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Proceedings of the ERDA Seniannual SOLAR PHOTOVOLTAIC PROGRAM Review Meeting

Orono, Maine
August 3-6, 1976

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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PROCEEDINGS OF THE
ERDA SEMIANNUAL SOLAR PHOTOVOLTAIC PROGRAM
REVIEW MEETING

University of Maine at Orono
Orono, Maine
August 3-6, 1976

Organized by the University of Maine at Orono
for the Energy Research and Development Administration
Contract Number E(49-18)-2477

College of Engineering and Science
University of Maine at Orono
Orono, Maine 04473

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PREFACE

This report of the Proceeding of the Subject Meeting has been assembled to provide the participants and other interested parties with a compilation of abstracts of the talks given. Copies of visual aids used have been printed in the best available form.

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NATIONAL SOLAR PHOTOVOLTAIC

PROGRAM REVIEW MEETING

University of Maine at Orono
Aug 3-6, 1976

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MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY SYSTEMS

Energy Research and Development Administration
Contract No. E(04-3)-1101, Project Agreement 8

Period of Contract:	1 December 1975 - 15 January 1977
Value of Contract:	$421,700
Principal Investigator:	Dr. A. B. Greenberg

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Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976
University of Maine at Orono
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I. Objectives

The overall objective of this project is to support the formulation, planning, and justification of the ERDA National Photovoltaic Plan through a) analyses that lead to the identification of promising terrestrial applications for photovoltaic solar energy conversion, to the recognition of attractive demonstration possibilities, and to the identification and resolution of critical external issues influencing the widespread utilization of the technology and b) planning support to refine the overall program strategy.

Specific objectives, in support of this overall goal, are a) to survey and evaluate near-term (1976-1985) applications and to identify those most likely to contribute significantly to the orderly growth of the market, b) to evaluate the most promising major (i.e. representing large total markets) missions for the mid-term (1985-2000) period and to determine the conditions under which photovoltaic technology can compete at array prices that are consistent with ERDA goals, c) to address critical external issues and identify the sensitivity to such factors of the technical requirements imposed on photovoltaic systems, and d) to quantify the non-internalized costs (i.e. costs not reflected in the price of electricity) of power generation by conventional and photovoltaic methods and to identify compensating incentives.

II. Previous Activities

This study is, in part, a continuation of an earlier NSF-supported mission analysis program, whose principal thrust was toward developing procedures for the technical and economic evaluation of candidate photovoltaic missions. These methods were then applied to some representation missions that could lead to potentially large photovoltaic markets in the southwestern United States in the 1980-2000 period. It was tentatively concluded that the use of photovoltaic arrays in either on-site residential applications or in central station power plants would be economically competitive when array prices are in the \$100-200/kW$_{pk}$ range (1975 dollars). The analyses were based on rather conservative assumptions and did not consider, for example, a) any relaxation in the current rigid criteria for utility system generation reliability, b) the use of concentrators, c) productive use of the thermal energy removed in cooling the arrays, or d) the employment of incentives.

III. Current Efforts

Current program activity is divided among six separate tasks. During the reporting period the principal emphasis was on Task 1 (Analysis of Near-Term Missions) but significant progress was also made in Task 2 (Analysis of Major Mid-Term Missions) and Task 6 (Societal Costs of Conventional and Photovoltaic Power Production.

During the first three months of the program the focus of the Task 1 effort was on a quick, preliminary survey of near-term applications (applications in which photovoltaic arrays could be economically competitive at array prices greater than about \$2/W$_{pk}$). The objective was the early identification of several promising applications, which were then to be considered as candidates for early demonstration. Four preferred candidates were identified: a) impressed current corrosion protection (ICP) for deep gas wells, b) ICP for oil and gas pipelines, c) railroad grade crossing signals, and d) lighted navigation buoys. It was estimated that these applications represent a combined market of $\sim$ 11000 kW$_{pk}$ through 1980 and $\sim$1600 kW$_{pk}$/yr thereafter.

Upon the conclusion of this interim survey, the main emphasis of effort under this task reverted to the mainline activity, a comprehensive survey of near-term markets. As potential markets have surfaced, the more promising ones have been subjected to a preliminary technical and economic analysis. The result has been the identification of a number of additional applications that appear to represent significant markets. On the basis of these results it is conservatively estimated that the cumulative 1976-1980 non-military market in the United States will amount to ~ 8 MW_{pk} and that the annual market between 1980 and 1985 will average ~15 MW_{pk}/yr. Overseas and military markets can be expected to swell these totals but these markets are not included within the scope of the study.

The initial focus under Task 2 has been on examining the effect on the competitive position of photovoltaic technology of liberalizing some of the more conservative assumptions that were made in the earlier NSF-supported study. One of the first things to be investigated was the effect of relaxing the rather rigid utility system reliability criterion that had been applied. It was found, however, that this change resulted in an increase rather than a decrease in the amount of conventional backup capacity that must be provided when photovoltaic power generation is substituted for conventional generation.

A second area of investigation to be pursued during the reporting period has been the use of very high concentration (X ~ 1000) in central station power plant applications. Although this study is still in progress, some preliminary results have been obtained. Estimates were made of the basic capital cost (per kilowatt of rated plant capacity) of a photovoltaic plant in which a field of heliostats concentrates sunlight on a tower-mounted cylindrical array of GaAlAs/GaAs solar cells. These costs were then compared with those for two other types of solar power plants having essentially the same performance characteristics and were found to be about 50% greater. In this preliminary analysis, however, no consideration was given to possible uses for the large amount of heat removed in cooling the GaAs arrays. Analyses are therefore being made of the quantity and quality of this thermal energy, for a range of system parameters, in order that its impact on the economics can be assessed.

Under Task 6, a comprehensive program to collect data on power production impacts from a wide variety of sources was carried out, and a systematic effort was made to reduce these data to a consistent quantitative basis. During the report period the emphasis was on coal-fired power generation, taking into account all elements of the generation system, from coal mine to power lines. It was found that the dominant non-internalized costs associated with this generation method result from the SO_x emission that occurs even when the latest emission standards are satisfied. The total non-internalized cost is estimated to be between 3 and 6 mills per kWh of electric energy generated.

IV. Summary of Key Results

A summary of the main accomplishments during the report period is presented in the next-to-last chart that is included with this report.

V. Future Plans

During the next six months the emphasis will change substantially. The study of near-term markets (Task 1) will be brought to a conclusion and the focus will shift to Task 2, the investigation of missions in which photovoltaic technology can be expected to find really large markets when array prices are at or below \$500/kW_{pk}. Much of this effort will be concentrated on load-point applications. The final chart lists these planned activities in greater detail.

THE AEROSPACE CORPORATION

Mission Analysis of Photovoltaic Solar Energy Systems

CONTRACTING AGENCY:

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

CONTRACT NUMBER:	E(04-3)-1101, PROJECT AGREEMENT 8
PERIOD OF CONTRACT:	12 MONTHS (1 December 1975 - 15 January 1977)
AMOUNT OF AWARD:	$421,700
PRINCIPAL INVESTIGATOR:	DR. A. B. GREENBERG

Photovoltaic Mission Analysis

OBJECTIVES

OVERALL OBJECTIVE

- TO SUPPORT THE FORMULATION, PLANNING, AND JUSTIFICATION OF THE ERDA NATIONAL PHOTOVOLTAIC PLAN
  - IDENTIFY PROMISING APPLICATIONS, ATTRACTIVE DEMONSTRATIONS, CRITICAL EXTERNAL ISSUES
  - PROVIDE ANALYTICAL SUPPORT TO REFINE THE ERDA TECHNOLOGY IMPLEMENTATION PLAN (program strategy)

TASK BREAKDOWN

TASK 1 ANALYSIS OF NEAR-TERM MISSIONS

- PRELIMINARY IDENTIFICATION/EVALUATION OF ATTRACTIVE DEMONSTRATION CANDIDATES
- SURVEY OF POTENTIAL NEAR-TERM MARKETS
- EVALUATION OF CANDIDATE MISSIONS

TASK 2 ANALYSIS OF MAJOR MID-TERM MISSIONS/MARKETS

- RELATIVE EVALUATION OF MID-TERM (1985 and later) MISSIONS REPRESENTING LARGE POTENTIAL MARKETS
- DETERMINATION OF CONDITIONS FOR DEVELOPMENT OF LARGE PHOTOVOLTAIC MARKETS

TASK 3 REVIEW AND UPDATING OF ERDA TECHNOLOGY DEVELOPMENT PLAN

TASK 4 CRITICAL EXTERNAL ISSUES

TASK 5 THE IMPACT OF INCENTIVES

TASK 6 COMPARISON OF THE TRUE SOCIETAL COSTS OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION

Planned Activities

1 JANUARY THROUGH 30 JUNE 1976

TASK 1: ANALYSIS OF NEAR-TERM MISSIONS

- CONDUCT PRELIMINARY SURVEY, IDENTIFY PREFERRED APPLICATIONS FOR DEMONSTRATION
- IMPLEMENT SURVEY OF POTENTIAL USERS, CONSTRUCT APPLICATION TREE
- CARRY OUT TECHNICAL/ECONOMIC ANALYSES OF MORE PROMISING APPLICATIONS

TASK 2: ANALYSIS OF MAJOR MID-TERM MISSIONS

- DETERMINE EFFECT OF RELAXED UTILITY-SYSTEM RELIABILITY CRITERION ON PHOTOVOLTAIC ECONOMICS
- INVESTIGATE USE OF HIGH CONCENTRATION IN CENTRAL STATION MISSIONS
- BEGIN ANALYSIS OF PRODUCTIVE USES FOR REJECT THERMAL ENERGY IN SUCH MISSIONS

TASK 3: REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN

- REVIEW VOLUME/PRICE SCENARIOS IN LIGHT OF INTERIM RESULTS OF TASK 1

TASK 4: CRITICAL EXTERNAL ISSUES

- BEGIN EXAMINATION OF SELECTED GROUP OF EXTERNAL ISSUES IDENTIFIED IN TASKS 1 AND 2

TASK 6: SOCIETAL COSTS OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION

- CONTINUE DATA COLLECTION - LITERATURE SEARCH, INTERVIEWS
- EVALUATE TOTAL NON-INTERNALIZED COSTS TO SOCIETY OF COAL-FIRED POWER GENERATION

Preliminary Survey of Near-Term Applications

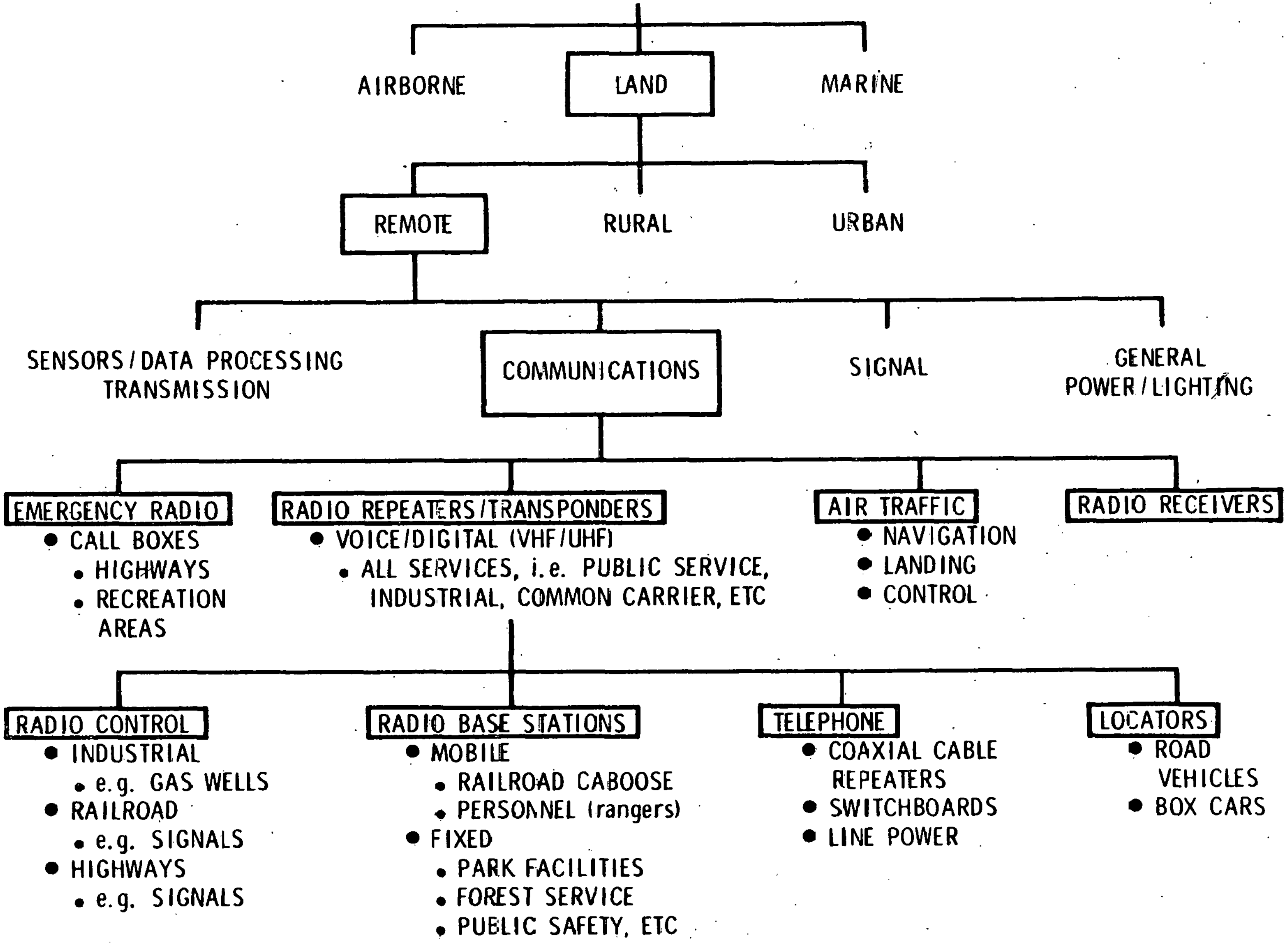
TOP RANKING APPLICATIONS

- SIGNALS AND CONTROLS
  - RAILROAD CROSSINGS
  - HIGHWAYS
  - OIL/GAS WELLS
  - PIPELINES
  - BUOYS
- SECURITY
  - PERIMETER CONTROL
  - PHOTOVOLTAIC EQUIPMENT SELF-PROTECTION
- IMPRESSED CURRENT CORROSION PROTECTION
  - NATURAL GAS WELLS
  - OIL/GAS PIPELINES
  - OFFSHORE PUMPING PLATFORMS
  - BUOYS
- COMMUNICATIONS
  - MICROWAVE REPEATERS
  - TELEMETRY
    - OIL/GAS WELL, PIPELINE MONITORS
    - REMOTE ENVIRONMENTAL INSTRUMENTATION
    - BUOY INSTRUMENTATION

ESTIMATED POTENTIAL MARKETS FOR PREFERRED CANDIDATES

APPLICATION	BASE	ESTIMATED MARKET TO 1980 (kW_{pk})	SUBSEQUENT (kW_{pk}/yr)	BREAKEVEN ARRAY PRICE $(\$/W_{pk})$
IMPRESSED CURRENT CORROSION PROTECTION				
DEEP GAS WELLS	7400 WELLS	5600	1100	3.5 - 7.5
OIL/GAS PIPELINES	23500 mi	4400	130	2 - 5
RAILROAD GRADE CROSSINGS	2200 CROSSINGS	920	420	7 - 14
LIGHTED NAVIGATION AIDS	1000 BUOYS	30	?	50

Element of Photovoltaic Applications Tree



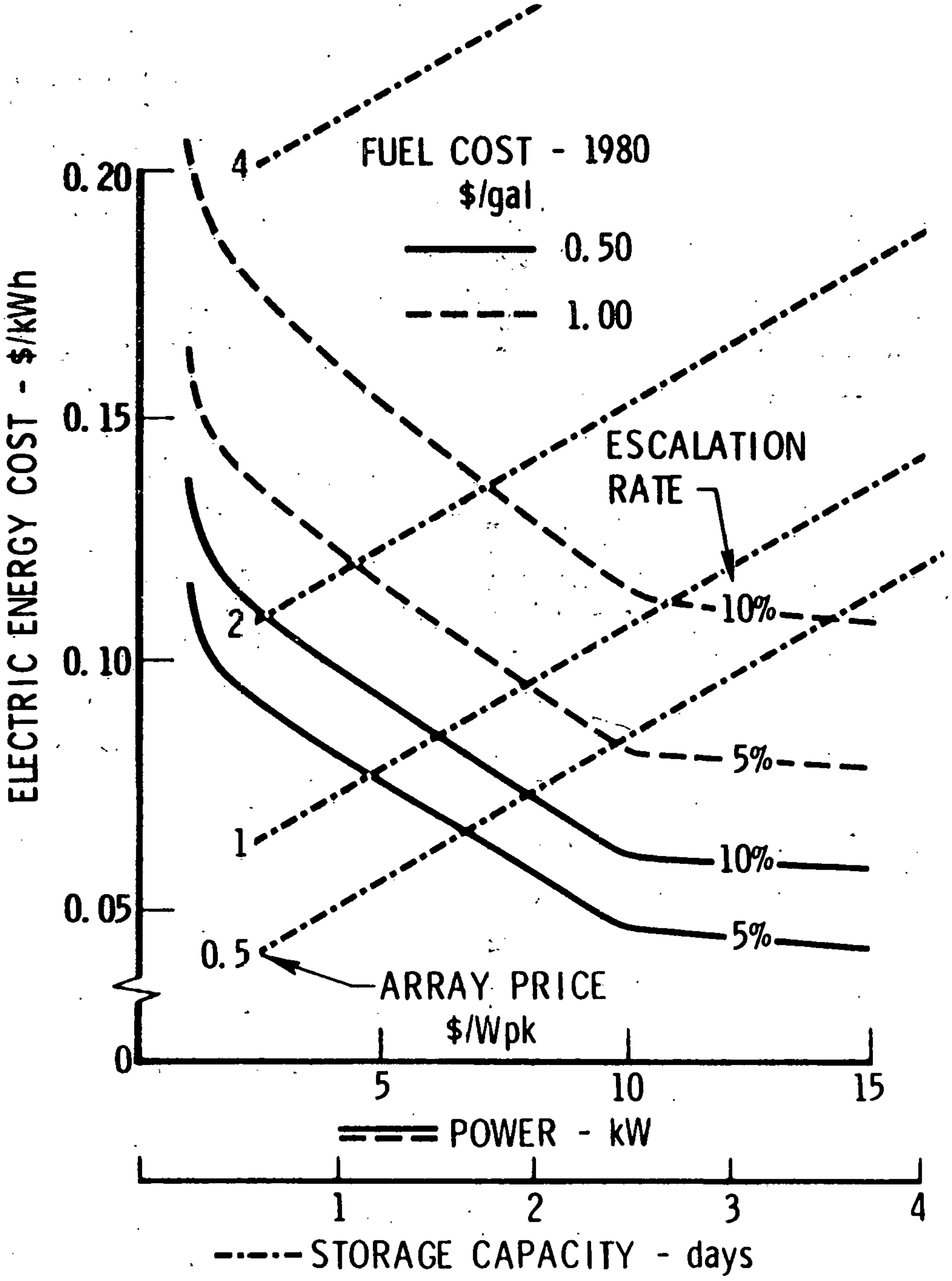
- AIRBORNE
- LAND
  - REMOTE
    - SENSORS / DATA PROCESSING TRANSMISSION
    - COMMUNICATIONS
      - EMERGENCY RADIO
        - CALL BOXES
          - HIGHWAYS
          - RECREATION AREAS
      - RADIO REPEATERS / TRANSPONDERS
        - VOICE/DIGITAL (VHF/UHF)
          - ALL SERVICES, i.e. PUBLIC SERVICE, INDUSTRIAL, COMMON CARRIER, ETC
        - RADIO CONTROL
          - INDUSTRIAL
            - e.g. GAS WELLS
          - RAILROAD
            - e.g. SIGNALS
          - HIGHWAYS
            - e.g. SIGNALS
        - RADIO BASE STATIONS
          - MOBILE
            - RAILROAD CABOOSE
            - PERSONNEL (rangers)
          - FIXED
            - PARK FACILITIES
            - FOREST SERVICE
            - PUBLIC SAFETY, ETC
        - TELEPHONE
          - COAXIAL CABLE REPEATERS
          - SWITCHBOARDS
          - LINE POWER
        - LOCATORS
          - ROAD VEHICLES
          - BOX CARS
      - AIR TRAFFIC
        - NAVIGATION
        - LANDING
        - CONTROL
      - RADIO RECEIVERS
    - SIGNAL
    - GENERAL POWER / LIGHTING
  - RURAL
  - URBAN
- MARINE

1980 Electric Energy Costs

═══ DIESEL GENERATORS

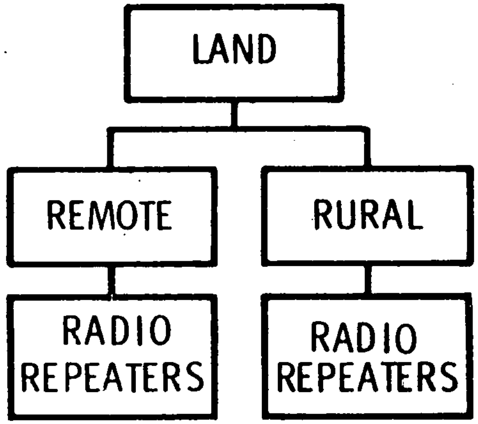
-·-·- PHOTOVOLTAIC ARRAYS

[Present value cost of 15 yr of service divided by total amount of energy produced: general inflation rate = 5% discount rate = 9%]



Potentially Large Photovoltaic Markets

MICROWAVE REPEATERS



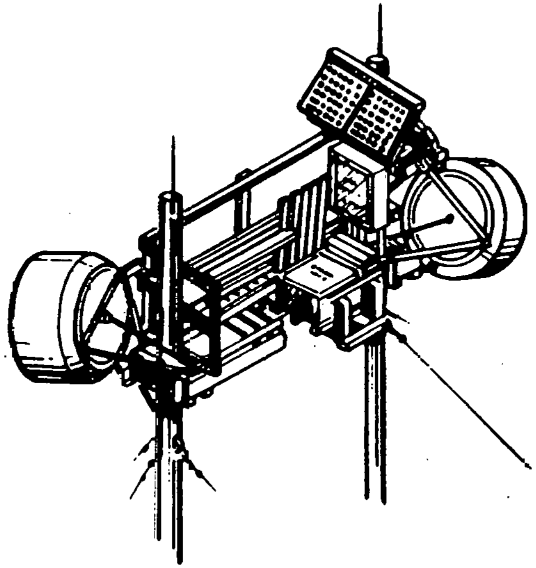
LAND

REMOTE

RURAL

RADIO REPEATERS

RADIO REPEATERS



VHF AND
MICROWAVE

⇩

MICROWAVE ONLY
PRIVATE SERVICES ONLY

1. VOICE
2. DIGITAL

PRELIMINARY ESTIMATES

EQUIVALENT CONTINUOUS POWER*, W	350	
ARRAY SIZE, PEAK W	2400	
SIZE OF MARKET**	CUM-1980	ANNUAL
UNITS	180	500
kW_{pk}	500	1000
BREAK-EVEN ARRAY PRICE vs DIESEL: $1.0/$W_{pk}$, vs UTILITY: $5.6/$W_{pk}$		
DATE OF REALIZATION	1979	

*Typical for Private Line Service

**Excludes Common Carrier and Government Service

Potentially Large Photovoltaic Markets

PRELIMINARY ESTIMATES - DOMESTIC CIVILIAN MARKETS

APPLICATION	AVERAGE POWER, Watts*	BREAKEVEN COST $/Peak Watt	CUMULATIVE MARKET - 1980, kW$_{pK}$	ANNUAL MARKET AFTER 1980, kW$_{pK}$	TARGET YEAR FOR INITIAL USE
HIGHWAY CALL BOXES (radio)	0.5	200.0 (Batteries)	100	50	NOW
ENVIRONMENTAL SENSORS	0.5	200.0 (Batteries)	12	6	NOW
HIGHWAY SIGNALS FLASHING HAZARD, etc.	10	216.0 (Utility)	(1680 to 16,800)		1978**
HIGHWAY BRIDGE DECKING CORROSION PREVENTION	20	100.0 (Utility) 70.0 (Battery)	30	100	1978**
RAILROAD GRADE CROSSING SIGNALS/GATES	55	14.0 (Utility)	600	400	1977
GAS WELL CORROSION PROTECTION	50	7.0 (Utility)	2000	1000	NOW FOR SHALLOW WELLS 1978 FOR DEEP WELLS
PIPELINE CORROSION PROTECTION	300	5.0 (Utility)	50	150	1979
RADIO REPEATERS	350	5.6 (Utility) 1.0 (Diesel)	500	1000	1979
OTHERS	--	--	--	--	
TOTALS PROBABLY IN RANGE OF			8 MW$_{pK}$	15 MW$_{pK}$	

