross-connecting these strings. Since Type I systems are designed to meet the voltage requirement without a converter, the operating current density per section must be smaller and more sections must be added to the system as more parallel strings are added.

The results of the study are shown in Figure 7. The calculations are all based on an individual cell section reliability of 0.98. Note that, in general, the more parallel strings that the system has, the more reliable it is. Cross connecting these strings further increases the reliability because the failure of one section does not render an entire string useless.

4.1 A Study to Compare the Performance of Various Systems

A study has been made to compare the power output, voltage, and current of n cells connected in series (series system) with n cells connected in parallel (parallel system).

It is necessary to compare the two systems under equivalent conditions, which means that the systems operate at the same percentage of maximum power or short circuit current, or at a voltage such that the average voltage per cell for the series system equals that of the parallel system. If the

comparison is made under equivalent conditions, the following conclusions can be drawn:

- (1) The parallel system will produce higher power.
- (2) The average voltage per cell for the series system will equal that for the parallel system.
- (3) The average current for the parallel system will be greater than the common series current.

It was found that the current distribution for the parallel system will be skewed such that:

$$\frac{S_P}{S_S} = \frac{1}{K \bar{X} I_S}$$

where:

S_P = Standard deviation of the reciprocals of the parallel currents.

S_S = Standard deviation of the section voltages for the series system.

$K \bar{X}$ = Average V-A slope of the n cells

I_S = The common series current.

5.0 CONCLUSIONS

The computer program for fuel cell system parameter optimization has been modified and expanded. Nomograms are presented for approximating the minimum system weight for various energy and power levels. The minimum system weight can be further reduced by using batteries to supply a portion of the peak loads. The reduction in weight can be fifty percent or more if the peak power is four to five times the base load.

Reliability studies of various series-parallel fuel cell systems show that in general, a parallel system is more reliable than a series system. The analysis for comparing the performance of series versus parallel systems indicated:

- (1) The parallel system will produce higher power.
- (2) Average voltage per cell for series system will be equal to that for parallel system,
- (3) Average current for parallel system will be greater than that for series system, and
- (4) The current distribution for a parallel system will be skewed.