Load

** Dependent on Customer Acceptance Factors

Analysis of Major Mid-Term Missions

- BACKGROUND
  - EARLIER AEROSPACE CORPORATION STUDY SHOWED
    - CENTRAL STATION POWER AND ON-SITE RESIDENTIAL MISSIONS EQUALLY ATTRACTIVE IN SOUTHWEST
    - PHOTOVOLTAIC TECHNOLOGY COMPETITIVE FOR ARRAY PRICES OF \$100-200/kW_{pk}
  - RESULTS WERE BASED ON CONSERVATIVE ASSUMPTIONS, DID NOT CONSIDER
    - USE OF CONCENTRATORS
    - PRODUCTIVE USE OF REJECT THERMAL ENERGY
    - RELAXATION OF RIGID UTILITY SYSTEM RELIABILITY STANDARDS
    - INTRODUCTION OF INCENTIVES

- PLANNED EXTENSIONS OF EARLIER WORK
  - INVESTIGATE EFFECT OF RELAXATION OF RELIABILITY STANDARDS
  - ANALYZE CONCENTRATOR TRADE-OFFS (Esp for Central Station Applications)
  - BEGIN STUDY OF PRODUCTIVE USES FOR THERMAL ENERGY
  - EXTEND ANALYSIS TO OTHER ON-SITE APPLICATIONS
    - COMMERCIAL, INDUSTRIAL, MULTIFAMILY RESIDENTIAL, COMMUNITY
  - INVESTIGATE EFFECT OF GEOGRAPHIC LOCATION
  - EXTEND INVESTIGATION OF UTILITY INTERFACE TRADE-OFFS
    - STAND-ALONE vs GRID BACKUP
    - OPTIMUM ROLE OF STORAGE

Effect of Relaxation of Generation Reliability Criterion

ARRAY AREA ($10^6 m^2$)	STORAGE CAPACITY (10^6 kWh)	BACKUP CAPACITY REQUIRED FOR 100 MW PHOTOVOLTAIC PLANT			
		CENTRAL ARIZONA UTILITY		SOUTHERN CALIFORNIA UTILITY	
		MAXIMUM LOSS OF LOAD		MAXIMUM LOSS OF LOAD	
		2.4 hr/yr	24 hr/yr	2.4 hr/yr	24 hr/yr
	CENTRAL STATION POWER PLANTS				
2	0	27.2 MW	36.8 MW	48 MW	61 MW
	0.5	14.3	22.5	20	30
	1.0	14.3	22.5		
3	0			47	60
	0.5			3	5.5
	RESIDENTIAL ON-SITE SYSTEMS				
2	0	150	158	80	88
	1.0	140	154	60	66
4	0	95	104	48	59
	1.0	59	67	13	18
6	0	72	83	36	48
	1.0	24	32	9	12

Capital Cost Comparison

100 MW SOLAR POWER PLANTS - INTERMEDIATE LOAD

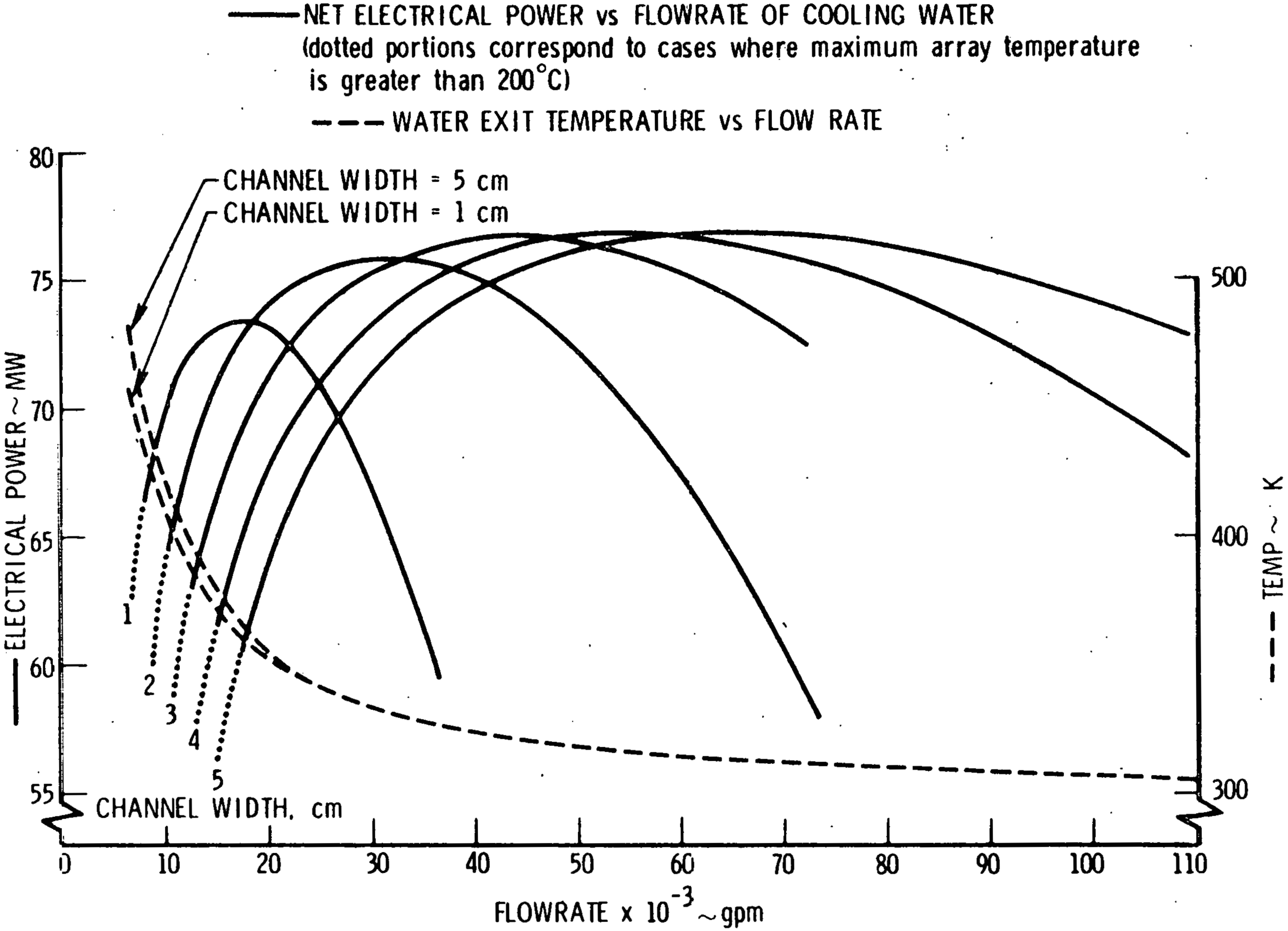
	SOLAR THERMAL CENTRAL RECEIVER	PHOTOVOLTAIC		
		FLAT PLATE	CENTRAL RECEIVER	
CELL MATERIAL	--	Si	Al GaAs / GaAs	Al GaAs / GaAs
COLLECTOR AREA (m^2)	$1(10^6)$	$2(10^6)$	$1.75(10^6)$	$1.75(10^6)$
CONCENTRATION RATIO	600	1	1000	2250
ARRAY AREA (m^2)	--	$2(10^6)$	$1.75(10^3)$	$0.78(10^3)$
STORAGE CAPACITY (hr)	6	6	6	6
	CAPITAL COSTS	- $\$/kW_{rated}$		
LAND, STRUCTURES, FACILITIES POWER CONDITIONING, MISC	92	100	100	100
COLLECTORS, SUPPORT STRUCTURE	620	500	1085	1085
RECEIVER, TOWER, HEAT EXCHANGER	121	--	15	15
PHOTOVOLTAIC ARRAYS	--	225(1125)	350	156
STORAGE	121	120	120	120
TURBINE, GENERATOR, COOLING TOWER	102	--	20	20
TOTAL BASIC COST	1056	945(1845)	1690	1496

ASSUMPTIONS:

SILICON ARRAY PRICE: $\$100/kW_{pk}$ ($\$500/kW_{pk}$)

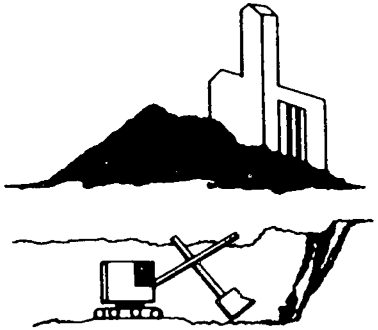
GaAs ARRAY PRICE: $\$20,000/m^2$

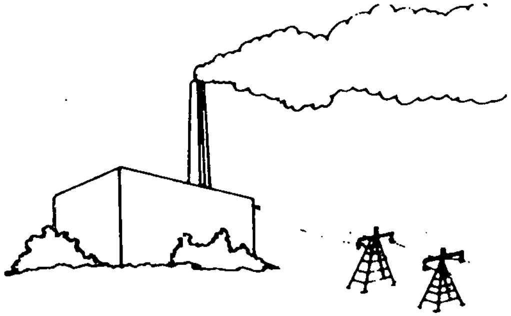
Photovoltaic Central Receiver Power Plant



Societal Costs of Electric Power Production

COAL-FIRED GENERATION





FUEL PRODUCTION		FUEL TRANSPORTATION		POWER GENERATION	
DAMAGE SOURCE	SOCIETAL DAMAGE TO:	DAMAGE SOURCE	SOCIETAL DAMAGE TO:	DAMAGE SOURCE	SOCIETAL DAMAGE TO:
COAL DUST MINE WASTES COAL DEBRIS LAND DISTURBANCE UNDERGROUND DISTURBANCE EXPOSURE TO POTENTIAL ACCIDENTS	PROPERTY VALUES ROAD AND HIGHWAYS AGRICULTURE: ENVIRONMENT ANIMAL LIFE HUMAN LIFE HEALTH OF MINERS MINE-SITE COMMUNITIES LAND (subsidence) WATER SYSTEMS	ACCIDENT OVERLOADING OF ROAD BEDS	PEOPLE: INJURIES AND DEATHS INCREASED ROADBED MAINTENANCE PROPERTY DAMAGE	EMISSION OF: SO_x (sulfates) NO_x PARTICULATES METALLIC TRACE ELEMENTS CO POLYCYCLIC HC	PHYSICAL HEALTH MATERIALS AESTHETICS MENTAL HEALTH CLIMATE DOMESTIC ANIMALS WILDLIFE, VEGETATION

Expected Societal Costs for Coal-Fired Power Plants

NATIONAL AVERAGE, URBAN PLANT, AND RURAL PLANT

POWER GENERATION FUEL CYCLE ELEMENT	SOCIETAL COSTS (mills/kWh)		
	NATIONAL AVERAGE	TYPICAL RURAL PLANT	TYPICAL URBAN PLANT
POWER GENERATION			
SO_X	2.56	1.21	3.17
NO_X	0.36	0.17	0.45
PARTICULATES	0.18	0.09	0.22
SUBTOTAL	3.10	1.47	3.84
FUEL TRANSPORTATION	0.13	0.13	0.13
FUEL PRODUCTION	~1.5	~1.5	~1.5
TOTAL COSTS	4.73	3.10	5.47

- SOCIETAL DAMAGES ARE UNEVENLY DIVIDED. ESPECIALLY AFFECTED ARE:
  - PERSONNEL AND FAMILIES WORKING IN THE POWER PLANT FUEL CYCLE
  - FAMILIES WHO CHOOSE OR ARE OBLIGED TO LIVE IN THE POLLUTION AREA
  - CHILDREN, AND THE ELDERLY AND PHYSICALLY WEAK WHO DO NOT HAVE STRONG RESISTANCE AGAINST DISEASE
- BEFORE COMPLIANCE WITH THE FEDERAL COAL HEALTH AND SAFETY ACT AND NEW SOURCE PERFORMANCE STANDARDS OF CLEAN AIR ACT, SOCIETAL COSTS WERE 2 TO 3 TIMES THE PRESENT AND EXPECTED FUTURE COSTS

Summary of Accomplishments

1 JANUARY 1976 THROUGH 30 JUNE 1976

TASK 1: ANALYSIS OF NEAR-TERM MISSIONS

- PREFERRED APPLICATIONS FOR DEMONSTRATION IDENTIFIED IN PRELIMINARY SURVEY
- SURVEY OF POTENTIAL USERS IMPLEMENTED, APPLICATIONS TREE CONSTRUCTED
- PRELIMINARY EVALUATION OF MANY APPLICATIONS COMPLETED

TASK 2: ANALYSIS OF MAJOR MID-TERM MISSIONS

- RELAXATION OF UTILITY-SYSTEM RELIABILITY CRITERION SHOWN NOT TO IMPROVE PHOTOVOLTAIC COMPETITIVE POSITION
- STUDY OF USE OF HIGH CONCENTRATION IN CENTRAL STATION MISSIONS UNDER WAY
- EFFECT OF INSOLATION SPECTRAL VARIATIONS ON GaAs CELLS SHOWN TO BE UNIMPORTANT

TASK 3: REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN

- VOLUME/PRICE SCENARIOS UNDER REVIEW IN THE LIGHT OF INTERIM RESULTS OF TASK 1

TASK 4: CRITICAL EXTERNAL ISSUES

- EXTERNAL ISSUES TO BE INVESTIGATED TENTATIVELY IDENTIFIED
- STUDY OF BARRIERS TO FEEDBACK OF EXCESS ON-SITE PHOTOVOLTAIC POWER TO GRID INITIATED

TASK 6: SOCIETAL COSTS OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION

- STUDY OF SOCIETAL COSTS OF COAL-FIRED POWER PRODUCTION NEARLY COMPLETED

Planned Activities

1 JULY 1976 TO 31 DECEMBER 1976

TASK 1: ANALYSIS OF NEAR-TERM MISSIONS
- CONCLUDE SURVEY OF POTENTIAL USERS
- MONITOR AND EVALUATE PLANNED ERDA PHOTOVOLTAIC MARKET STUDIES

TASK 2: ANALYSIS OF MAJOR MID-TERM MISSIONS
- ANALYZE CENTRAL STATION MISSIONS, DETERMINE COST OF PHOTOVOLTAIC POWER AS A FUNCTION OF ARRAY COST AND EFFICIENCY, WITH/WITHOUT CONCENTRATION
  - DETERMINE EFFECT OF CONCENTRATOR TYPE, DEGREE OF CONCENTRATION
  - ASSESS PROPER ROLE OF STORAGE
  - ASSESS POSSIBLE USE OF REJECT THERMAL ENERGY
- IDENTIFY AND CHARACTERIZE POTENTIAL APPLICATIONS FOR PHOTOVOLTAIC TOTAL ENERGY SYSTEMS
  - CHARACTERIZE POSSIBLE ELECTRICAL AND THERMAL OUTPUTS
  - IDENTIFY POTENTIAL APPLICATIONS AND CHARACTERIZE ELECTRICAL/THERMAL LOADS
  - MAKE PRELIMINARY IDENTIFICATION OF MOST PROMISING APPLICATIONS
- CARRY OUT SURVEY AND ANALYSIS OF LOAD-POINT APPLICATIONS REPRESENTING MAJOR MARKETS
  - IDENTIFY CANDIDATE APPLICATIONS FOR LOAD-POINT PHOTOVOLTAIC ELECTRICITY
  - DETERMINE COLLECTOR/ARRAY COST AND EFFICIENCY RANGES FOR ECONOMIC VIABILITY
    - STAND-ALONE vs UTILITY BACKUP
- INVESTIGATE PROJECTED COST OF ELECTRIC AND THERMAL ENERGY FROM COMPETING SOURCES

TASK 3: REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN
- ESTIMATE TOTAL NEAR-TERM, MID-TERM MARKETS

TASK 4: CRITICAL EXTERNAL ISSUES
- STUDY FEASIBILITY OF FEEDBACK OF POWER FROM ON-SITE PHOTOVOLTAIC SYSTEMS TO GRID
- INVESTIGATE ENVIRONMENTAL EFFECTS OF ARRAY PRODUCTION

TASK 5: IMPACT OF INCENTIVES
- INVESTIGATE IMPACT OF VARIOUS TYPES OF INCENTIVES ON PHOTOVOLTAIC ECONOMICS

TASK 6: SOCIETAL COSTS OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION
- CONCLUDE ASSESSMENT OF SOCIETAL COSTS OF COAL-FIRED GENERATION; DEFER STUDY OF NUCLEAR GENERATION

INTEGRATION OF SOLAR GENERATION INTO ELECTRIC UTILITY SYSTEMS

ERDA CONTRACT NO. E(04-3) - 1117

PERIOD OF CONTRACT: June 15, 1975 - June 15, 1976

VALUE: $80,000

PRESENTED BY: GERALD W. BRAUN
SENIOR RESEARCH ENGINEER
SOUTHERN CALIFORNIA EDISON COMPANY
2244 WALNUT GROVE AVENUE
ROSEMEAD, CALIFORNIA

PRINCIPAL INVESTIGATOR: DR. IRA THIERER

STUDY TEAM: JOHN W. BALLANCE, D. P. STEINBERG
R. L. SHEDDEN, M. J. ZIOL, J. W. GRISWOLD,
D. A. SCHUIL

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC
PROGRAM REVIEW MEETING

AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE

ABSTRACT

The operation of solar power plants as a part of a large electric utility has been studied using Southern California Edison Company loss of load probability and production cost simulation computer programs. A solar generation model has been developed which includes effects of hourly solar input variation, cloud induced forced outages, use of energy storage, and peak shaving dispatch. The contribution of solar generation to the system's ability to serve forecast loads has been determined for varying amounts of installed solar capacity and for varying energy storage capabilities associated with the solar units. The effect of solar on the optimum mix of conventional resources has also been studied.

It was found that stored solar energy can be used to effect a peak shaving dispatch strategy. Used in this way, the effect of thermal energy storage is significant and greatly enhances the economic value of the solar units. Storage also accommodates the output of additional collection capability which adds to the units economic value by increasing the annual energy production. In an electric system containing relatively little solar generation, small amounts of storage, allowing one or two extra hours of operation, will allow a solar unit to achieve most of the potential economic value. As the solar percentage is increased, system reserve margin requirements are also increased. This can be partially offset by increasing the amount of storage. The current dollar economic value of solar units ranged from a maximum of nearly $700/kw to as low as $250/kw.

The addition of solar generation would be accompanied by adjustments in the mix of non-solar resources to both optimize economics and maintain acceptable levels of service reliability. Despite its usefulness solar generation will not directly replace any single resource type. In

present electric systems, solar would primarily displace intermediate generation. As the system resource mix approaches optimum levels, increased amounts of solar would begin to displace small amounts of base load generation. However, additional peaking capacity would be required to maintain acceptable levels of system reliability as the level of solar generation is increased. The amount of peaking required for this purpose can be significantly reduced by adding thermal energy storage to the solar units.

Proper dispatch and maintenance strategies can allow significant percentages of solar units to be integrated into the system. Electric system operating practices will have to be modified to reflect the unique characteristics of solar generation, and to accomplish successful integration of their operation with the remainder of the system.

ERDA/SCE SOLAR INTEGRATION STUDY

NEED FOR ANALYSIS BY UTILITY

HOW IS ELECTRIC SYSTEM AFFECTED?

IMPLICATIONS FOR DESIGN AND OPERATION?

VARIABLES:

- SOLAR PENETRATION (0-20%)
- STORAGE CAPABILITY (0-6 MWh/MW)
- DISPATCH STRATEGY

STRATEGY

DEVELOP RESOURCE PLANS WITH AND WITHOUT SOLAR

- SERVING SAME LOAD WITH THE SAME RELIABILITY
- HAVING OPTIMUM NON-SOLAR RESOURCE MIX

DETERMINE INCREMENTAL EFFECT OF SOLAR

- REDUCTION IN REQUIRED AMOUNT OF NON-SOLAR GENERATION (FOR SAME RELIABILITY)
- PRODUCTION COST (SERVING SAME LOAD)

VALUE OF SOLAR IS THE DIFFERENCE BETWEEN TOTAL COST OF ELECTRICITY GENERATION BY NON-SOLAR RESOURCES IN BASE CASE VS IN CASES OPTIMIZED AROUND SOLAR

ASSUMPTIONS

100 MW SOLAR THERMAL CENTRAL STATION

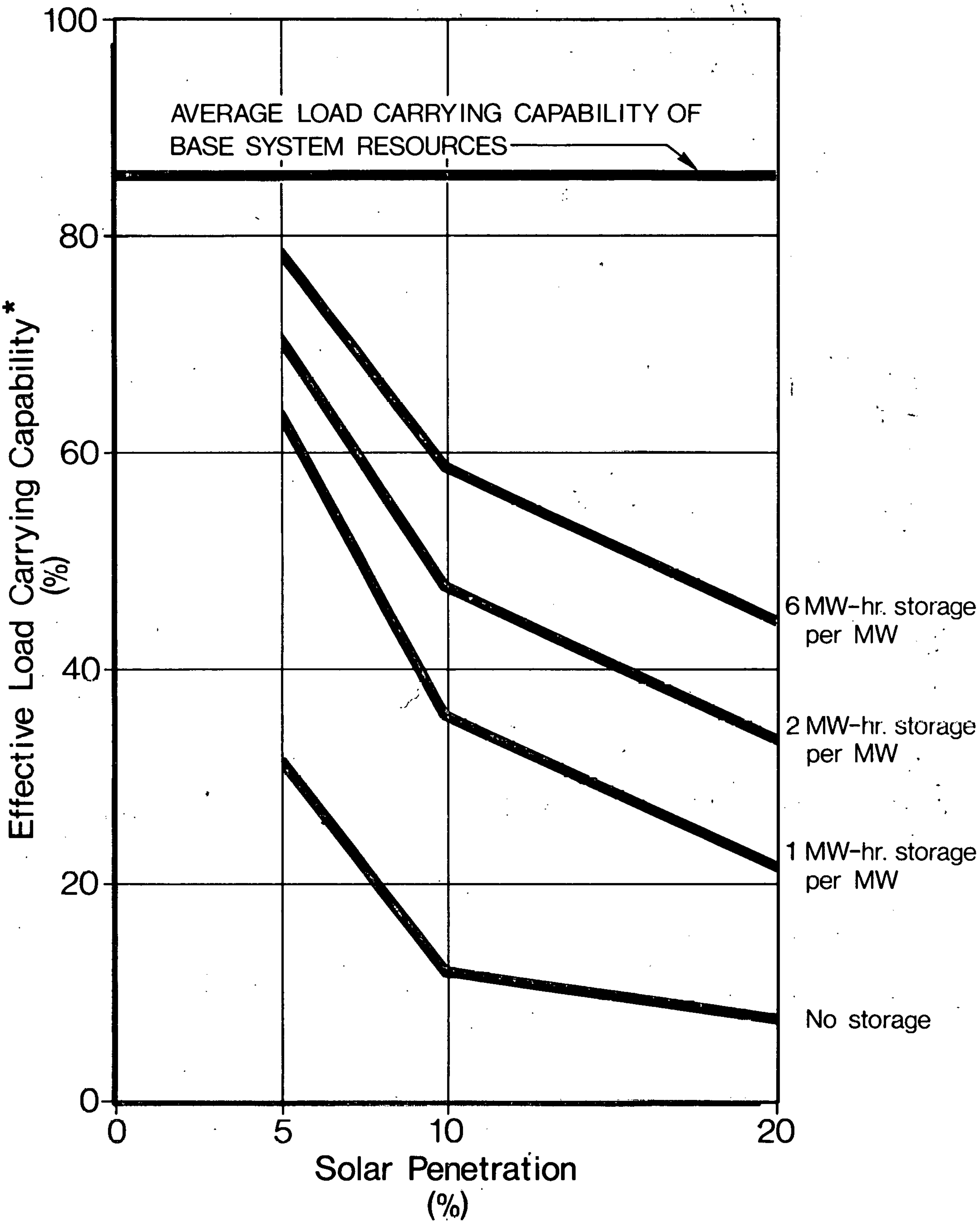
70 MW FROM THERMAL-ENERGY STORAGE

OUTAGE AT DAILY INPUT LESS THAN 50%
OF POSSIBLE

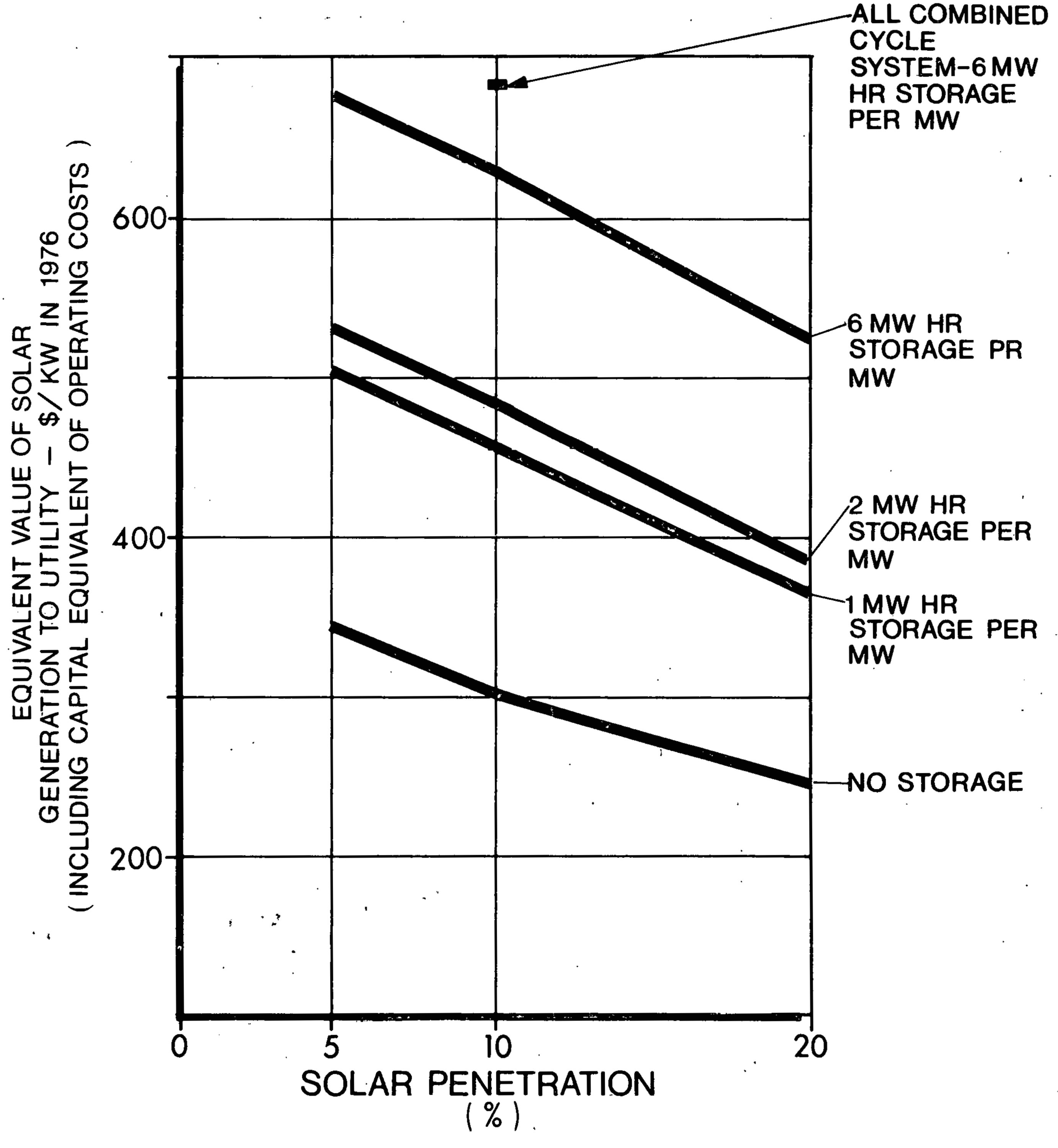
SCE LOAD PATTERN AND 1986 PEAK DEMAND
FORECAST

ALL RESOURCES CONSTRUCTED IN 1986

EFFECTIVE LOAD CARRYING CAPABILITY OF* SOLAR GENERATION vs. SOLAR PENETRATIO

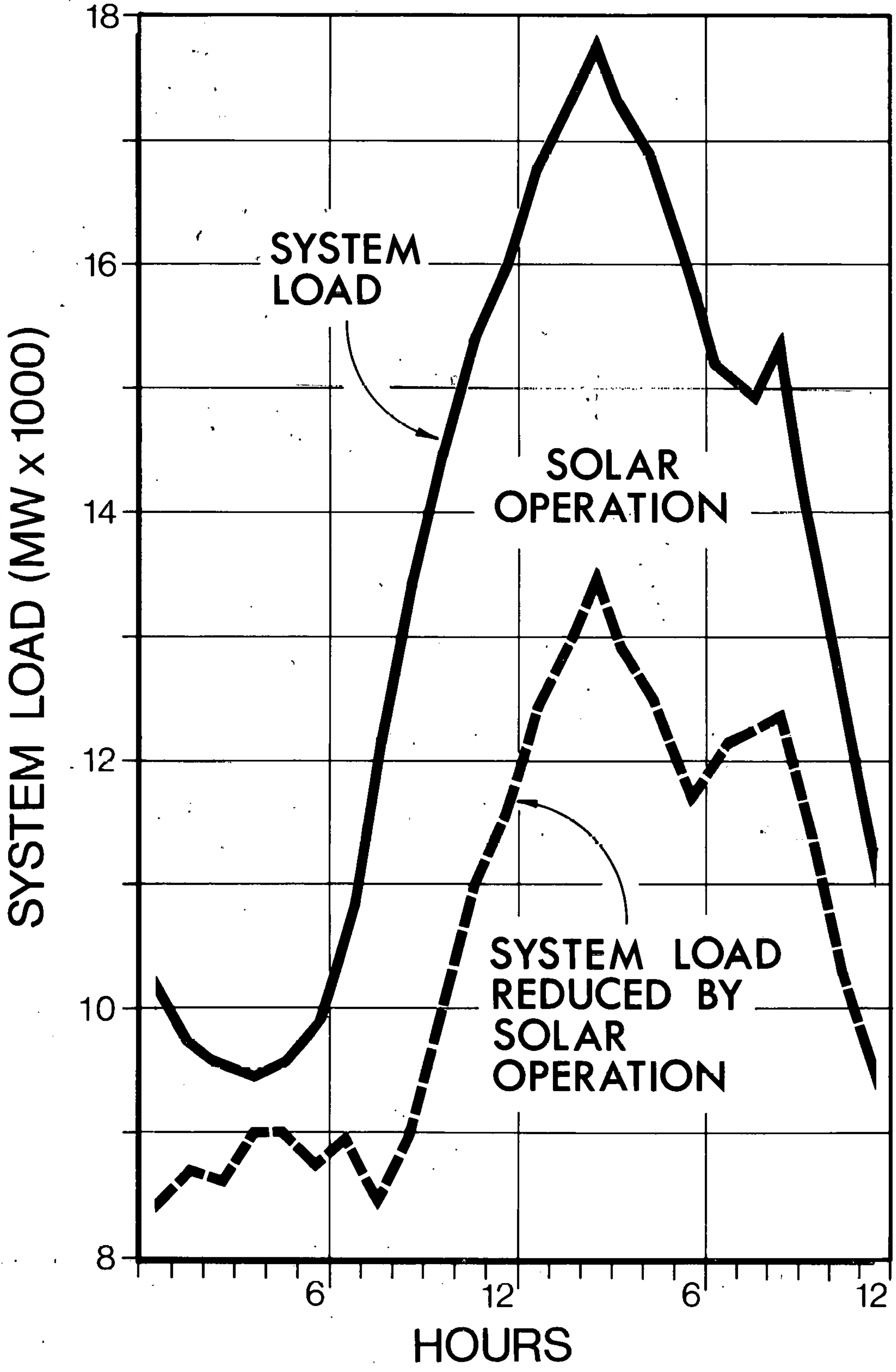


EQUIVALENT VALUE OF SOLAR GENERATION TO UTILITY



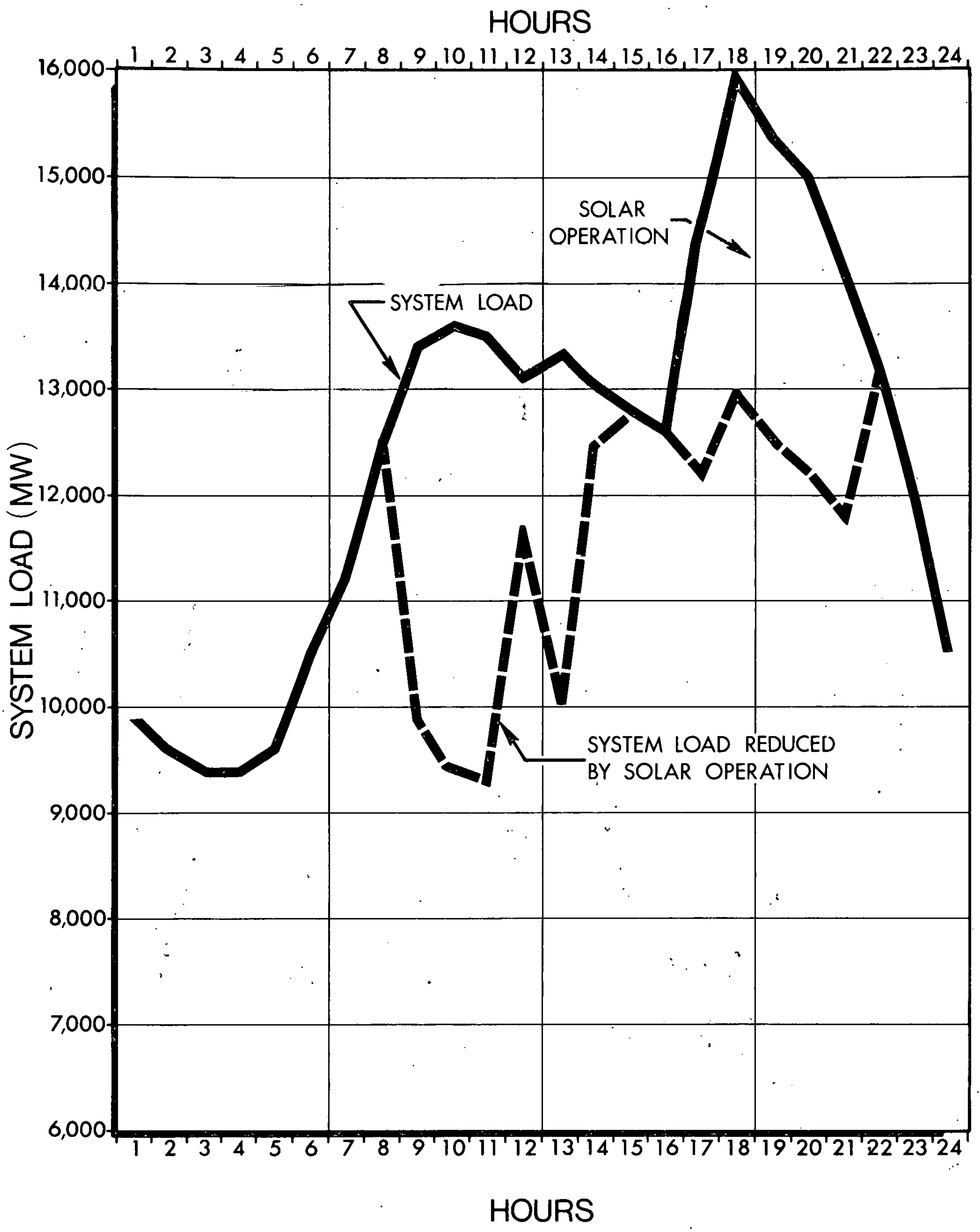
SOLAR UNIT OPERATION AUGUST PEAK DAY

20% SOLAR PENETRATION,
6 MW-HRS OF STORAGE PER MW CAPACITY,
1.71 MW OF COLLECTOR PER MW CAPACITY



SOLAR UNIT OPERATION–DECEMBER PEAK DAY

20% SOLAR PENETRATION, 6 MW-HRS OF STORAGE PER MW CAPACITY, 1.71 MW OF COLLECTOR PER MW CAPACITY



INTEGRATION STUDY OVERALL CONCLUSIONS

RELIABILITY - WITHOUT STORAGE SOLAR LCC VANISHES AT HIGH SOLAR % : SIGNIFICANT LCC AT LOW % WITH LITTLE OR NO STORAGE

VALUE - ENERGY STORAGE SIGNIFICANTLY ENHANCES ECONOMIC VALUE. SMALL AMOUNTS OF STORAGE INCREASE ALLOWABLE COLLECTOR COST BY AS MUCH AS 50%

OVERALL CONCLUSIONS

COST -	MIRRORS ARE KEY COST PROBLEM
OPERATION -	SOPHISTICATION REQUIRED AT HIGH % SOLAR. LIMITS ON SOLAR % ARE ECONOMIC NOT TECHNICAL
IMPACT -	COLLECTOR AFFECTS REQUIREMENTS FOR BASE AND INTERMEDIATE STORAGE AFFECTS REQUIREMENTS FOR PEAKING CAPACITY

SYSTEMS ENGINEERING AND ANALYSIS TASK PHOTOVOLTAICS SYSTEMS DEFINITION PROJECT OF THE ERDA NATIONAL SOLAR PHOTOVOLTAIC PROGRAM

By

Billy W. Marshall
Task Leader
Sandia Laboratories
Albuquerque, NM 87115

Donald G. Schueler
Project Manager

Presented at the
National Solar Photovoltaic Program Review Meeting
August 3 - 6, 1976
University of Maine at Orono
Orono, Maine 04473

SYSTEMS ENGINEERING AND ANALYSIS TASK
OF THE
ERDA PHOTOVOLTAICS SYSTEMS DEFINITION PROJECT

By

Billy W. Marshall
Sandia Laboratories
Albuquerque, NM 87115

Responsibility for the Systems Definition Project of the ERDA National Solar Photovoltaic Program was assigned to Sandia Laboratories in November 1975. The Project is divided into two tasks; the Tracking and Concentrator Subsystems Development Task and the Systems Engineering and Analysis Task. Only the latter task will be described herein, the former task is the subject of a separate presentation by D. G. Schueler. Specific objectives of the task are: 1) identify and critically evaluate alternative photovoltaic systems and applications; 2) identify subsystem requirements including array configurations, power conditioning, and storage subsystems; and 3) validate systems analysis results and baseline designs by subsystem interface and integration experiments. These objectives are specifically intended to aid the Test and Demonstration Project by system definition and analysis of demonstration projects and the Low-Cost Silicon Solar Array Project by development of array design and performance requirements. To accomplish these objectives, technical work is being performed by contract with industry and universities with support work performed at Sandia.

Previous work has been directed primarily toward three efforts: 1) the conceptual design and analysis contracts with General Electric, Spectrolab Inc., and Westinghouse; 2) development of a broad base of solar data for the entire US using existing weather data; and 3) definition of a power conditioning development program. The technical tasks required in the conceptual design studies have been completed and final reports are presently being prepared and reviewed. The results of these studies will be summarized by each contractor at a later session of this conference and distribution of the final reports is expected by October 1976. Solar data tables are presently being prepared for various collector types and orientation and selected results are included in the visual aid material.

The three conceptual design study contracts were extended through the end of September 1976, with each contractor to consider separate tasks. Amoung these tasks are utility/user-owner interface considerations for on-site systems, penetration analysis for intermediate size systems, utility reliability assessment for systems including photovoltaic plants, design and analysis of a stand-alone residential photovoltaic system, and a more detail look at intermediate size systems with a view toward defining experiments. Amoung the efforts currently underway at Sandia are a comparison of the three conceptual design studies, development of the direct normal solar data for 26 US locations using ERDA/NOAA rehabilitated weather data, array cost-efficiency tradeoff studies, comparisons of array cost and efficiencies for combined versus photovoltaic alone arrays, development of application analysis and system optimization analysis, and assessment of present and projected power conditioning equipment availability.

Many of these activities will be continued through the next six months and other tasks will be added. Included in the results to be available in the next period is a preliminary application ordering and system optimization, subsystem design information based on the comparative studies of the three conceptual designs, results from the conceptual design extensions, and analyses of specific designs for photovoltaic experiments and demonstrations.

ERDA

SYSTEMS DEFINITION PROJECT
SANDIA LABORATORIES
D. G. SCHUELER, PROJECT MANAGER

SYSTEMS ENGINEERING AND ANALYSIS TASK
B. W. MARSHALL, TASK LEADER

NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW
ORONO, MAINE
AUGUST 3-6, 1976

SYSTEMS ENGINEERING AND ANALYSIS TASK

OBJECTIVES

- IDENTIFY AND CRITICALLY EVALUATE ALTERNATIVE PHOTOVOLTAIC SYSTEMS AND APPLICATIONS
- IDENTIFY SUBSYSTEM REQUIREMENTS INCLUDING ARRAY CONFIGURATIONS, POWER CONDITIONING, AND STORAGE SUBSYSTEMS
- VALIDATE SYSTEMS ANALYSIS RESULTS AND BASELINE DESIGNS BY SUBSYSTEM INTERFACE AND INTEGRATION EXPERIMENTS

SYSTEMS ENGINEERING AND ANALYSIS TASK

- CONCEPTUAL DESIGN STUDIES
  - Existing Studies
  - Extensions
- SOLAR DATA
  - Solar Insolation Maps
  - Data Tapes
- POWER CONDITIONING
- IN-HOUSE ACTIVITIES
  - Conceptual Design Comparisons
  - Application Analysis and System Optimization
  - System Simulation
  - Cell Efficiency - Array Cost Studies
  - PV Only vs Combined System Comparisons

CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS

SYSTEMS TO BE ANALYZED

1. ON-SITE RESIDENTIAL

   1 - 10 kWe PEAK DEMAND

   30 - 100 kWh DAILY DEMAND

2. CENTRAL STATION POWER PLANT

   50 - 1000 MWe DEMAND

3. INTERMEDIATE RANGE SYSTEM

   100 KWe - 10 MWe DEMAND

TASKS OF CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS

1. PREPARE CONCEPTUAL DESIGNS
2. DEVELOP ANALYTICAL PROCEDURES TO IDENTIFY AND EVALUATE PARAMETER SENSITIVITIES
3. DEVELOP AND UTILIZE COST MODEL
4. IDENTIFY MAJOR ECONOMIC AND TECHNICAL UNCERTAINTIES
5. ESTIMATE SYSTEM CAPITAL, OPERATING AND MAINTENANCE COSTS
6. ASSESS IMPACT OF SYSTEM LOCATION
7. IDENTIFY AND PERFORM ASSESSMENT OF FINANCIAL, ENVIRONMENTAL, LEGAL, INSTITUTIONAL AND RELATED FACTORS

CONCEPTUAL DESIGN EXTENSION TASKS

GENERAL ELECTRIC

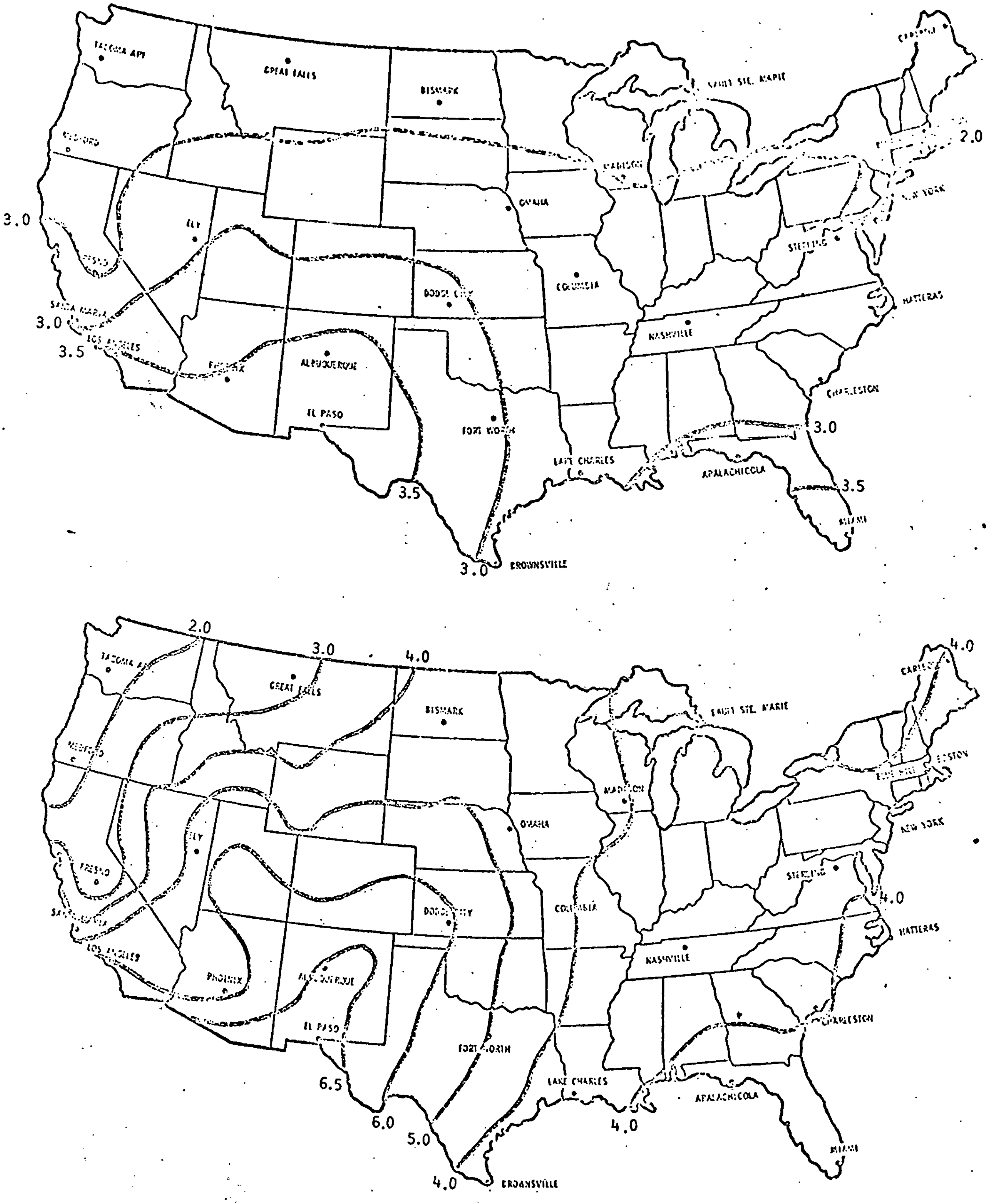
Intermediate PV Total Energy Systems, Analysis of Energy Feedback into Utility Grid, Penetration Analysis, Regional Market Analysis

SPECTROLAB

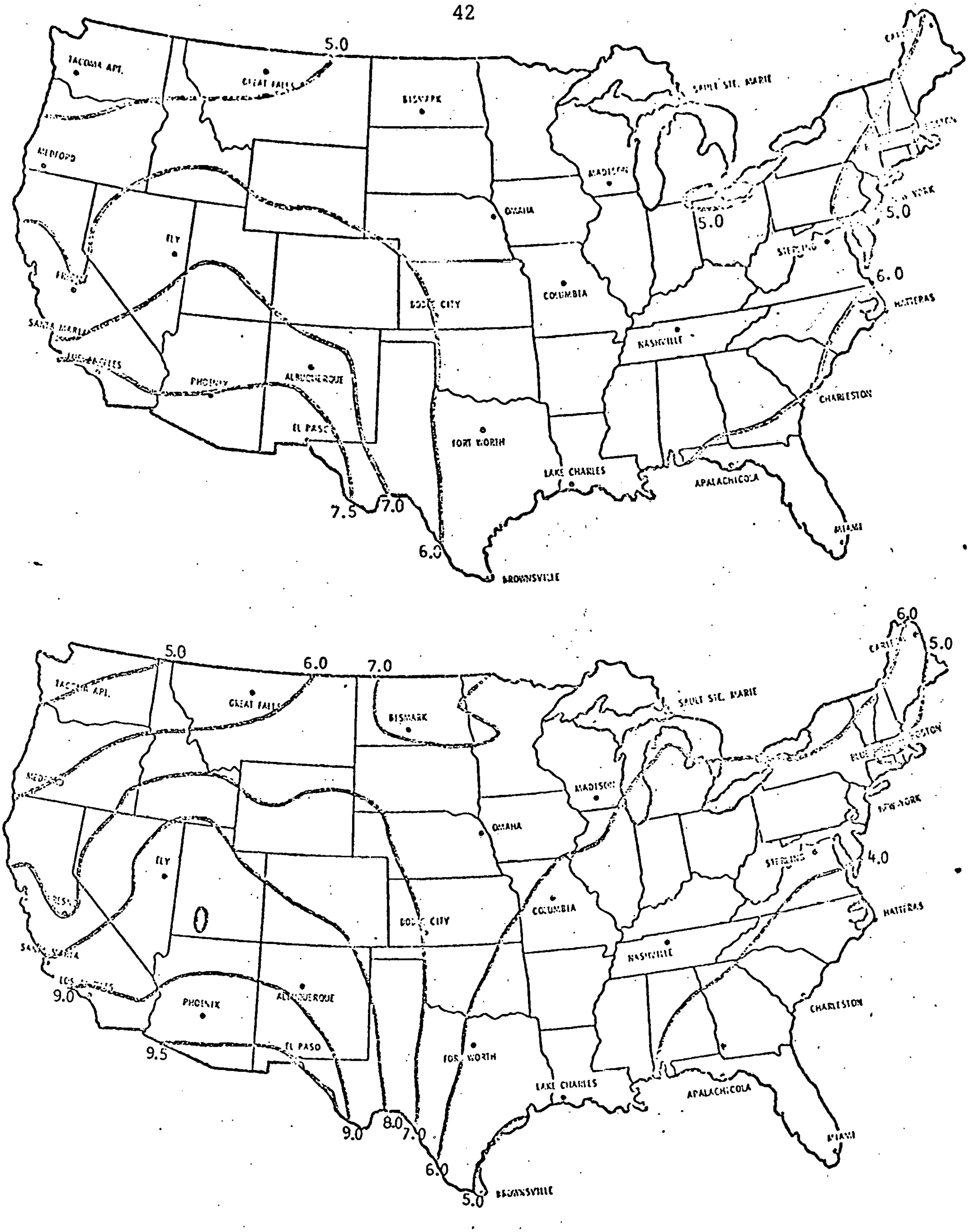
Expanded Characterization of System Configurations and Applications for Intermediate Size PV Systems