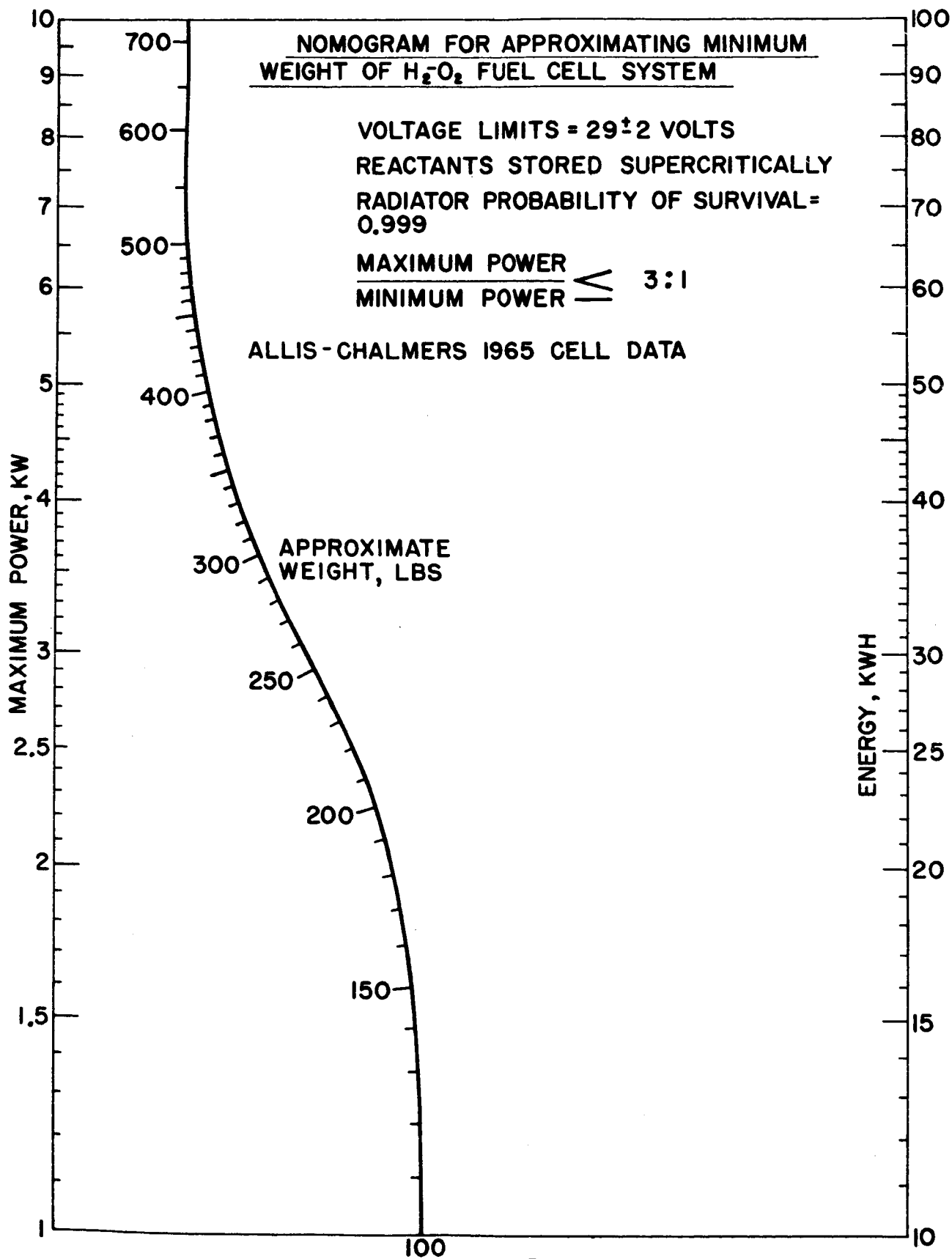


Figure 1

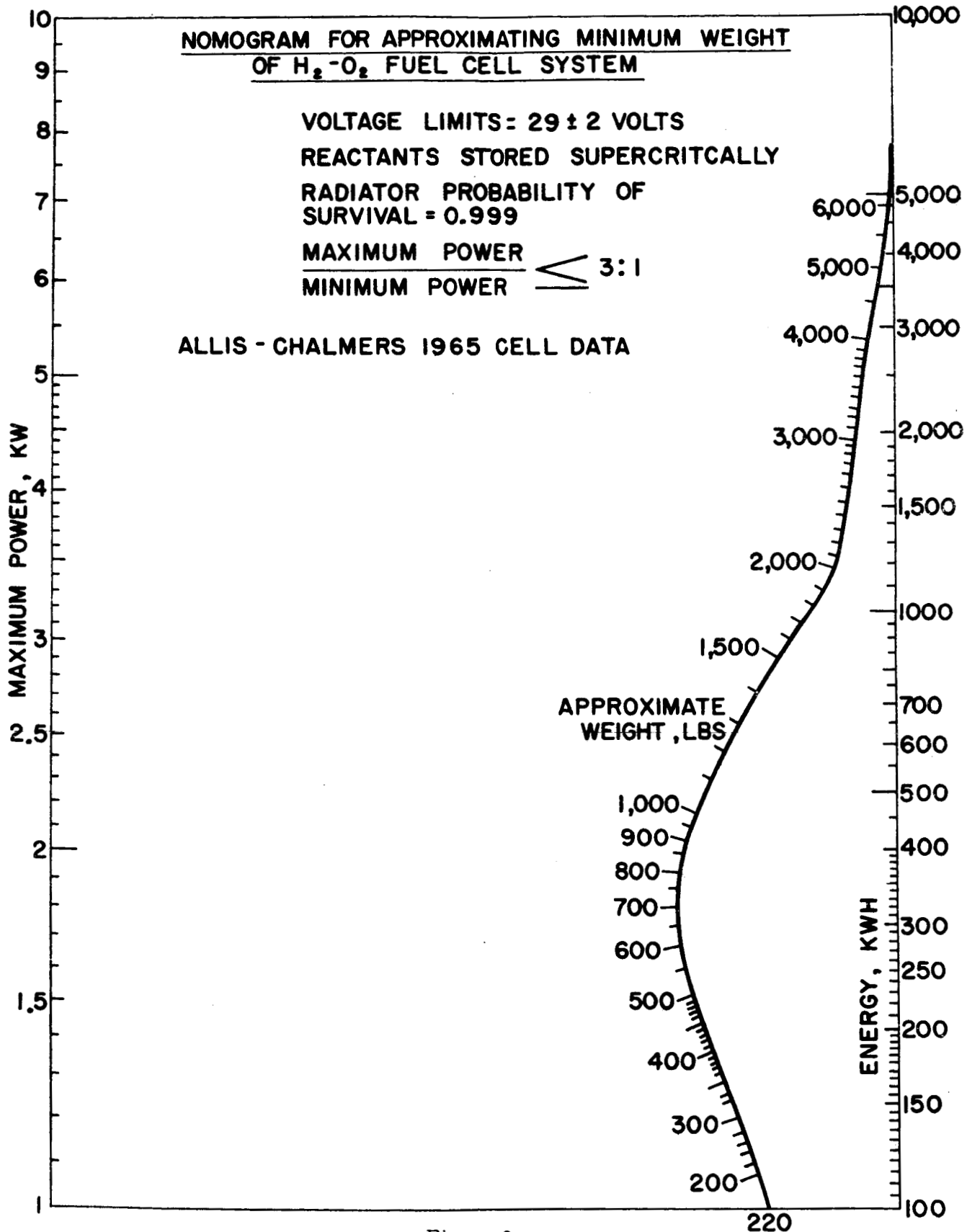


Figure 2

CELLS FILLED WITH 12 ml OF 40% KOH
 VARIATION OF KOH CONCENTRATION WITH LOAD AND TIME DURING A PERIOD IN
 WHICH NO WATER IS REMOVED