WESTINGHOUSE

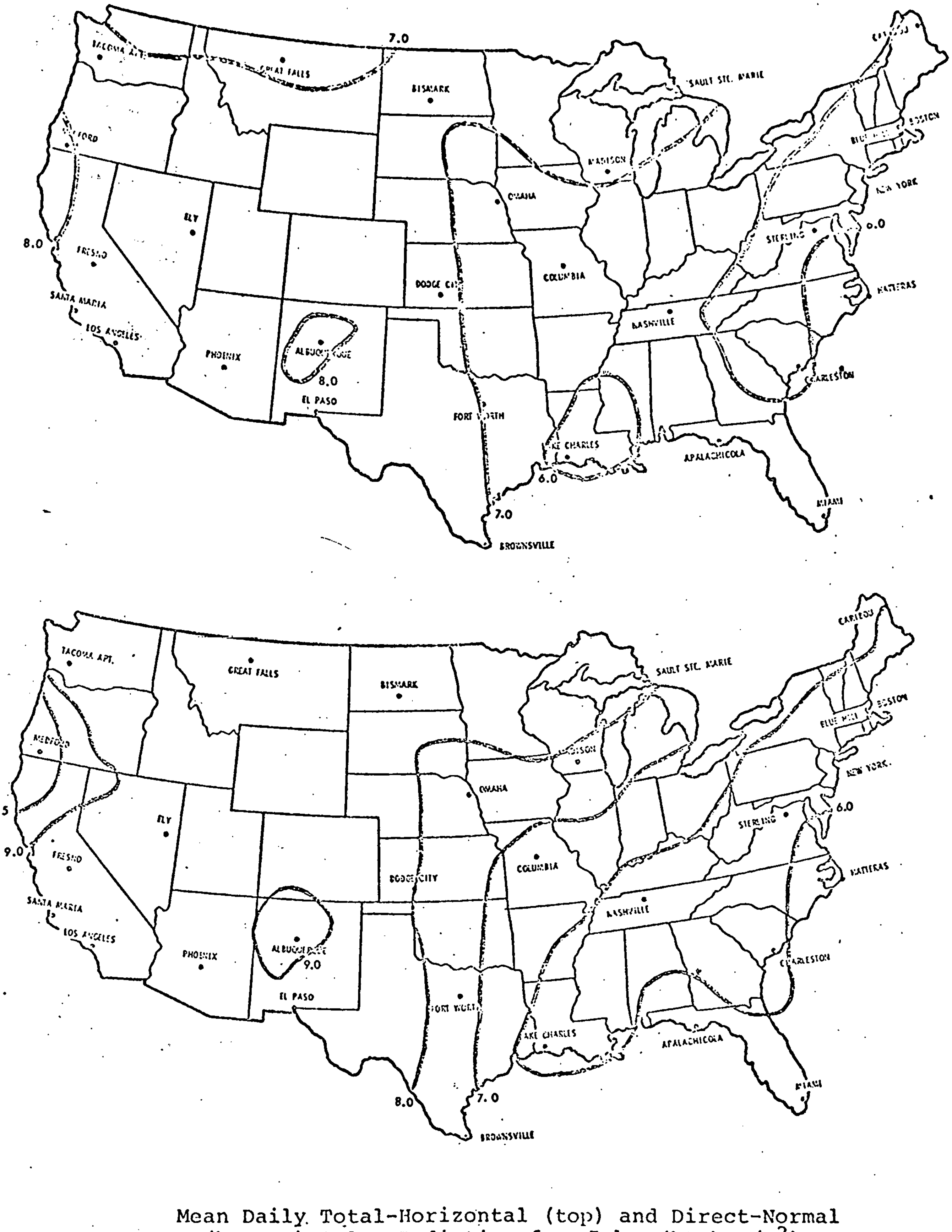
Analysis of Stand-Alone Residential PV System, Utility/Residence Interface Analysis, Fresnel Lens Design, Utility System Reliability Assessment Techniques



Mean Daily Total-Horizontal (top) and Direct-Normal (bottom) Solar Radiation for January (kW·hrs/m^2)



Mean Daily Total-Horizontal (top) and Direct-Normal (bottom) Solar Radiation for April (kW·hrs/m^2)



Mean Daily Total-Horizontal (top) and Direct-Normal (bottom) Solar Radiation for July (kW·hrs/m^2)

SOLAR DATA TAPES

ERDA/NOAA REHABILITATING TAPES

- COMPLETE BY JANUARY 77

SANDIA/AEROSPACE ADDING DIRECT NORMAL

- 26 STATIONS COMPLETE PERIOD OF RECORD
- COMPLETE BY MARCH 77

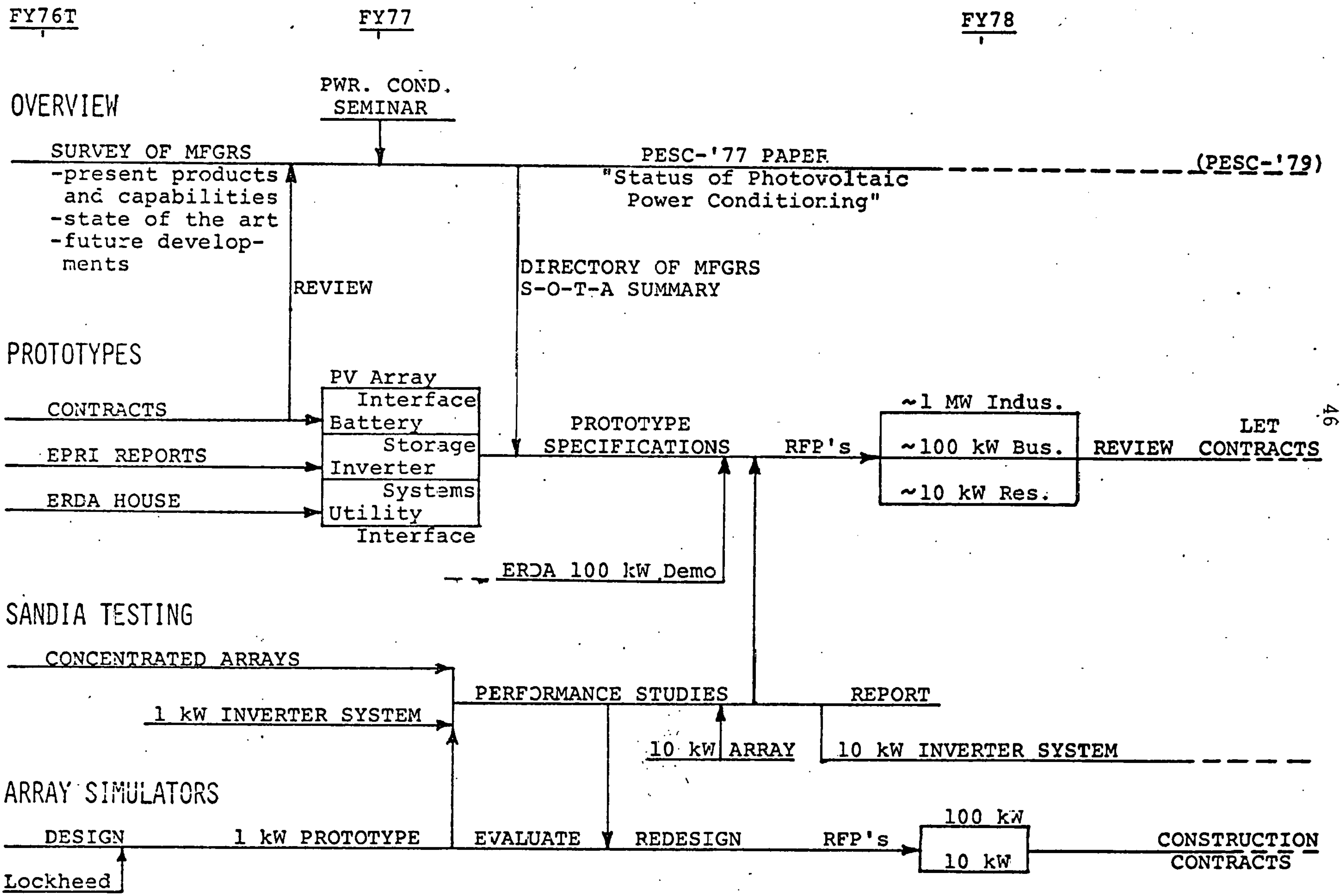
PHOTOVOLTAIC POWER CONDITIONING

OBJECTIVE: Assure conditioning equipment compatible with sytem requirements

GOALS:

1. Assess state-of-the-art in power conditioning
2. Review specific application requirements
    - a. Residential, 3-10 kW
    - b. Apartment building or small business, 50-100 kW
    - c. Shopping center, ~1 MW
    - d. Power station, > 100 MW
3. Identify (any) new development needed
4. Prototype development
5. Final design and cost

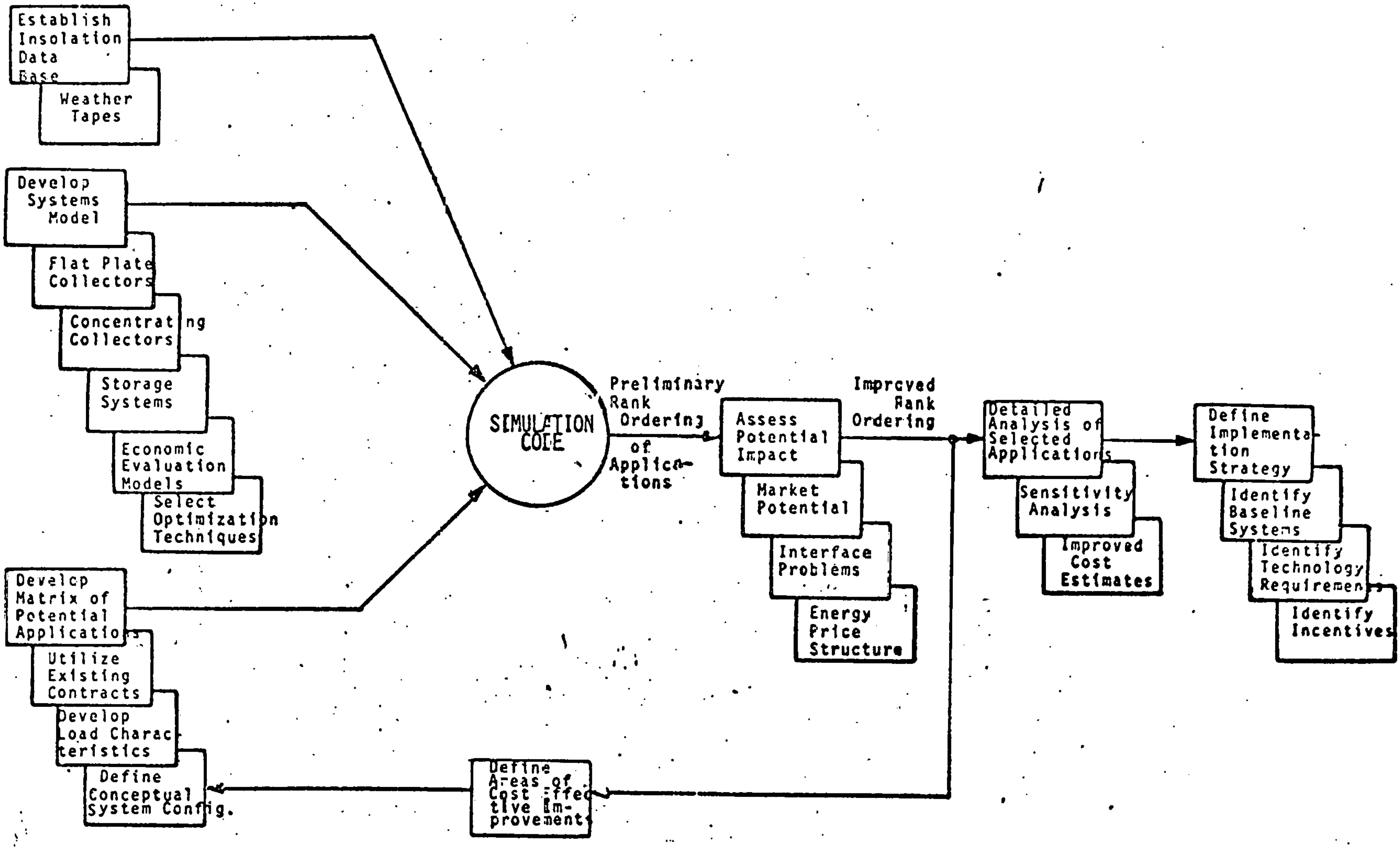
PHOTOVOLTAIC POWER CONDITIONING



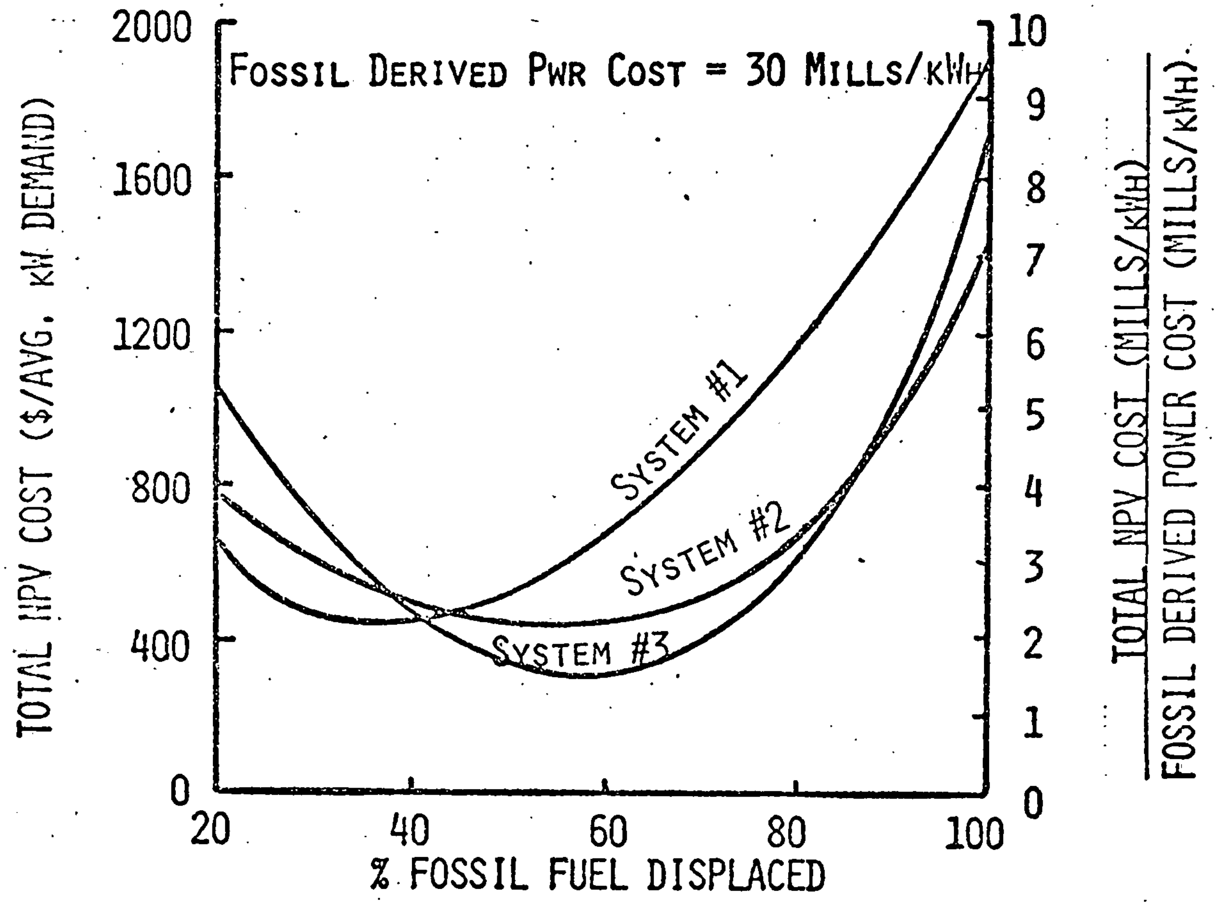
APPLICATION ANALYSIS AND SYSTEM OPTIMIZATION

OBJECTIVES:

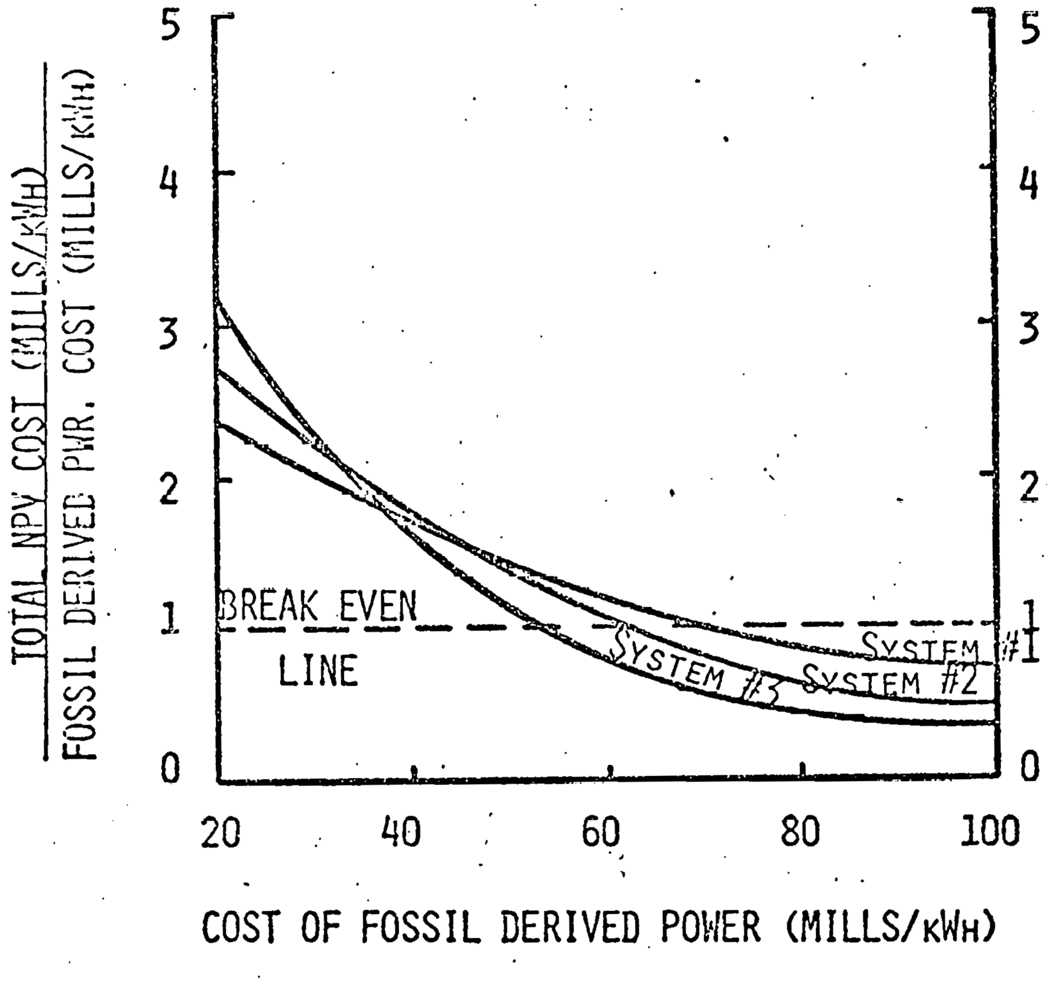
- TO IDENTIFY THE MOST PROMISING LONG TERM APPLICATIONS FOR PHOTOVOLTAIC SYSTEMS
- TO IDENTIFY TECHNOLOGY REQUIREMENTS FOR SYSTEM COMPONENTS
- TO ESTABLISH PRIORITIES FOR COMPONENT DEVELOPMENT

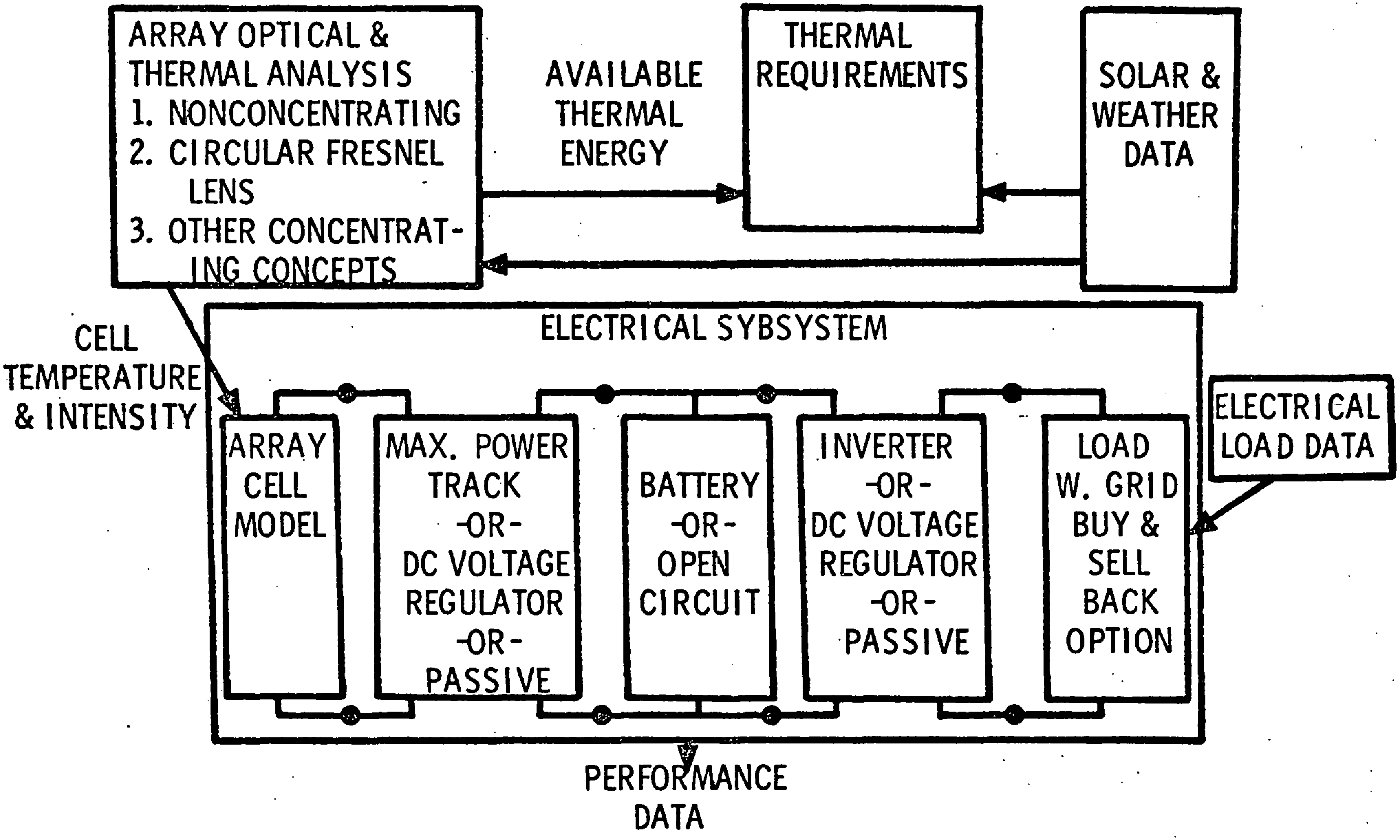

Establish Insolation Data Base
Weather Tapes
Develop Systems Model
Flat Plate Collectors
Concentrating Collectors
Storage Systems
Economic Evaluation Models
Select Optimization Techniques
Develop Matrix of Potential Applications
Utilize Existing Contracts
Develop Load Characteristics
Define Conceptual System Config.
SIMULATION CODE
Preliminary Rank Ordering of Applications
Assess Potential Impact
Market Potential
Interface Problems
Energy Price Structure
Improved Rank Ordering
Detailed Analysis of Selected Applications
Sensitivity Analysis
Improved Cost Estimates
Define Implementation Strategy
Identify Baseline Systems
Identify Technology Requirements
Identify Incentives
Define Areas of Cost Effective Improvements

SIMULATED SYSTEM RANKING CURVES



SIMULATED SYSTEM RANKING CURVES





SOLSYS PHOTOVOLTAIC SYSTEM SIMULATION

PHOTOVOLTAIC ARRAY COST-EFFICIENCY RELATIONSHIPS

$$TC = AC + \left(\frac{OC}{\eta I}\right)$$ (cost function)

$$\frac{\delta AC}{\delta \eta} = \frac{OC}{I}\left(\frac{1}{\eta^2}\right)$$ (sensitivity)

$$\Delta AC = \frac{OC}{I}\left(\frac{\Delta\eta}{\eta_1\eta_2}\right)$$ (differential)

$$\frac{\delta AC/AC}{\delta\eta/\eta} = \frac{OC}{AC}\left(\frac{1}{\eta I}\right)$$ (relative sensitivity)

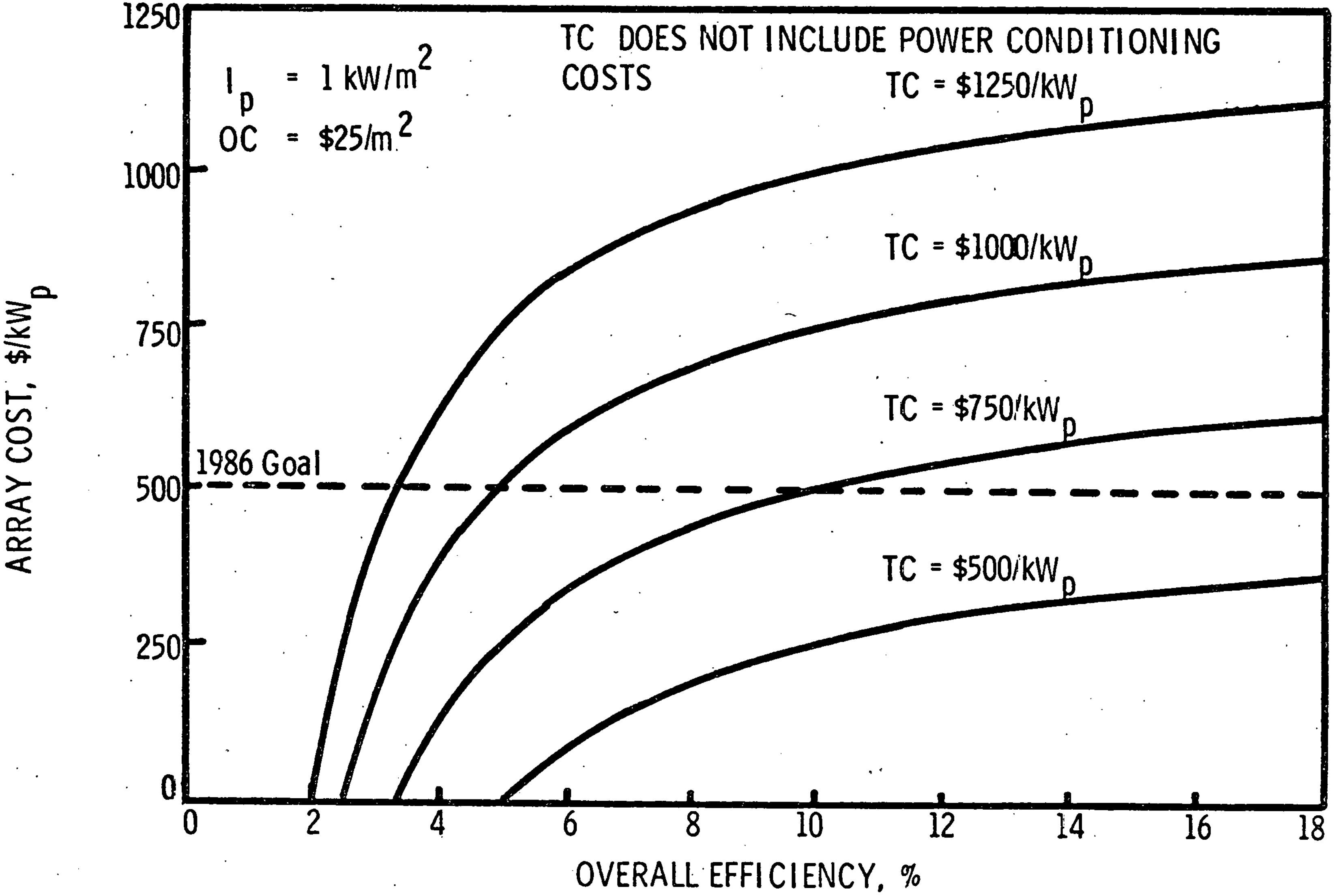
Where: TC = total cost of installed array in \$/kW

AC = array cost in \$/kW

OC = all other area proportional costs in \$/m^2

I = solar insolation in kW/m^2

η = overall array efficiency



ARRAY COST VERSUS ARRAY EFFICIENCY

ECONOMIC ARRAY COST

REVENUES = FIXED CHARGE RATE* CAPITAL COSTS

$$\text{CAPITAL COSTS (\$/kW)} = \left[AC + \frac{OC}{\eta I} + \frac{PC}{R} \right] * (1+\beta)$$

$$\text{REVENUES (\$/M}^2\text{-YR)} = ER\,|IE\ (\eta)|$$

$$\text{REVENUES (\$/kW-YR)} = ER\ (IE)/I$$

$$ER(\ E)/\ = FCR^* \{ AC + OC/\eta I + PC/R \} * (1+\beta)$$

$$AC = \frac{ER(IE)}{I(FCR)(1+\beta)} - \frac{OC}{I} - \frac{PC}{R}$$

SPECIAL CASE: $I = I_{AVE}$, $IE = 8760I$

$$AC = \frac{8760\ ER}{(FCR)(1+\beta)} - \frac{OC}{\eta I} - \frac{PC}{R}$$

WHERE:

AC = ARRAY COST, \$/kW

OC = OTHER COSTS, \$/M^2

PC = POWER CONDITIONING, \$/kW$_P$

ER = ELECTRIC RATE, \$/kWH

E = INCIDENT ENERGY, kWH/M^2-YR

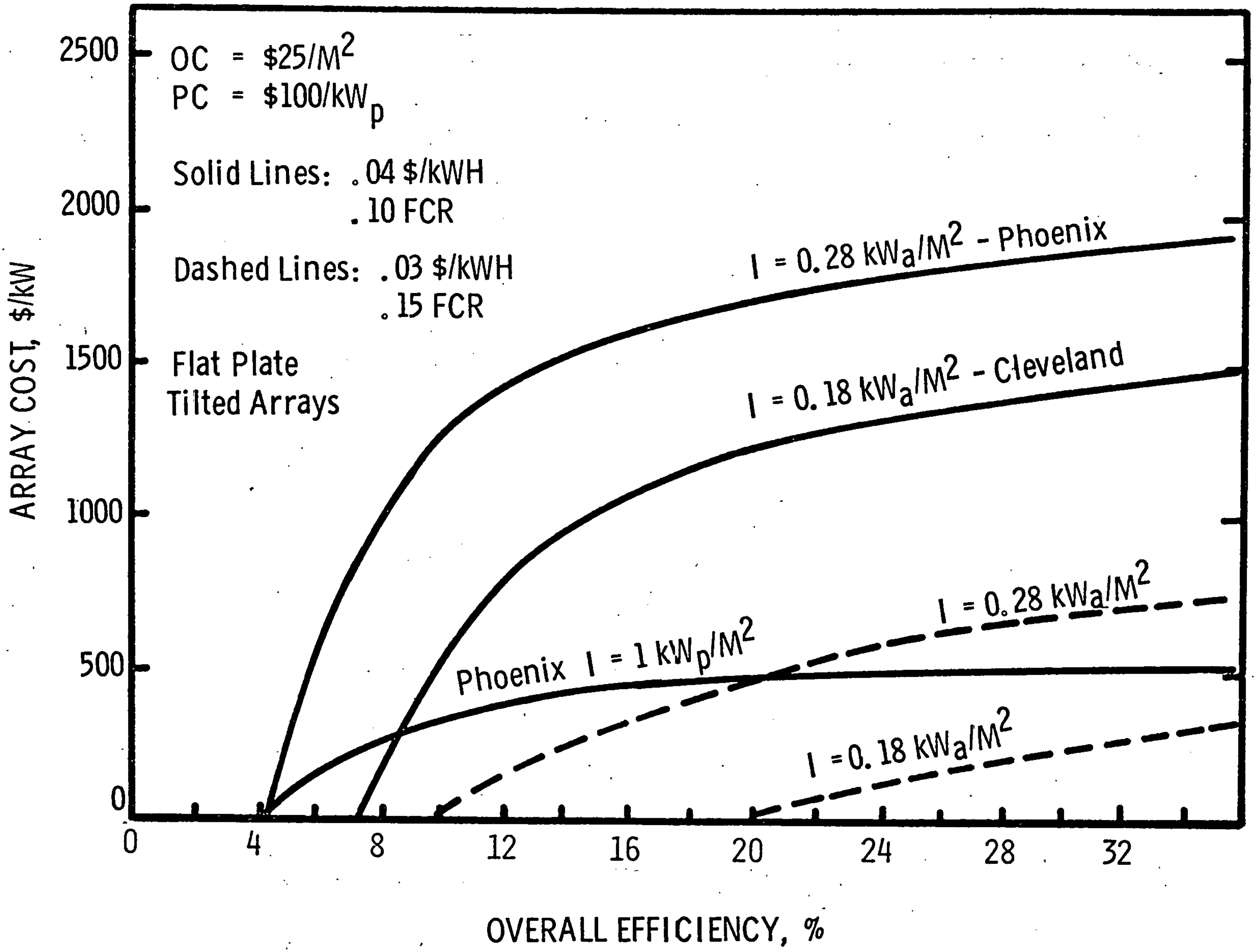
I = INSOLATION, kW/M^2

R = RATIO kW/kW$_P$

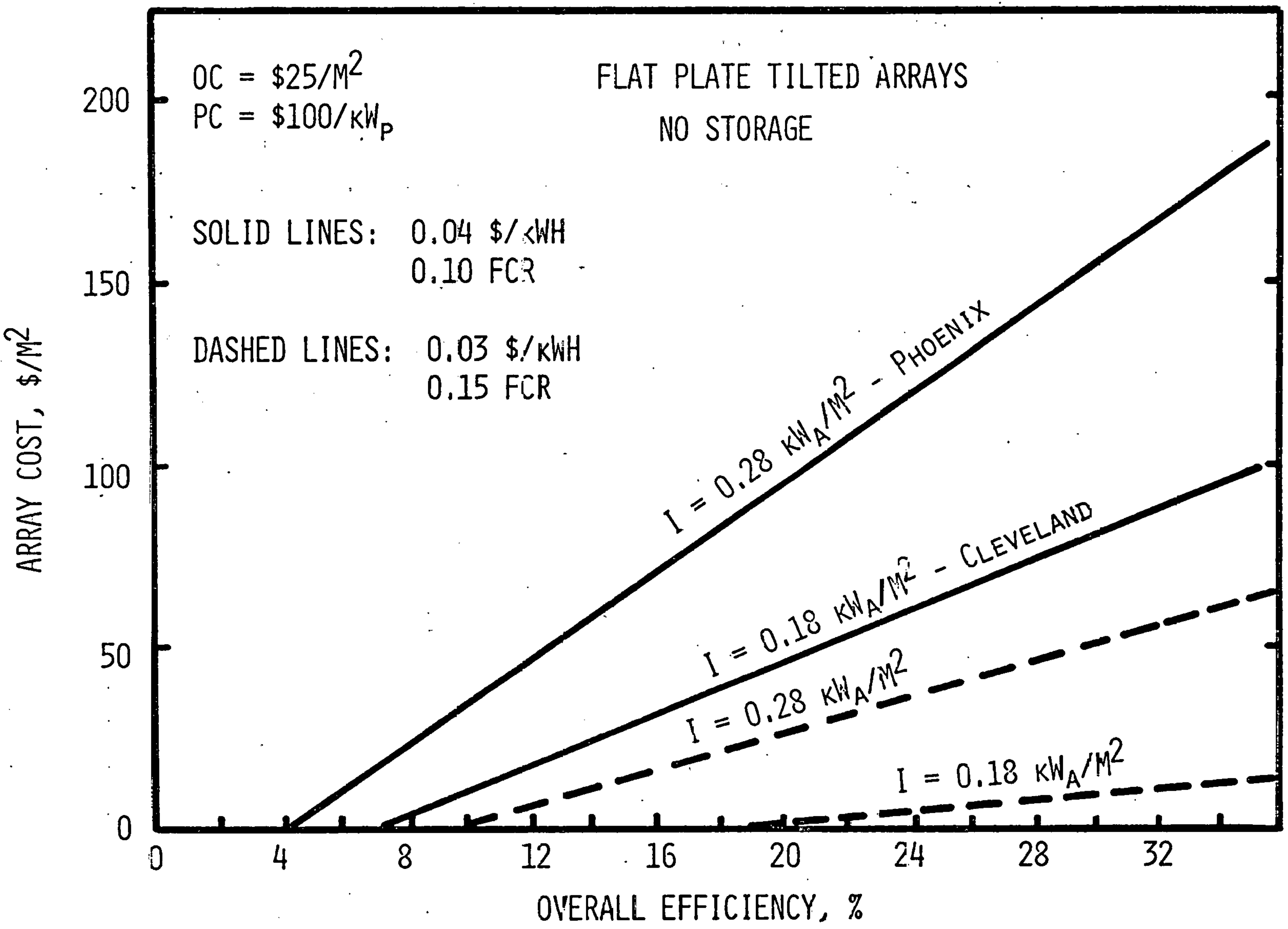
FCR = FIXED CHARGE RATE

η = OVERALL EFFICIENCY, $\eta = \eta_C\ \eta_P\ \eta_{OI}\ \eta_{EI}$

β = INDIRECT COSTS, IDC, AND CONTINGENCY COST FACTOR



ECONOMIC ARRAY COSTS



ALLOWABLE ARRAY COST VERSUS EFFICIENCY FOR SELECTED

PV/COMBINED SYSTEM COMPARISONS

EQUIVALENT SYSTEM FIRST COST

PV SYSTEM

$$X_e = \begin{array}{c}\text{ARRAY}\\\text{COST}\end{array} + \begin{array}{c}\text{ELECT.}\\\text{STORAGE}\\\text{COST}\end{array} + \begin{array}{c}\text{PC \&}\\\text{CONTROL}\\\text{COST}\end{array} + \begin{array}{c}\text{EQUIV.}\\\text{REPLACE.}\\\text{COST}\end{array} + \begin{array}{c}\text{EQUIV.}\\\text{O \& M}\\\text{COST}\end{array}$$

COMBINED SYSTEM

$$X_c = \begin{array}{c}\text{ARRAY}\\\text{COST}\end{array} + \begin{array}{c}\text{ELECT.}\\\text{STORAGE}\\\text{COST}\end{array} + \begin{array}{c}\text{PC \&}\\\text{CONTROL}\\\text{COST}\end{array} + \begin{array}{c}\text{THERMAL}\\\text{STORAGE}\\\text{COST}\end{array} + \begin{array}{c}\text{EXCESS}\\\text{THERMAL}\\\text{COST}\end{array} + \begin{array}{c}\text{EQUIV.}\\\text{REPLACE.}\\\text{COST}\end{array} + \begin{array}{c}\text{EQUIV.}\\\text{O \& M}\\\text{COST}\end{array}$$

ANNUAL FOSSIL FUEL DISPLACED

PV SYSTEM

$$E_{ff} = 3 * \text{ELECTRIC ENERGY PRODUCED } (E_e)$$

COMBINED SYSTEM

$$E_{ff} = 3 * \text{ELECTRIC ENERGY PRODUCED } (E_e) + 1.5 * \text{THERMAL ENERGY USED } (E_t)$$

EQUIVALENT COST OF CONVENTIONAL ENERGY DISPLACED

PV SYSTEM

$$V_e = \left[\begin{array}{c}\text{PRESENT UNIT}\\\text{ELECTRIC COST}\end{array}\right] * \left[\begin{array}{c}\text{ELECTRIC ENERGY}\\\text{PRODUCED}\end{array}\right] * \left[\begin{array}{c}\text{PRESENT VALUE OF}\\\text{FUTURE COST}\end{array}\right]$$

COMBINED SYSTEM

$$V_c = V_e + \left[\begin{array}{c}\text{PRESENT UNIT}\\\text{FOSSIL FUEL COST}\end{array}\right] * \left[\begin{array}{c}\text{THERMAL ENERGY}\\\text{USED}\end{array}\right] * \left[\begin{array}{c}\text{PRESENT VALUE OF}\\\text{FUTURE COST}\end{array}\right]$$

PV/COMBINED SYSTEMS COMPARISON

IF -

$$\frac{E_t}{E_e} > \frac{E_o}{2F_o}\left\{\frac{\left[1.17C_c + 59\left(1 - \frac{A_o}{A_c}\right)\eta + 15\eta + 30\left(1 - \frac{A_t}{A_c}\right) + 16\right]}{\eta\left[1.12C_e + 57\left(1 - \frac{A_o}{A_c}\right) + 14.4\right]}\right\}$$

THEN - COMBINED SYSTEM IS PREFERRED BASED ON VALUE OF CONVENTIONAL ENERGY DISPLACED

E_t - THERMAL ENERGY USED

E_e - ELECTRICAL ENERGY USED

E_o - COST AT INITIAL YEAR OF ELECTRICAL ENERGY

F_o - COST AT INITIAL YEAR OF FOSSIL FUEL

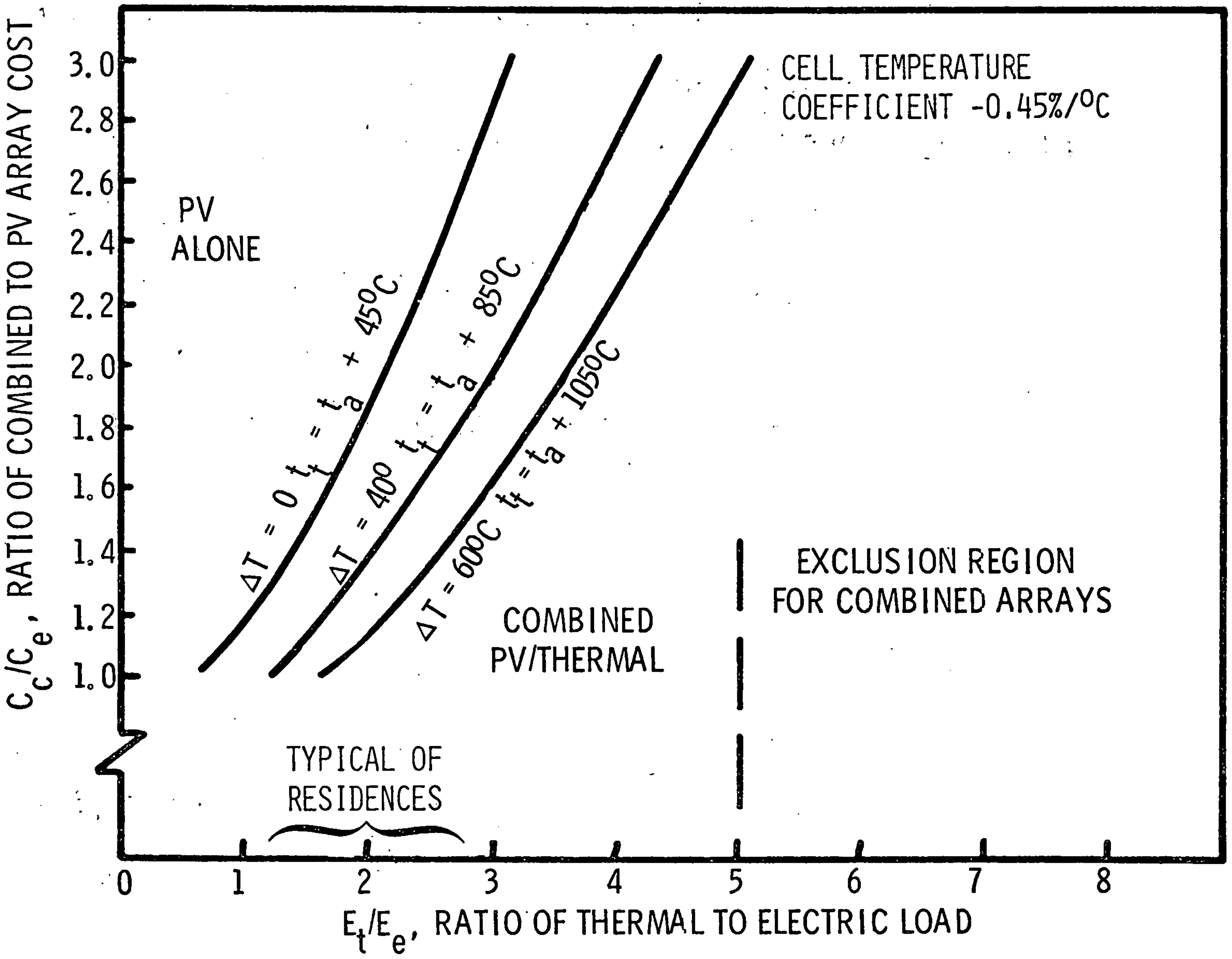
C_c - COST OF COMBINED ARRAY

C_e - COST OF PV ONLY ARRAY

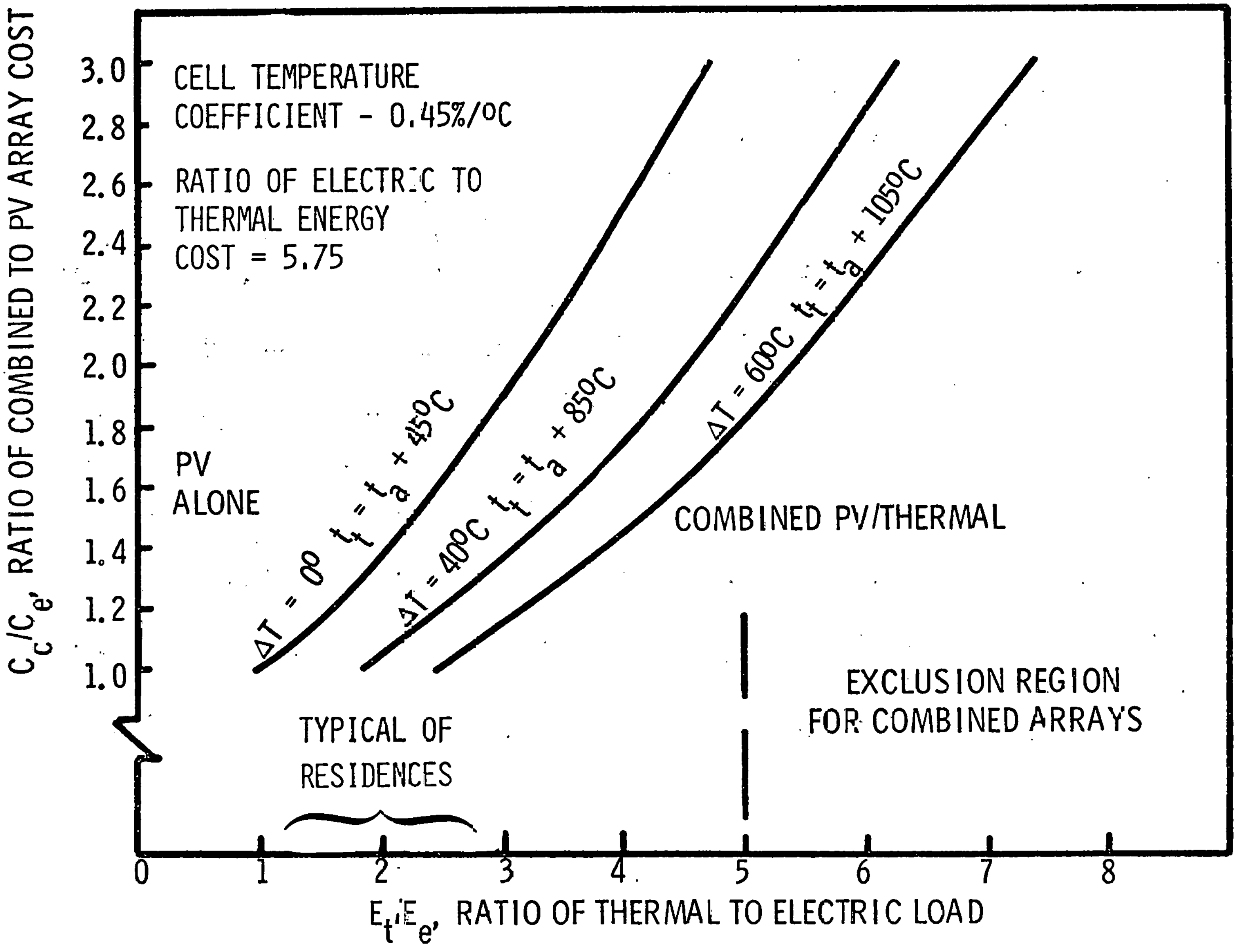
η - RATIO OF ARRAY ELECTRIC EFFICIENCIES OF COMBINED TO PV ONLY SYSTEM

$\eta = 1 - .0045\,(T_c - T_r) - \tau_g$ FOR 1 SUN CELLS (SPECTROLAB)

$\eta = 1 - .0035\,(T_c - T_r) - \tau_g$ FOR 43 SUN CELLS (SLA)



COMPARISON OF PHOTOVOLTAIC AND COMBINED SYSTEMS
BASED ON FOSSIL FUEL DISPLACED



COMPARISON OF PHOTOVOLTAIC AND COMBINED SYSTEMS
BASED ON COST OF ENERGY DISPLACED

ACTIVITIES DURING NEXT SIX MONTHS

PRELIMINARY APPLICATION ORDERING AND SYSTEM OPTIMIZATION

ANALYSES OF SPECIFIC DESIGNS FOR EXPERIMENTS AND DEMONSTRATIONS

RESULTS FROM CONCEPTUAL DESIGN COMPARISONS FOR SUBSYSTEM DESIGN

DETAIL SUBSYSTEMS ANALYSIS - STRUCTURE, OPERATION, COSTS

WEATHER AND SOLAR DATA TAPES AVAILABLE

DEFINE AND IMPROVE SOLAR DATA MAPS AND TABLES

OTHER SYSTEMS CONSIDERATIONS - UTILITY TIE-IN, THERMAL ENERGY VALUE,
ENERGY CONSERVATION IN PV BUILDINGS

DEVELOPMENT OF LOW COST THIN FILM POLYCRYSTALLINE SILICON SOLAR CELLS FOR TERRESTRIAL APPLICATIONS

National Science Foundation
Grant Number: AER 73-07843 A01

Period of Grant

December 1, 1974 - November 30, 1976

Value of Grant: $300,000

THIN FILMS OF SILICON ON LOW COST SUBSTRATES

Energy Research and Development Administration
Contract Number: E(04-3)-1285

Period of Contract

September 1, 1976 - October 31, 1977

Value of Contract: $181,950

Ting L. Chu, Principal Investigator
Professor, Southern Methodist University
Dallas, Texas 75275

Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976

University of Maine at Orono

Orono, Maine 04773

I. Objective

The objective of this grant is to develop low-cost polycrystalline silicon solar cells for terrestrial utilization.