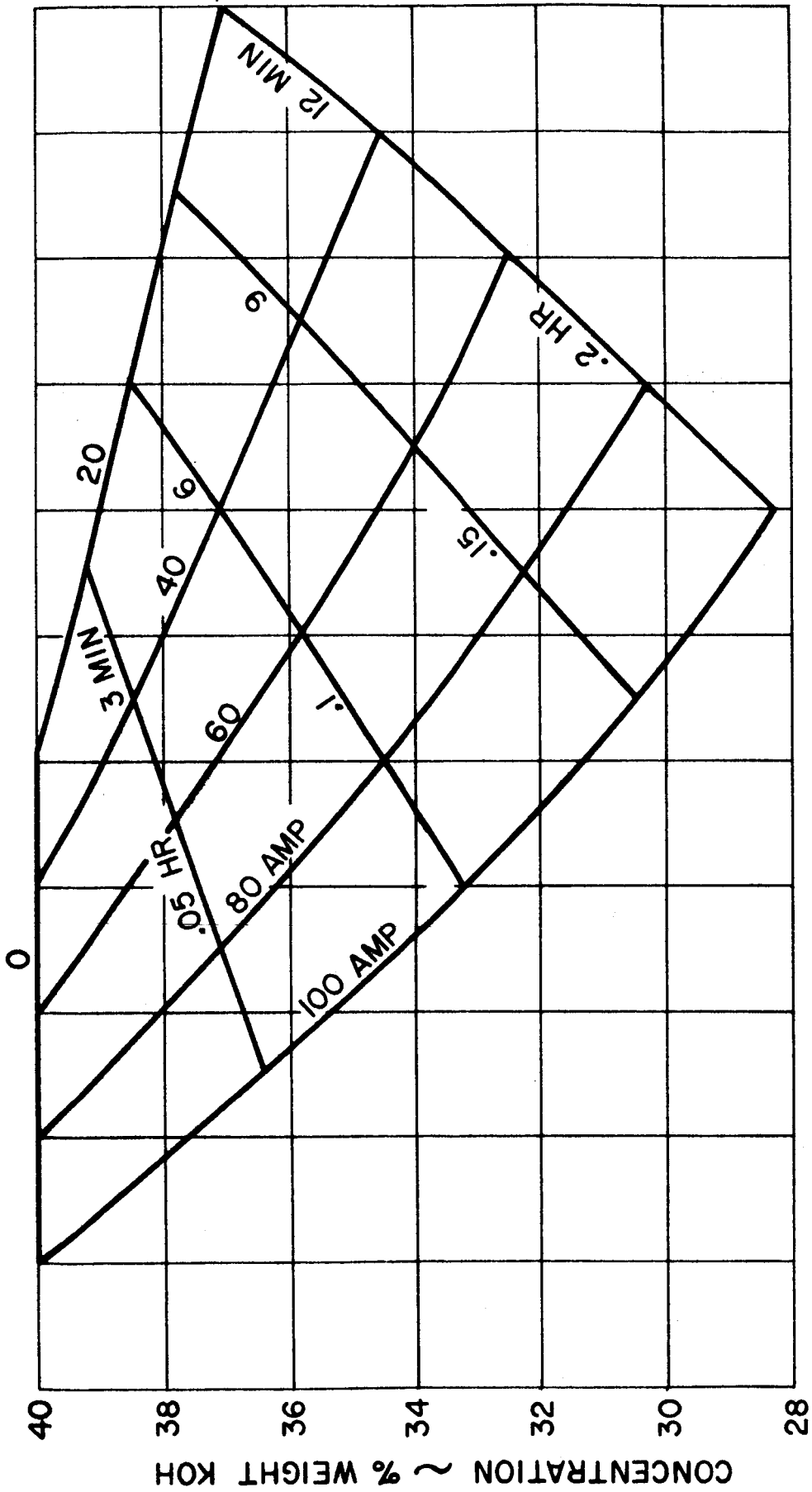


FIGURE 3

D
CONCENTRATION GRADIENTS ALONG CELL LENGTH FOR
ELEMENTS IN ELECTROLYTE AT 200 ASF

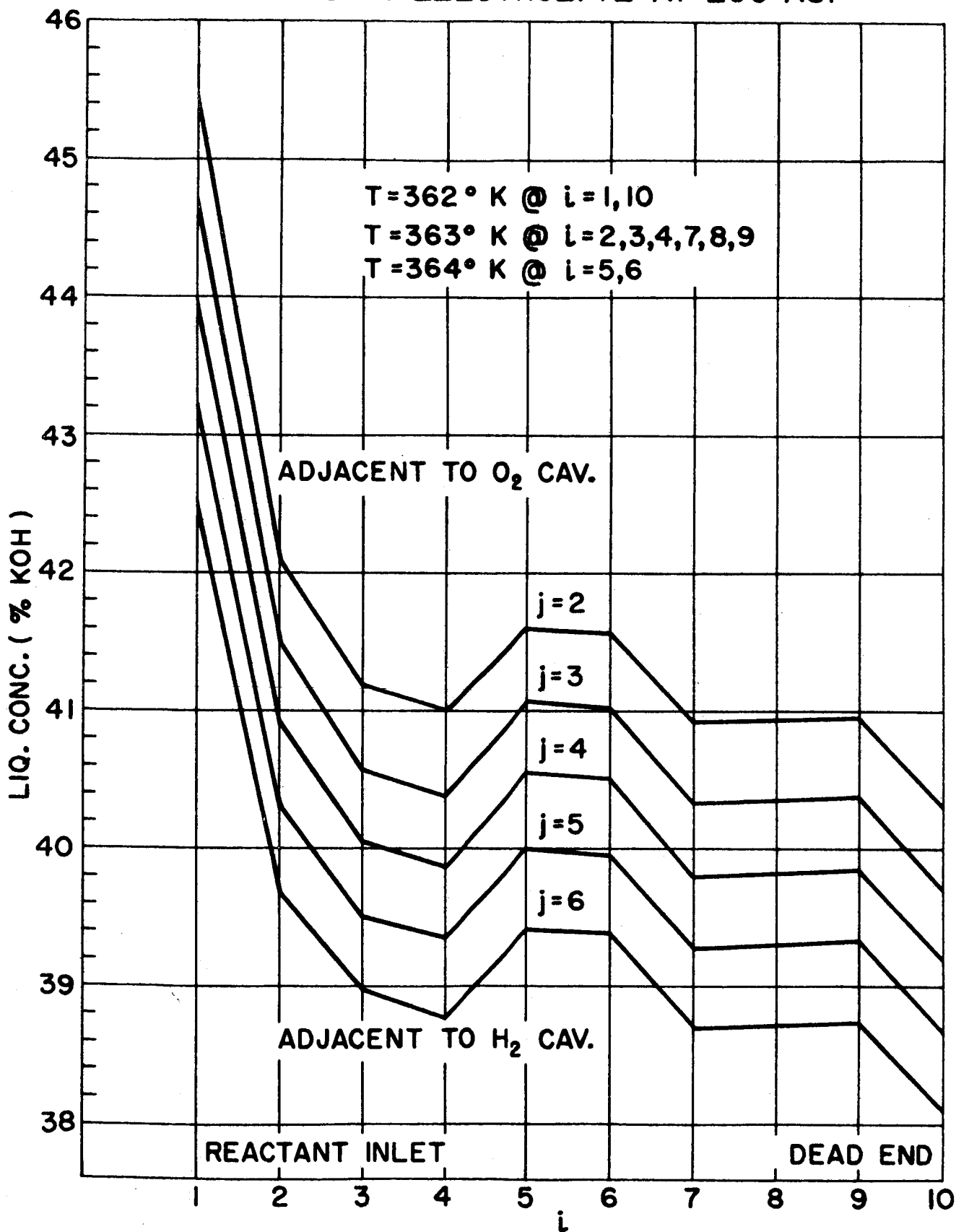


Figure 4

CONCENTRATION GRADIENTS ALONG CELL LENGTH FOR
ELEMENTS IN WATER REMOVAL MEMBRANE & GAS

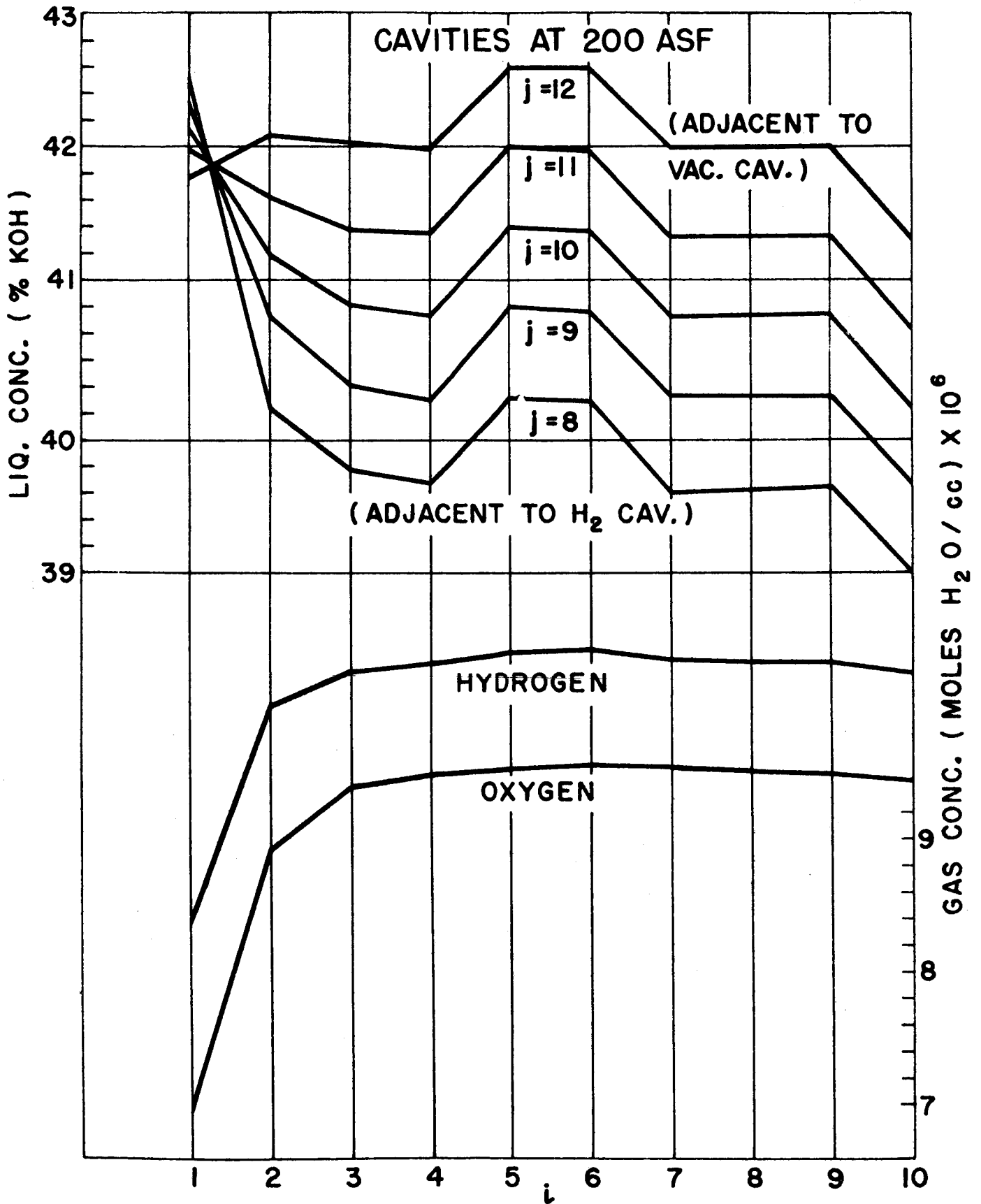


Figure 5

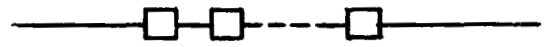
SYSTEM CONFIGURATIONS

TYPE I

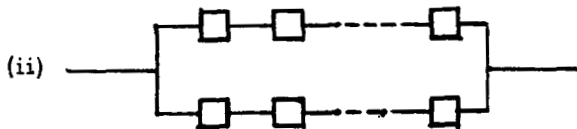
TYPE II



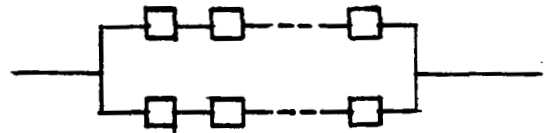
35 cell sections in series



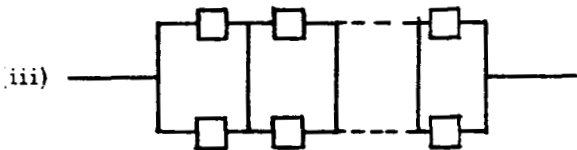
42 cell sections in series



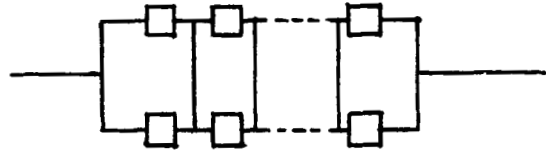