II. Previous Activities

During the second-half of 1975, major efforts were directed to (1) the improvement in the structural properties of silicon on graphite substrates, (2) the purification of metallurgical silicon, (3) the preparation of metallurgical silicon substrates, and (4) the fabrication and characterization of solar cells on graphite and metallurgical silicon substrates.

The structural properties of silicon on graphite substrates was substantially improved by unidirectional recrystallization. Silicon layers with crystallites up to two centimeters long and several millimeters wide were obtained. The unidirectional solidification technique was also used successfully for the preparation of metallurgical silicon substrates.

The purification of metallurgical silicon by the conventional zone-refining technique was concluded to be unsuitable economically for low cost cells. The treatment of molten metallurgical silicon with chlorine or chlorine and oxygen mixtures has been found to be very effective for reducing the concentration of aluminum, but the concentration of iron was essentially unchanged.

Using chemically treated metallurgical silicon recrystallized on graphite as substrates, solar cells of 20 cm^2 area with AM1 efficiencies of up to 4% have been prepared by the chemical vapor deposition technique.

III. Current Efforts

The recent work has been directed to (1) the purification of metallurgical silicon, (2) the deposition and characterization of epitaxial silicon layers on recrystallized metallurgical silicon, (3) the fabrication and characterization of solar cells on recrystallized metallurgical silicon, and (4) the effects of grain boundaries on the characteristics of epitaxial mesa diodes on recrystallized siliocn substrates.

The treatment of molten metallurgical silicon with a number of reagents has been found to be effective for reducing substantially the concentration of aluminum; however, the concentration of iron was not appreciably lowered. Single crystals were pulled from chlorine and chlorine-oxygen treated metallurgical silicon. The upper sections of the crystals were found to be p-type with a room temperature resistivity of 0.2-0.4 ohm-cm, Hall mobility of

80-110 $cm^2\ v^{-1}\ sec^{-1}$, and minority carrier diffusion length of about 5 μm.

Silicon sheets prepared by the unidirectional solidification of chemically treated metallurgical silicon were used as substrates for the epitaxial growth of n-type silicon layers of 0.005-20 ohm-cm resistivity. At carrier concentrations higher than about $10^{17}\ cm^{-3}$, the measured mobilities were slightly lower than those in single crystalline silicon of similar carrier concentrations. At lower concentrations, however, the results were erratic and irreproducible due to the potential barriers at grain boundaries. The potential drop across the boundaries was found to increase rapidly with increasing resistivity of the layer. The effective minority carrier lifetime in lightly-doped epitaxial layers was found to be on the order of a few tenths of a microsecond.

Large area (30 cm^2) solar cells of the configuration SiO_2/n^+-silicon/p-silicon/p^+-metallurgical silicon (recrystallized)/graphite with AM1 efficiencies of up to 5.5% have been produced. The device does not have uniform structural characteristics, and the smaller area solar cells obtained by masking and etching techniques were found to vary considerably in dark current voltage characteristics and conversion efficiencies.

To study the effects of grain boundaries, epitaxial mesa diodes containing grain boundaries have been prepared, and their dark current-voltage characteristics compared with those free of boundaries.

IV. Summary of Key Results

(1) Iron cannot be readily removed from metallurgical silicon by the chemical treatment of the melt.

(2) At carrier concentrations of $10^{17}\ cm^{-3}$ or lower, the potential barrier across a grain boundary in epitaxial silicon becomes appreciable.

(3) Solar cells of 30 cm^2 area with AM1 efficiencies of up to 5.5% have been produced.

V. Future Plans

Future work will be directed to (1) the improvement of the preparation of metallurgical silicon substrates, (2) the deposition and characterization of silicon films on metallurgical silicon substrates, (3) the measurement of grain boundary properties, and (4) the fabrication and characterization of solar cells.

DEVELOPMENT OF LOW COST THIN FILM POLYCRYSTALLINE SILICON SOLAR CELLS FOR TERRESTRIAL APPLICATIONS

NSF Grant AER 73-07843 A01

Period of Grant

December 1, 1975 - November 30, 1976

Value of Grant: $300,000

THIN FILMS OF SILICON ON LOW COST SUBSTRATES

ERDA Contract E(04-3)-1285

Period of Contract

September 1, 1976 - October 31, 1977

Value of Contract: $181,950

Work performed at Southern Methodist University

Principal Investigator: Ting L. Chu

POLYCRYSTALLINE SILICON SOLAR CELLS
INTRODUCTION

- Overall Objective: To develop low-cost polycrystalline silicon solar cells for terrestrial utilization.

- Approaches: Formation of p-n junction structures on low-cost substrates.

    - Deposition and characterization of silicon on graphite and metallurgical silicon substrates by the trichlorosilane ($SiHCl_3$) process.
    - Fabrication, characterization, and optimization of solar cells on graphite and metallurgical silicon substrates.
    - Purification of metallurgical silicon.
    - Fabrication and characterization of solar cells from purified metallurgical silicon.

- Key Results Reported at Last Review (January, 1976):

    - A unidirectional solidification technique has been developed for the preparation of silicon sheets with large crystallites on graphite substrates.
    - The treatment of the melt of metallurgical silicon with chlorine or chlorine-oxygen mixtures is effective in reducing the concentration of aluminum and is ineffective in reducing the concentration of iron.
    - Using chemically treated and unidirectionally solidified metallurgical silicon as substrates, solar cells of 20 cm^2 or larger in area with AM1 efficiencies of up to 4% have been produced.

TLC; 2
8/7

POLYCRYSTALLINE SILICON SOLAR CELLS

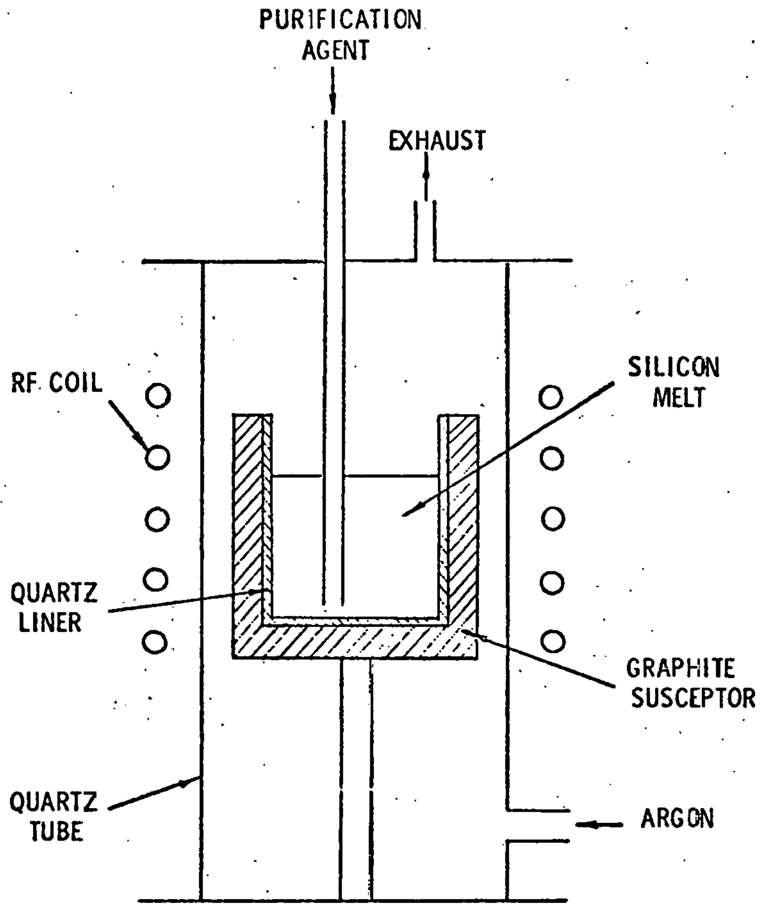
PLANNED ACTIVITY FOR LAST SIX MONTHS

PLAN	ACTION
● Purification of metallurgical silicon.	● Chemical treatment of the melt further investigated. Single crystals pulled from chemically treated metallurgical silicon and characterized.
● Characterization of unidirectionally recrystallized silicon on graphite.	● Epitaxial silicon layers deposited on recrystallized metallurgical silicon characterized.
● Fabrication and characterization of solar cells on recrystallized metallurgical silicon/graphite.	● Solar cells of about 30 cm^2 area with AMI efficiencies of up to 5.5% have been produced.
● Investigation of grain boundary properties.	● Epitaxial silicon mesa p-n junctions containing one grain boundary have been prepared and their dark current-voltage characteristics compared with those free of grain boundaries.

TLC;3
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
PURIFICATION OF METALLURGICAL SILICON BY CHEMICAL TREATMENT

- SCHEMATIC OF APPARATUS



- RESULTS

IMPURITY CONCENTRATION, PPM

	Metal. Silicon	HF Treat.	$Cl_2 + O_2$ Treat. Cl_2 Treat.
Al	3,000	100	<50
Fe	3,400	2,700	2,500

	$(GeO_2)_x(SiO_2)_y$ Treatment	$(B_2O_3)_x(SiO_2)_y$ Treatment
Al	250	490
Fe	3,700	2,300

- Preferential removal of iron from metallurgical silicon by chemical treatment unlikely.

TLC;4
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
CZOCHRALSKI CRYSTALS FROM CHEMICALLY TREATED METALLURGICAL SILICON

- IMPURITY CONCENTRATION, PPM

Cl_2 Treated

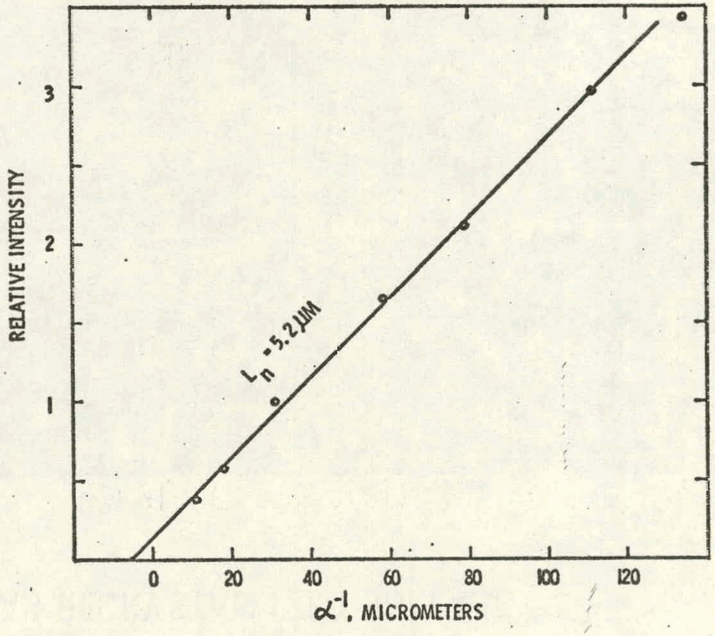
	Al	Fe
Top Section	<100	10
Middle Section	<100	700
Bottom Section	150	11,700

Cl_2 - O_2 Treated

Top Section	<100	11
Middle Section	<100	480
Bottom Section	<100	21, 300

- PROPERTIES

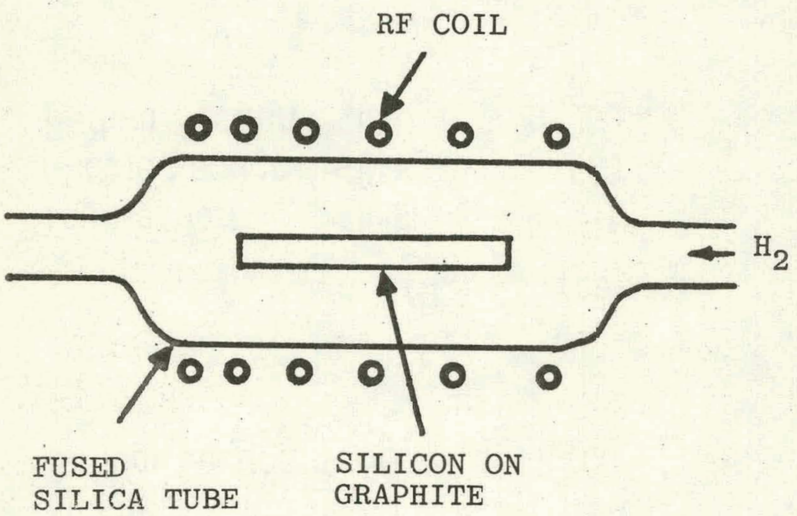
Resistivity: 0. 2 - 0. 4 ohm-cm, p-type
Hall Mobility: 80 - 100 $cm^2 v^{-1} sec^{-1}$
Minority Carrier Diffusion Length:



TLC;5
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
UNIDIRECTIONAL SOLIDIFICATION OF METALLURGICAL SILICON ON GRAPHITE

- SCHEMATIC OF APPARATUS



- AS RECRYSTALLIZED SURFACE

TLC;6
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
EPITAXIAL SILICON LAYERS ON RECRYSTALLIZED METALLURGICAL SILICON

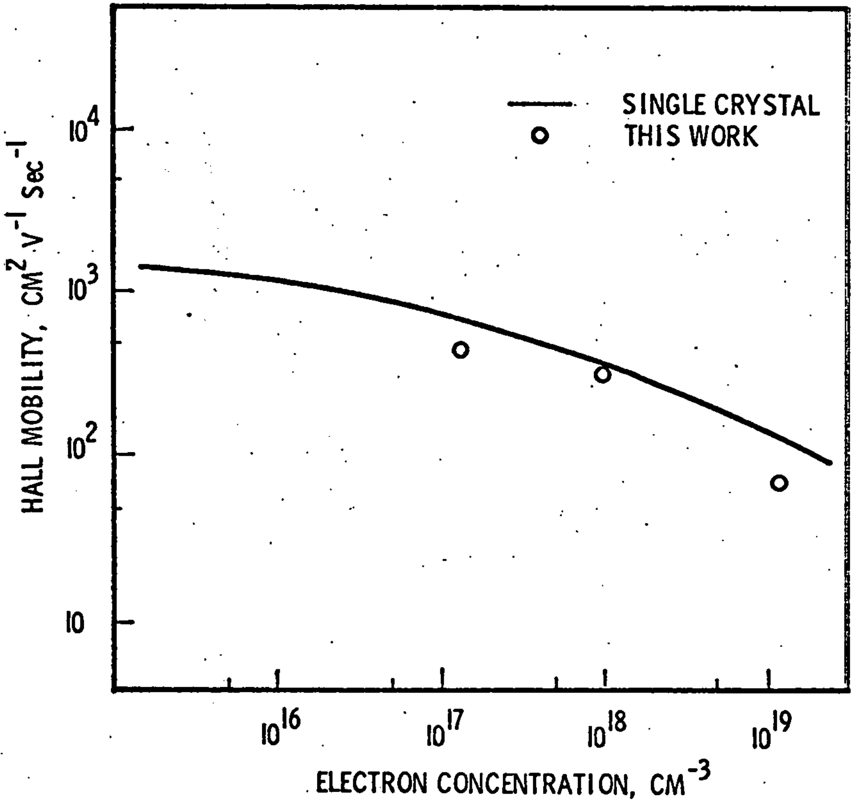
- PREPARATION

  Thermal reduction of trichlorosilane with hydrogen containing phosphine to yield n-layers of 0.005-20 ohm-cm resistivity.

- MINORITY CARRIER LIFETIME

RESISTIVITY ohm-cm	EFFECTIVE LIFETIME μ sec
0.02	0.02
0.07	0.2
10	0.45
20	0.65

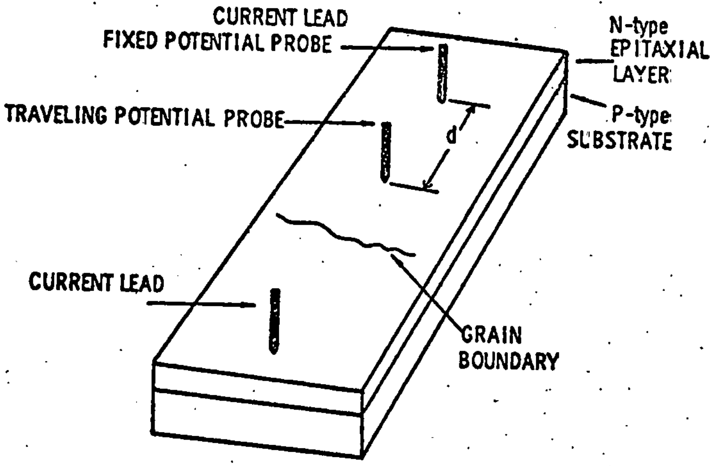
- HALL MOBILITY



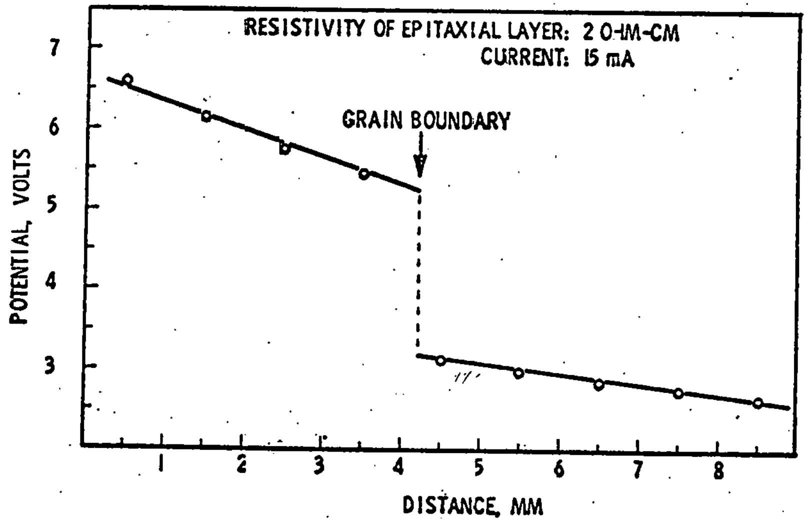
TLC;7
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
POTENTIAL DROP ACROSS GRAIN BOUNDARIES IN EPITAXIAL SILICON LAYERS

- SCHEMATIC OF APPARATUS



- RESULTS

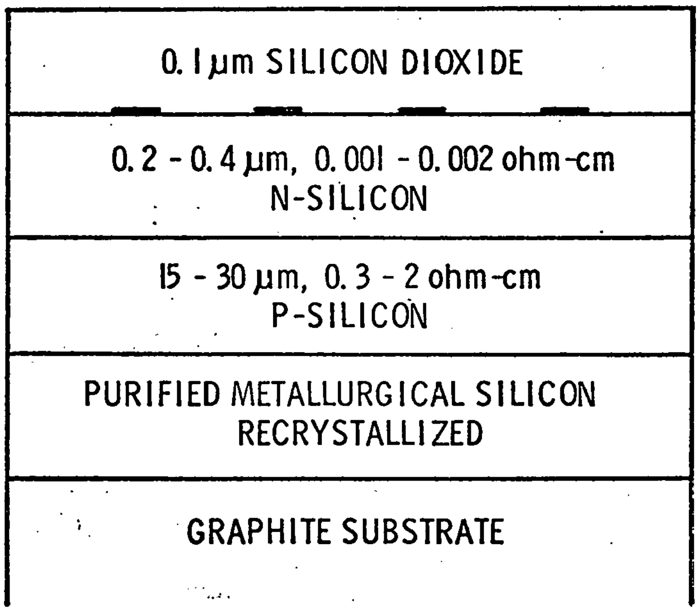


RESISTIVITY ohm-cm	CURRENT mA	POTENTIAL DROP, volts
0.025	15	0.005
0.07	15	0.015
2	15	2.0
10	3	5.5
20	3	9.0

TLC;8
8/7

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
LARGE AREA SILICON SOLAR CELLS ON METALLURGICAL SILICON / GRAPHITE

- **CONFIGURATION**



0.1 µm SILICON DIOXIDE

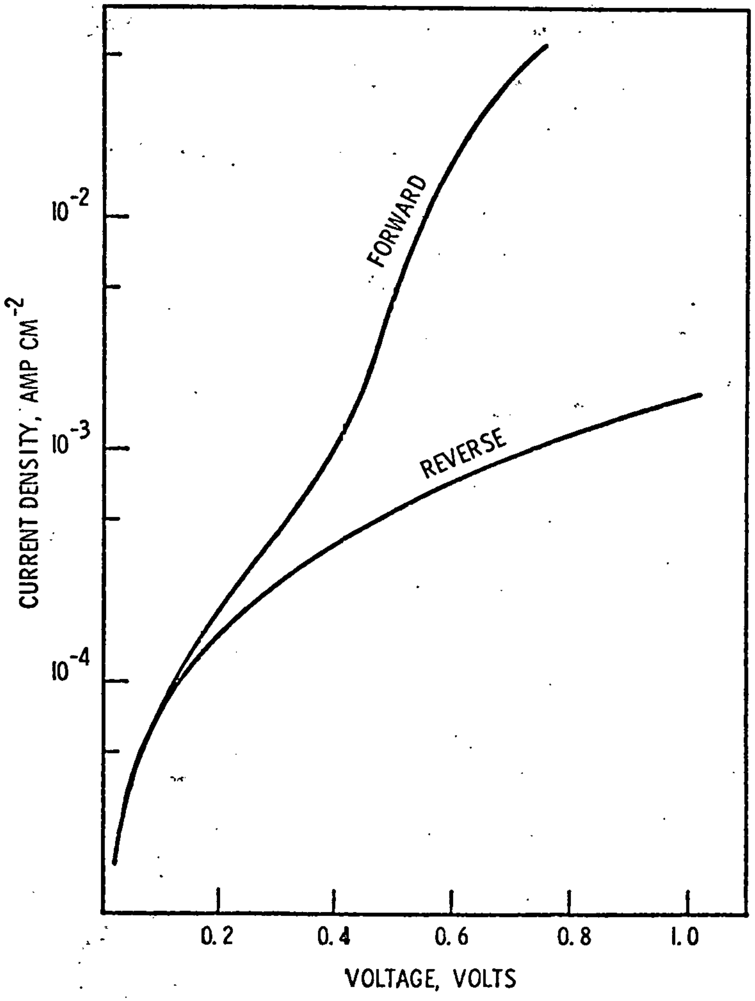
0.2 - 0.4 µm, 0.001 - 0.002 ohm-cm
N-SILICON

15 - 30 µm, 0.3 - 2 ohm-cm
P-SILICON

PURIFIED METALLURGICAL SILICON
RECRYSTALLIZED

GRAPHITE SUBSTRATE

- **DARK CHARACTERISTICS**

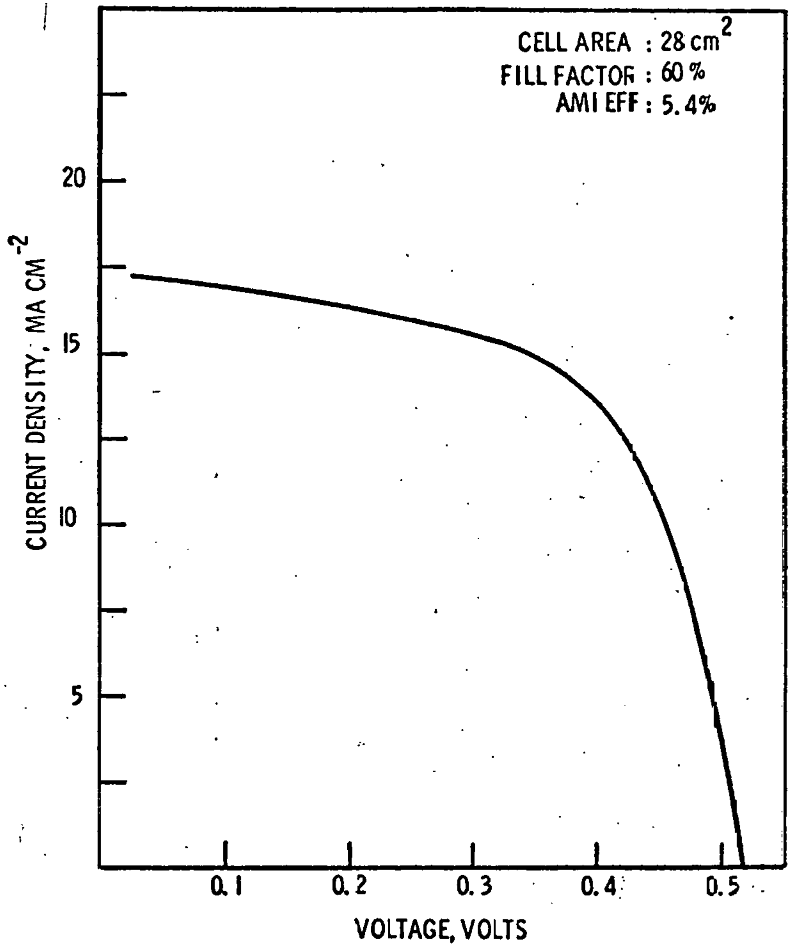


TLC;9
8/76

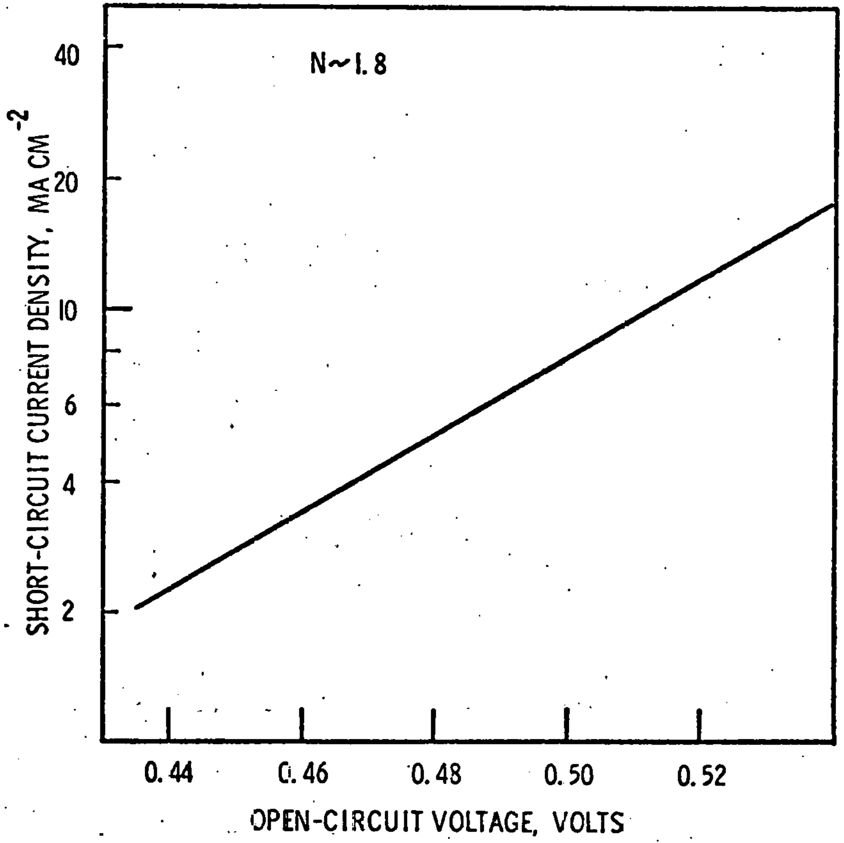
POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE

LARGE AREA SILICON SOLAR CELLS ON METALLURGICAL SILICON / GRAPHITE

- CHARACTERISTICS UNDER ILLUMINATION AT 100 MW/CM^2.



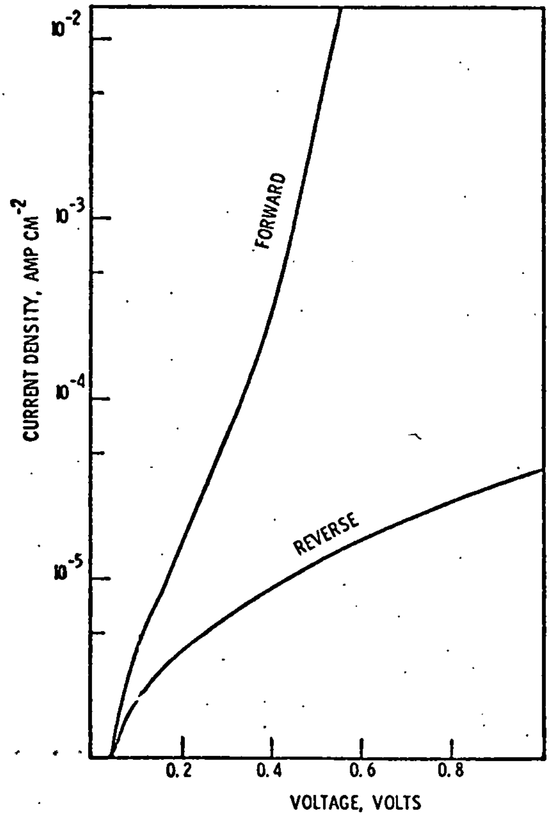
- RELATION BETWEEN V_{OC} AND I_{SC}.



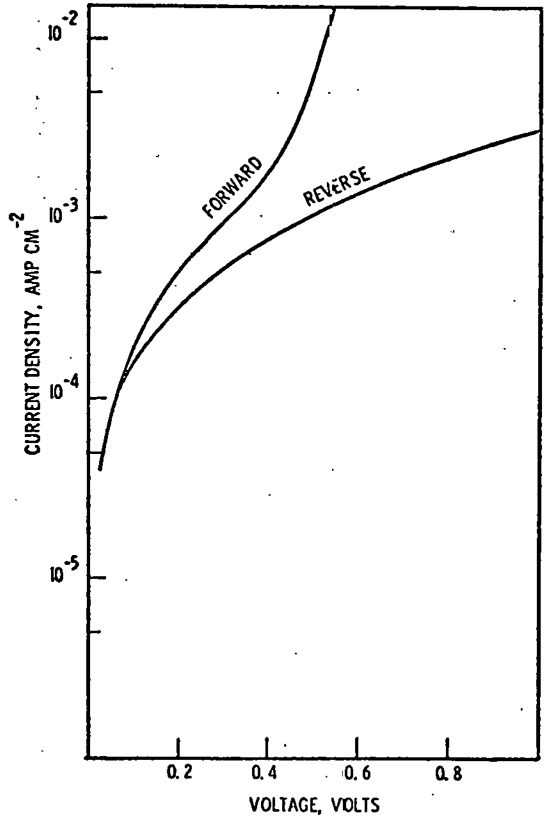
TLC;10
8/74

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE

DARK CHARACTERISTICS OF SMALL AREA SOLAR CELLS



CELL AREA: 4.5 cm^2
AMI EFF: 6.3%

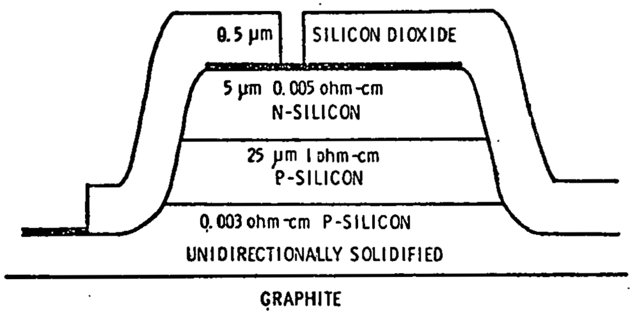


CELL AREA: 4.7 cm^2
AMI EFF: 5.3%

TLC;II
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS - PROGRESS TO DATE
EFFECTS OF GRAIN BOUNDARIES ON DARK CHARACTERISTICS OF P-N JUNCTIONS

- CONFIGURATION

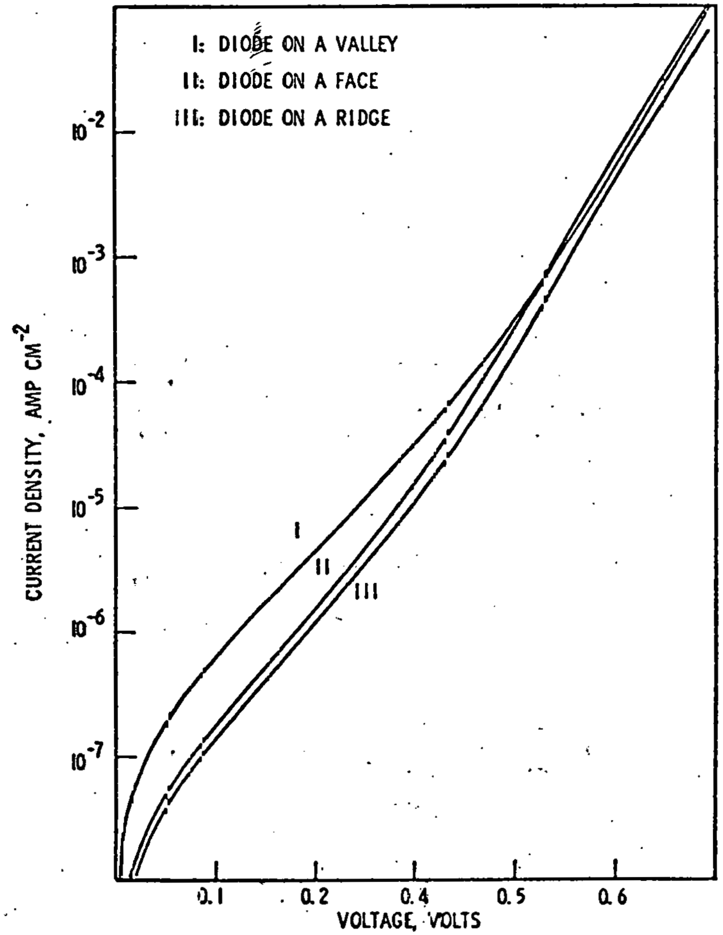


- TWO EXPONENTIAL MODEL

$$I = I_{01}\,[\mathrm{Exp}\,(qV/kT)\ -1] + I_{02}\,[\mathrm{Exp}\,(qV/A_2kT)\ -1] + \frac{V}{R_{sh}}$$

	I	II	III
I_{01}, A/cm^2	1.46×10^{-11}	1.6×10^{-11}	8.3×10^{-12}
I_{02}, A/cm^2	9.2×10^{-8}	1×10^{-8}	3.5×10^{-9}
A_2	1.92	1.63	1.66

- DARK CHARACTERISTICS



TI C;I2
6

POLYCRYSTALLINE SILICON SOLAR CELLS

SUMMARY OF KEY RESULTS

- Iron cannot be readily removed from metallurgical silicon by the chemical treatment of the melt.
- At carrier concentrations of 10^{17} cm^{-3} or lower, the potential barrier across a grain boundary in epitaxial silicon is appreciable and increases with decreasing carrier concentration.
- Solar cells, about 30 cm^2 area, of the configuration silicon dioxide/n$^+$-silicon/p-silicon/chemically treated metallurgical silicon (recrystallized)/graphite have AMI efficiencies of up to 5.5%.

TLC;13
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS

MAJOR PROBLEMS

- Iron concentration in metallurgical silicon not appreciably lowered by the chemical treatment of the melt.
- Non-uniform structural characteristics of unidirectionally solidified metallurgical silicon.
- Formation of large area low-resistance grid contact to the non-planar surface of solar cells.

TLC;14
8/76

POLYCRYSTALLINE SILICON SOLAR CELLS

PLANNED ACTIVITY FOR NEXT SIX MONTHS

- Improvement of the preparation of metallurgical silicon substrates.
- Deposition and characterization of silicon films on metallurgical silicon substrates.
- Measurement of grain boundary properties.
- Fabrication and characterization of solar cells.

TLC;15
8/76

EPITAXIAL SILICON TECHNOLOGY FOR LOW-COST SOLAR CELLS

NATIONAL SCIENCE FOUNDATION

NSF GRANT AER74-15532

1 MAY 1975 to 30 April 1976
$160,000

R. V D'Aiello
RCA LABORATORIES
PRINCETON, NEW JERSEY 08540

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and
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YASHIVA UNIVERSITY
NEW YORK, NEW YORK 10033

Presented at the NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

August 3-6, 1976

UNIVERSITY OF MAINE at ORONO
ORONO, MAINE 04473

EPITAXIAL SILICON TECHNOLOGY FOR LOW COST SOLAR CELLS

ABSTRACT

The major objective of this program was to demonstrate a means of improving the quality of solar cell devices by the use of thin epitaxial layers grown on EFG ribbon silicon. The role of specific defects contained in the EFG ribbon in relation to cell performance was to be examined.

The first portion of this program was devoted to a study of the improvements in material quality and electrical characteristics obtainable by the growth of epitaxial layers on presently available EFG ribbon silicon. Comparative studies were made of solar cells and small area diodes fabricated by epitaxy and by direct diffusion into similar quality ribbon to establish the improvements obtainable..

The epitaxial structures have incorporated an in situ grown n-p junction, as well as an impurity gradient in the base region to provide a drift field for enhanced carrier transport to the junction.

Analytical studies, X-ray topography, EBIC-SEM and electrical characterization, of the defect structure in these devices were conducted to establish the relative importance of the defects which adversely affect cell performance.

Our most recent efforts were directed towards an understanding of the causes and towards methods of improving the poor performance of cells containing specific defects. Gettering techniques and surface etching treatments were applied to the ribbon prior to epitaxial growth or diffusion formation of the solar cell structures.

The major results and conclusions of our study are:

1. Epitaxial layers grown on EFG silicon ribbon substrates exhibit improved metallurgical and electrical quality.

2. Epitaxial layers of ∿ 50 μm are adequate to produce 10% (AM-1) efficient solar cells.

3. Epitaxial solar cells typically yield about 20% higher output than cells made by direct diffusion into EFG material.

4. Defects in EFG ribbon effect cell performance.
    a. SiC inclusions - severe, high; leakage, low F.F.
    b. Grain boundaries - moderate-severe, high R_s, lower J_{sc}
    c. Twins - relatively harmless.

5. Gettering and surface etching are effective in improving solar cell performance. These treatments results in less sensitivity to the effects of grain boundaries and SiC inclusions.

Experiments were conducted to determine whether etching of the surface of the ribbon prior to use (in direct diffusion or epitaxy) reduced the impact of the inclusions on the cell performance. Some improvement was noted, but more experimental work is needed concerning this aspect of the problem. In particular, high-temperature gettering processes prior to use may be advantageous in this regard by possibly leaching out the "lifetime killers" in the vicinity of the inclusions.

While the potential economic impact of improved solar cells on ribbon substrates using epitaxy is clear, accurate estimates are not possible on the basis of the one-year program described here. First, one needs to know what constitutes reproducible-quality ribbon silicon and what its cost would be. The cell yield would have to be known to establish a cost. Second, using such material the additional cost of epitaxial deposition would have to be weighed against the improved cell yield in order to evaluate the economic benefits of using epitaxy. Of course, the epitaxial equipment which would be used for such cell production would differ radically from the conventional equipment now in use, which was designed to process relatively small devices (e.g., transistors, integrated circuits). Since the inherent chemical costs do not constitute the limiting cost factor in epitaxy, the design of special high-capacity equipment would represent an essential feature of any economical attempt to exploit the benefits of epitaxial solar cells for low-cost terrestial applications.

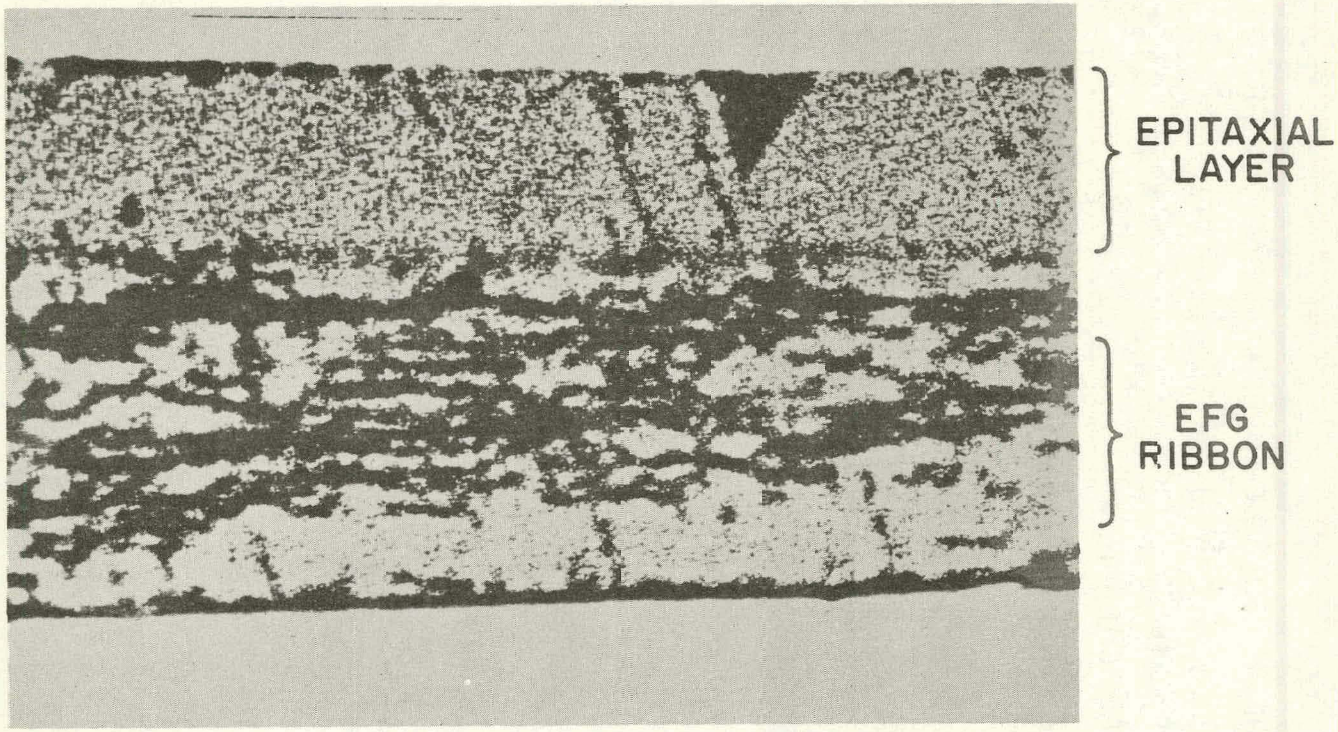
OVERALL OBJECTIVE

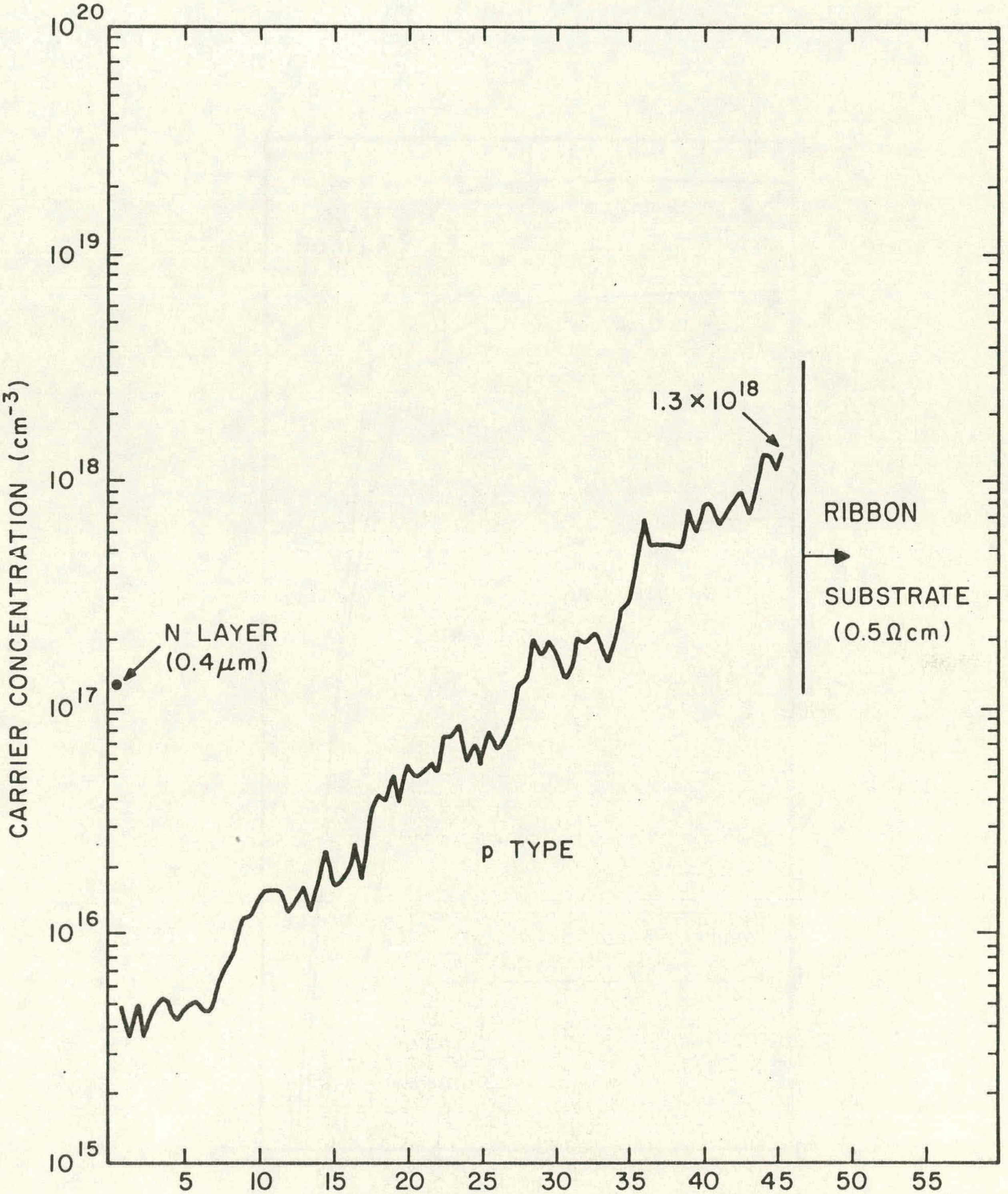
The major objective of this program was to demonstrate a means of improving the quality of solar cell devices fabricated by the use of thin epitaxial layers deposited on EFG "ribbon" silicon. The program encompassed analytical studies aimed at relating defects in the EFG ribbon to solar cell performance, and the fabrication of solar cells on a comparative basis, i.e.: direct diffusion vs. epitaxial growth on ribbon of similar quality.