2 parallel strings of 32 sections



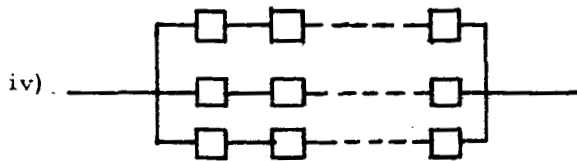
21 parallel strings of 21 cell sections



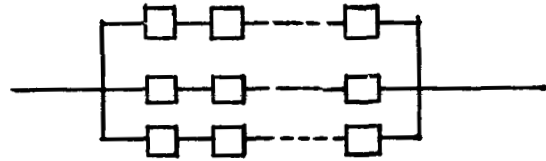
2 parallel cell strings of 32 cell sections
(cross connected)



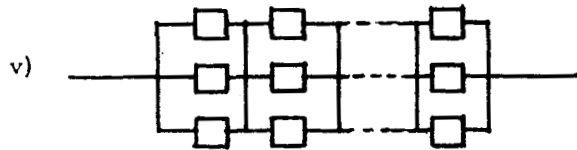
2 parallel strings of 21 cell sections
(cross connected)



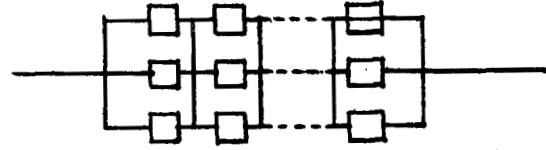
3 parallel strings of 32 cell sections



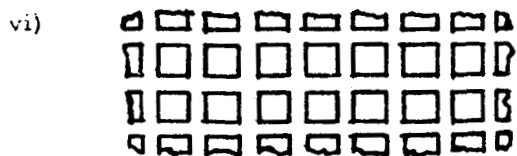
3 parallel strings of 14 cell sections



3 parallel strings of 32 cell sections
(cross connected)



3 parallel strings of 14 cell sections
(cross connected)



37 cell sections (redundant system)



42 cell sections (redundant system)

Figure 6

TABLE OF RELIABILITIES

Based on Individual Section Reliability of 0.98

TYPE I

Circuit	RELIABILITY		System producing 1 kw at any voltage
	System producing 2 kw at		
	27 volts	22 volts	
1	0.4930746	0.4930746	0.4930746
2	0.274	0.773	0.773
3	0.274	0.988	0.988
4	0.536	0.892	0.896
5	0.968018	0.999744	0.999744
6	0.9939716	0.999994	0.999994

TYPE II

Circuit	RELIABILITY	
	System producing 2 kw at any voltage	System producing 1 kw at any voltage
1	0.428	0.428
2	0.428	0.88124
3	0.428	0.9912
4	0.847898	0.985
5	0.985	0.9999
6	~ 1.0	~ 1.0

Figure 7