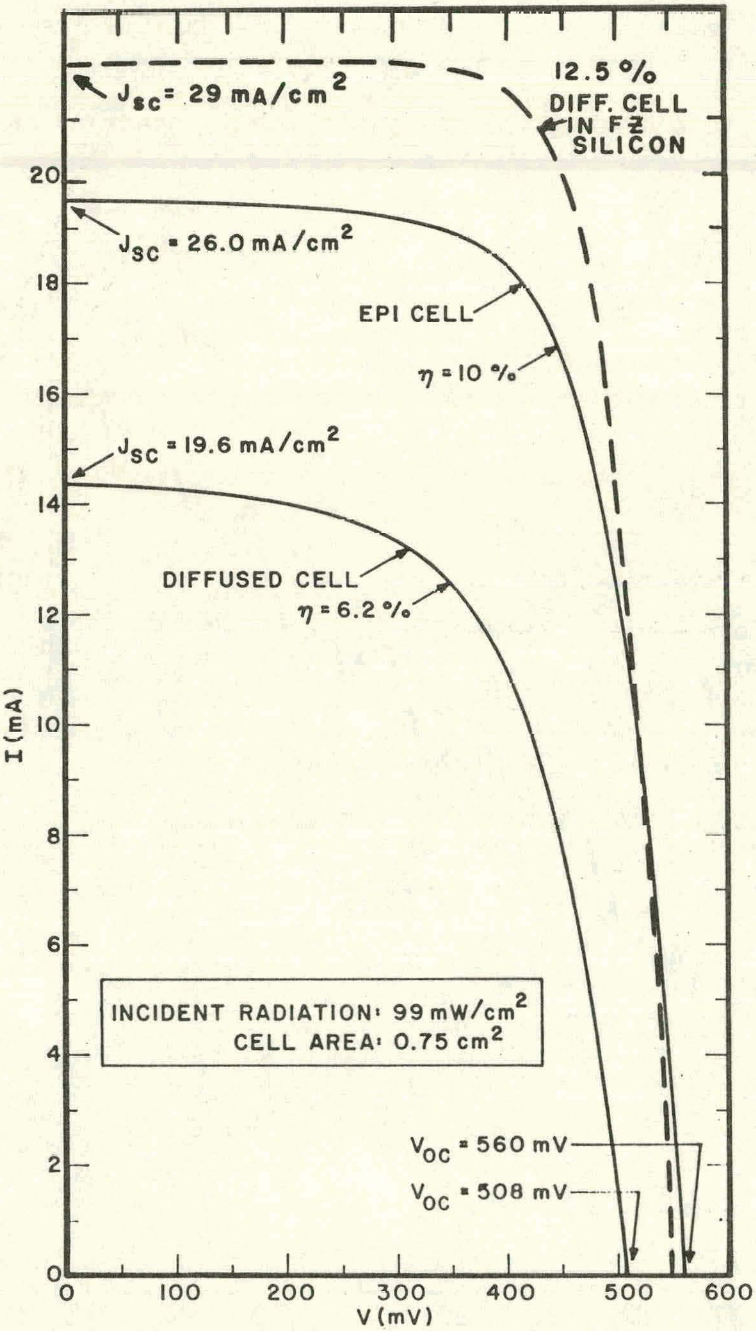
ACTIVITIES - JANUARY '76 to APRIL '76 (end of contract)

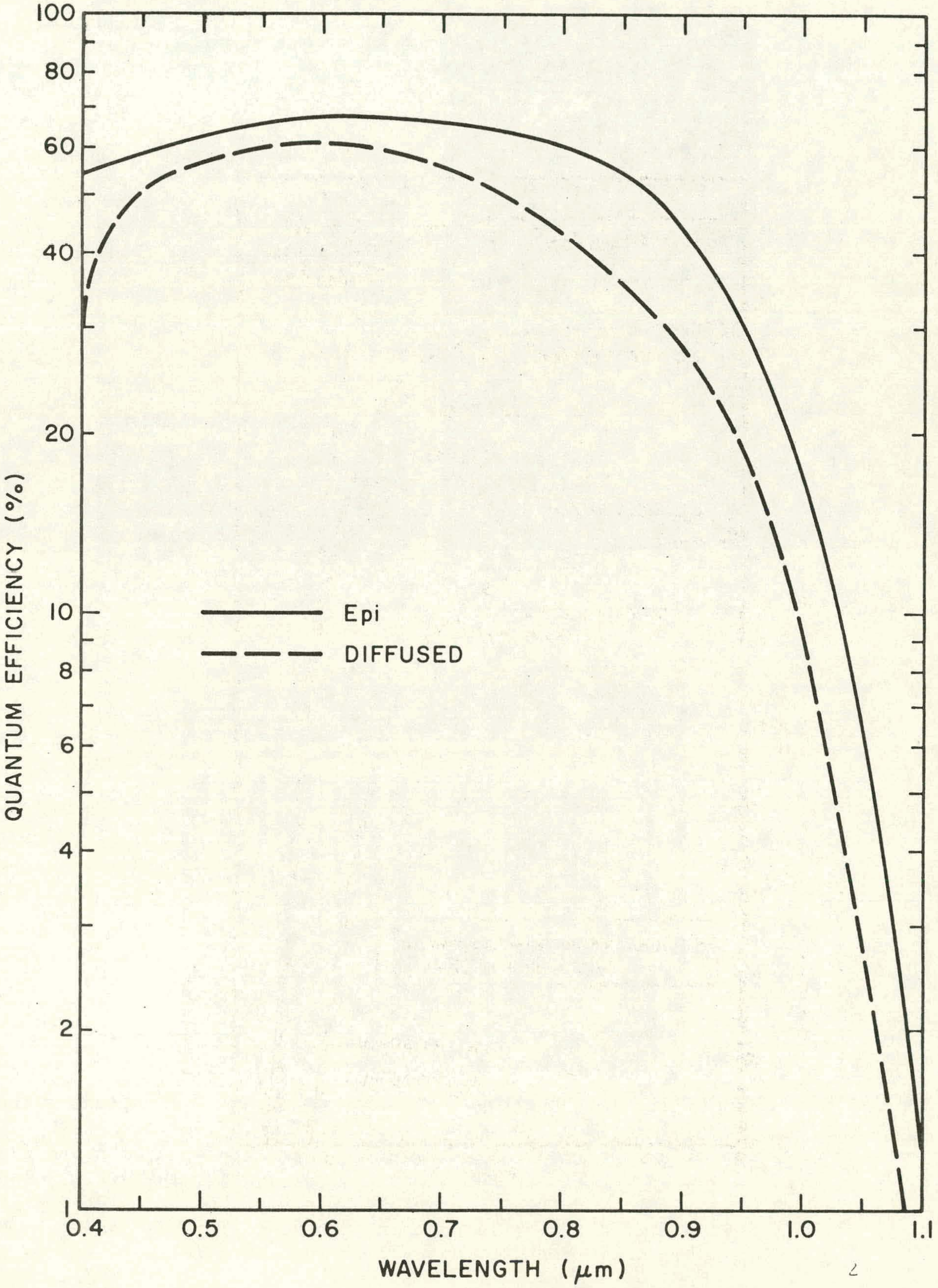
1. Solar cell structures - comparative gettering and surface etching studies of epitaxial and diffused structures on EFG ribbon.

2. Effect of major defects on cell performance SEM(EBIC), X-ray topography and electrical characteristics.
   a. Boundary effects
   b. Effect of inclusions

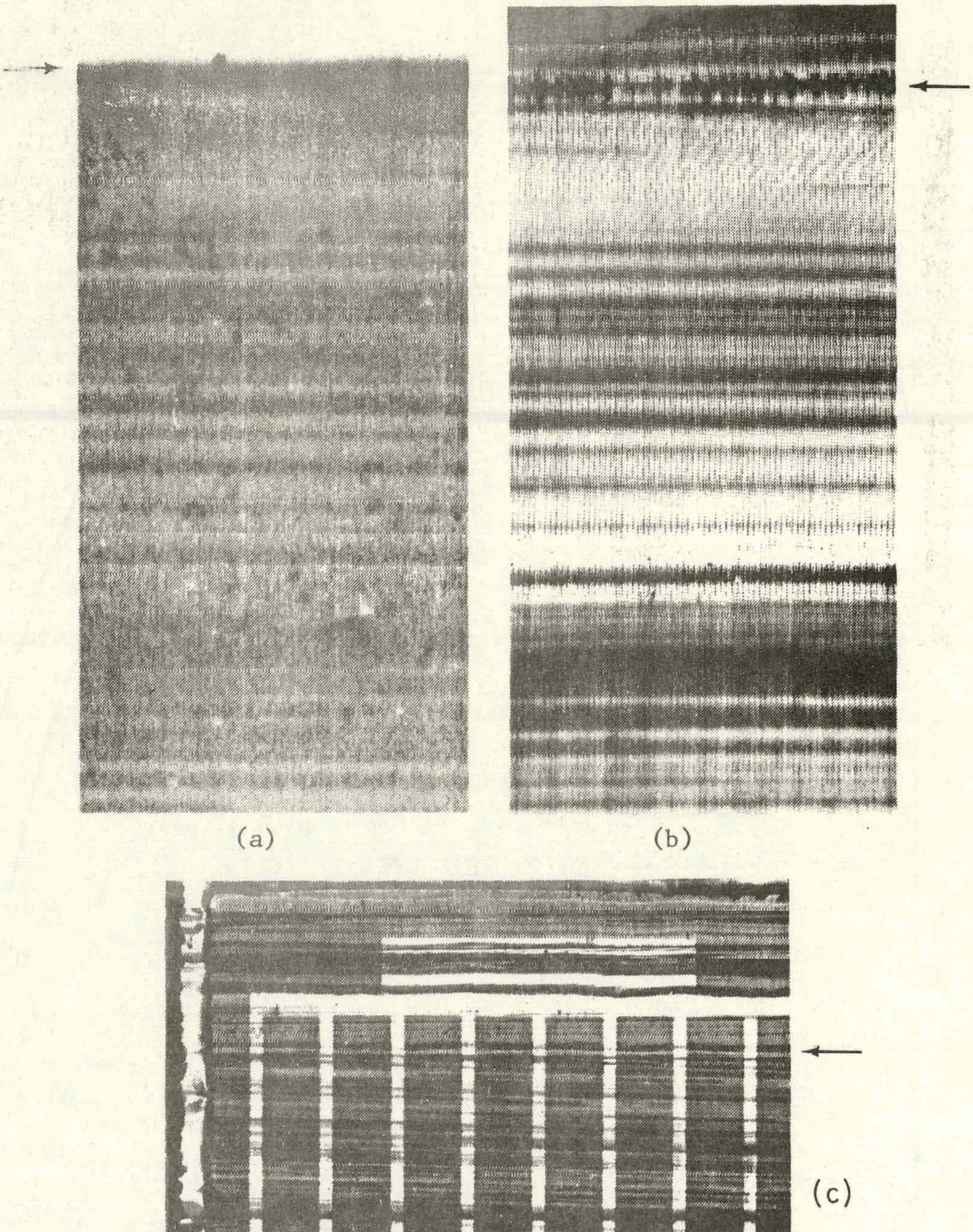

EPITAXIAL LAYER
EFG RIBBON


10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
CARRIER CONCENTRATION (cm^{-3})
N LAYER
($0.4 \mu m$)
1.3×10^{18}
RIBBON
SUBSTRATE
($0.5 \Omega cm$)
p TYPE
5
10
15
20
25
30
35
40
45
50
55
DISTANCE FROM THE SURFACE (μm)

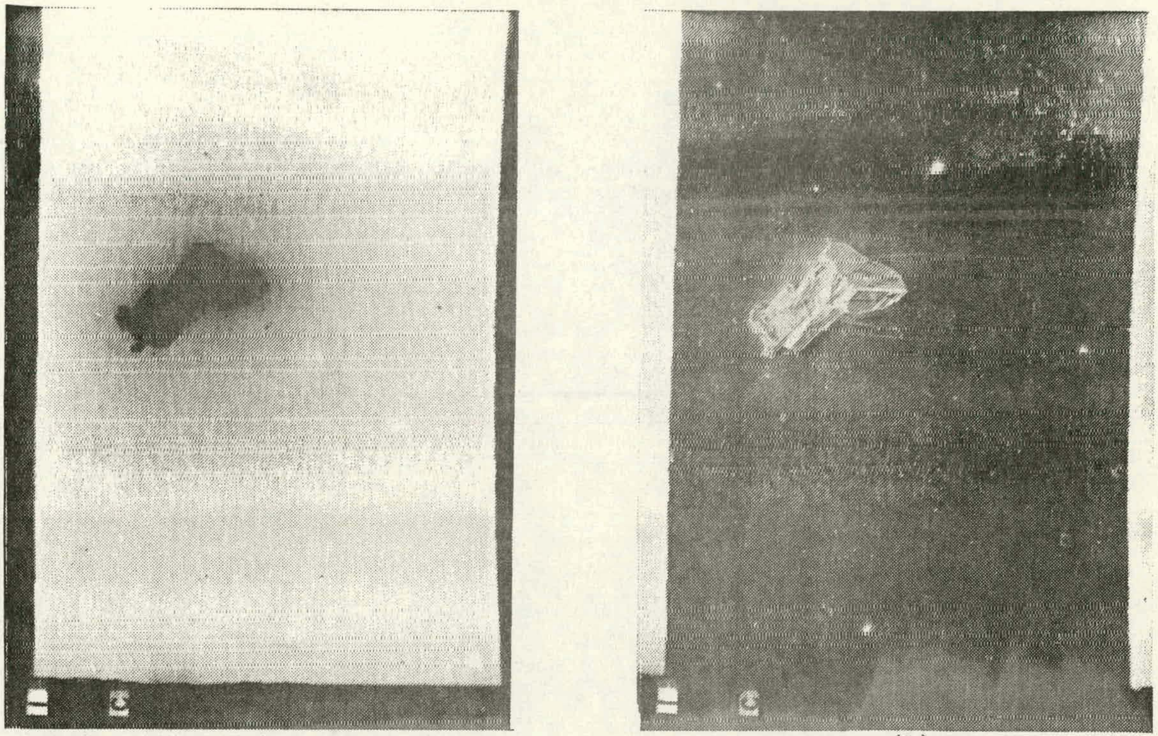

J_{sc} = 29 mA/cm^2
12.5 %
DIFF. CELL IN FZ SILICON
J_{sc} = 26.0 mA/cm^2
EPI CELL
η = 10 %
J_{sc} = 19.6 mA/cm^2
DIFFUSED CELL
η = 6.2 %
INCIDENT RADIATION: 99 mW/cm^2
CELL AREA: 0.75 cm^2
V_{OC} = 560 mV
V_{OC} = 508 mV
I (mA)
0
2
4
6
8
10
12
14
16
18
20
V (mV)
0
100
200
300
400
500
600


100
80
60
40
20
10
8
6
4
2
1
QUANTUM EFFICIENCY (%)
Epi
DIFFUSED
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
WAVELENGTH (μm)

2

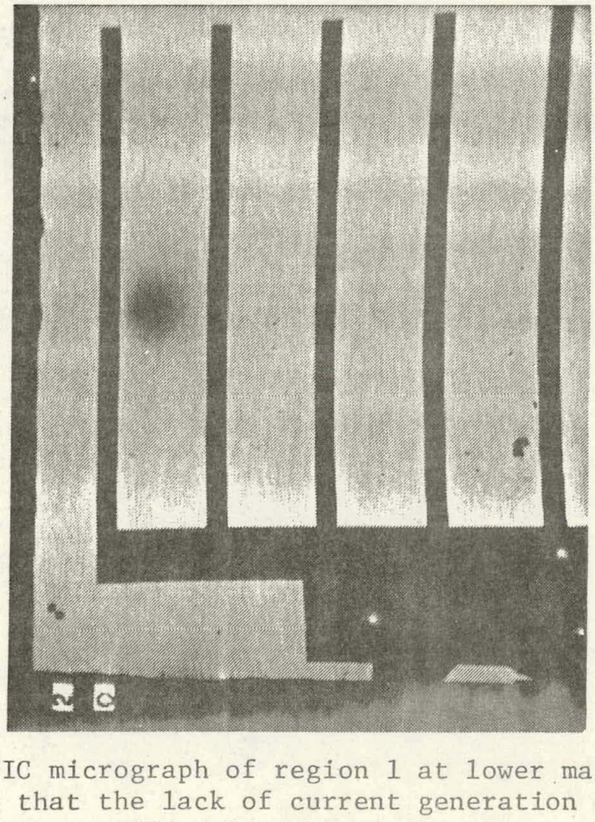


(a) Reflection topograph, (b) EBIC scan, and (c) optical micrograph of silicon ribbon solar cell. The regions of strain (dark bands) on the reflection topograph correlate well with the regions of low current (dark bands) on the EBIC scan. The grain boundary is indicated by the arrow in each picture. The complete solar cell pictured in (c) is adjacent to the cell in (a) and (b), but the same grain boundary extends through both cells.

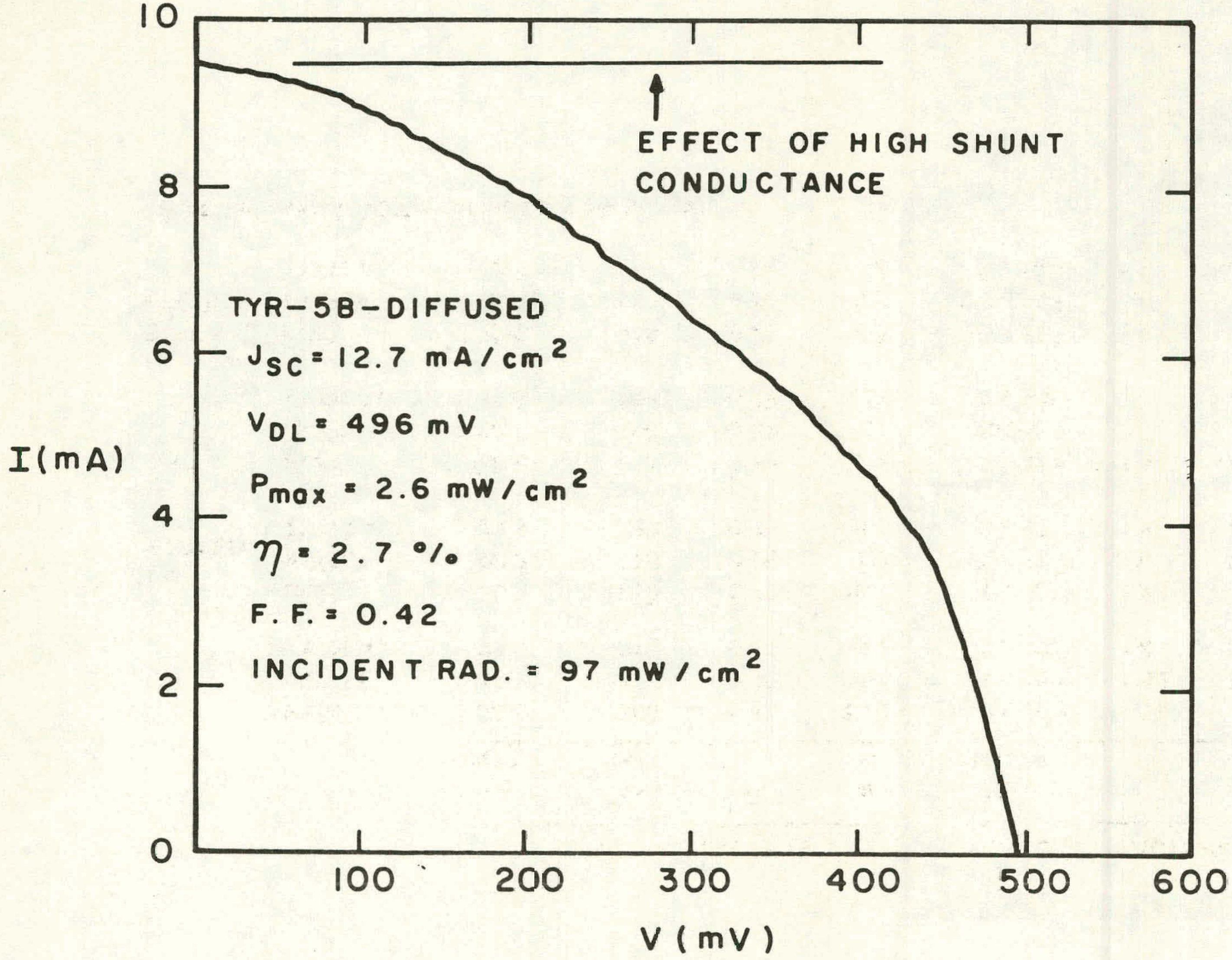


(a) (b)

Scanning electron micrographs of region 1.
(a) EBIC mode, (b) secondary electron emission.



SEM, EBIC micrograph of region 1 at lower magnification, showing that the lack of current generation extends into regions surrounding the inclusion.


10
8
6
4
2
0
I(mA)
100
200
300
400
500
600
V (mV)
EFFECT OF HIGH SHUNT CONDUCTANCE
TYR-5B-DIFFUSED
J_{SC} = 12.7 mA/cm^2
V_{DL} = 496 mV
P_{max} = 2.6 mW/cm^2
η = 2.7 %
F. F. = 0.42
INCIDENT RAD. = 97 mW/cm^2

		AM-1 PARAMETERS				DIODE CHARACTERISTICS		
		J_{sc} mA/cm^2	V_{oc} mV	F.F.	η %	J_{SAT} A/cm^2	n —	τ μs
EPI	BEST	26.0	560	0.70	10.0	2×10^{-9}	1.36	1.1
	WORST*	21.1	425	0.44	4.1	1×10^{-7}	1.62	0.4
	TYPICAL	24.0	510	0.64	8.1	3×10^{-8}	1.44	0.5
EPI ETCHED	BEST	25.2	550	0.70	10.1	1×10^{-9}	1.22	0.5
	WORST*	23.0	525	0.55	7.0	1×10^{-6}	2.0	0.3
	TYPICAL	24.5	530	0.65	8.7	6×10^{-9}	1.3	0.4
DIFF.	BEST	20.5	515	0.72	7.2	3×10^{-8}	1.6	~0.2
	WORST*	16.1	390	0.32	2.1	HIGH	~2	—
	TYPICAL	19.6	510	0.62	6.2	2×10^{-7}	1.7	~0.2
DIFF. ETCHED	BEST	22.2	518	0.73	8.3	9×10^{-9}	1.4	~0.2
	WORST*	19.0	500	0.63	6.2	6×10^{-5}	1.6	—
	TYPICAL	20.7	512	0.70	7.6	2×10^{-8}	1.5	~0.2

*Worst cells usually contain at least one SiC particle.

SUMMARY OF KEY RESULTS (OVERALL PROGRAM)

1. Epitaxial layers grown on EFG silicon ribbon substrates exhibit improved metallurgical and electrical quality.

2. Epitaxial layers of ~50 μm are adequate to produce 10% (AM-1) efficient solar cells.

3. Epitaxial solar cells typically yield about 20% higher output than cells made by direct diffusion into EFG material.

4. Defects in EFG ribbon effect cell performance
    a. SiC inclusions - severe, high, leakage, low F. F.
    b. Grain boundaries - moderate-severe, high R_s, lower J_{sc}
    c. Twins - relatively harmless

5. Cost comparison not clear since performance vs. system cost difficult at this time.

CHEMICAL VAPOR DEPOSITION GROWTH

Silicon Sheet Growth Development
for
Task 2: Large Area Silicon Sheet
of the
Low Cost Silicon Solar Array Project

U. S. Energy Research and Development Administration
Division of Solar Energy

JPL Contract No. 954372

Period of Contract: December 29, 1975 - June 30, 1977

Value: $269,000

This work is being performed for the Jet Propulsion Laboratory,
California Institute of Technology, under NASA
Contract NAS7-100, for ERDA

H. M. Manasevit

Co-principal Investigator

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Electronics Research Division
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R. P. Ruth, Co-principal Investigator and Program Manager

Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976

University of Maine at Orono

Orono, Maine 04473

The purpose of this 18-month contract, which started December 29, 1975, is to explore the chemical vapor deposition (CVD) method for the growth of Si sheet on inexpensive substrate materials for future terrestrial solar-cell applications. The work is carried out at the Rockwell Electronics Research Division in Anaheim, but also involves experimental solar cell fabrication and evaluation by the Photoelectronics Group of Optical Coating Laboratory, Inc., (OCLI) in City of Industry, California.

The objective of the contract is development of CVD techniques for producing large areas of Si sheet on inexpensive substrate materials, with sheet properties suitable for fabricating solar cells meeting the technical goals of the Low Cost Silicon Solar Array Project (LCSSAP). The techniques developed are to be directed toward minimum-cost processing, production of sheet having properties adequate to result in cells with terrestrial array efficiency of 10% or more, and eventual scale-up to large-quantity production.

The specific technical goals established for the contract include the following:

Si sheet area (per sample)	30 cm^2
Si sheet deposition rate	5 μm per min
Si sheet thickness	20 to 100 μm
Si sheet crystal structure	100 μm average grain size
Intragrain dislocation density	$<10^4$ per cm^2

The principal studies in the program are (1) establishing preferred CVD process parameters (temperature, reactant concentrations, carrier gas composition, doping impurities, growth rate) for optimized intragrain properties for the Si sheet grown on various substrate materials; (2) identifying suitable substrate materials that will survive the environment of the CVD process and be potentially inexpensive and available in large areas, yet be as favorable as possible to Si grain growth; and (3) achieving adequate grain size in the Si sheet to provide satisfactory solar cell properties.

The contract program is structured in terms of six main technical tasks, as follows: (1) modification and test of an existing CVD reactor system; (2) identification and/or development of suitable inexpensive substrate materials; (3) experimental investigation of CVD process parameters using various candidate substrate materials; (4) preparation of Si sheet samples for various special studies, including solar cell fabrication; (5) evaluation of the properties of the Si sheet material produced by the CVD process; and (6) fabrication and evaluation of experimental solar cell structures by OCLI, using standard and near-standard processing techniques. The first task has been completed, and others are in progress.

Many glass and ceramic manufacturers have supplied specially-prepared as well as commercially available materials for evaluation as low cost substrates. Si growth in He atmospheres on Corning Code 1715 glass has resulted in polycrystalline films with {100} and/or {110} preferred orientations, depending upon the deposition temperature in the 850-1000°C range. Encouraging results have also been obtained for films grown on glasses supplied by Owens-Illinois (GS211 and GS213). However, the glasses examined to date do not tolerate a H_2 atmosphere for Si growth at temperatures $>850^{\circ}C$. The high purity polycrystalline aluminas, on the other hand, have proved to be useful substrates for Si-growth in H_2 at $\gtrsim$1025°C. Aluminas from Coors with enlarged grains resulting from special supplementary firing procedures beyond those used in normal commercial processing have led to films containing grain dimensions as large as 200μm. In these experiments simultaneous Si growth on sapphire has been used for obtaining baseline data and for detecting the presence of contamination from companion substrates.

Undoped and B-doped films are presently being grown using both SiH_4 (in both He and H_2 atmospheres) and SiH_4-HCl mixtures. The latter studies will be used in experiments to influence the early stages of growth of the Si films and thus the ultimate properties of the resulting sheet materials. In addition, experiments have been initiated to study early growth phenomena on composite substrates consisting of thin deposited metal films on glass.

Various film characterization procedures — including SEM analyses, x-ray diffraction analyses, surface profilometry, and electrical measurements (resistivity, carrier concentration, mobility, spreading resistance profiles) -- have been used to correlate Si sheet properties with CVD parameters and substrate properties.

Si sheet samples have been submitted to OCLI for solar cell processing and measurement of photovoltaic performance. The most recent results obtained with layers B doped during deposition indicate that methods other than diffusion doping for junction formation - such as sequential impurity doping during film growth or ion implantation doping - may have to be used with these polycrystalline Si films to exploit their potential for low-cost large-area solar cell fabrication.

CHEMICAL VAPOR DEPOSITION GROWTH

Silicon Sheet Growth Development

(Task 2, JPL LCSSAP)

Process Description

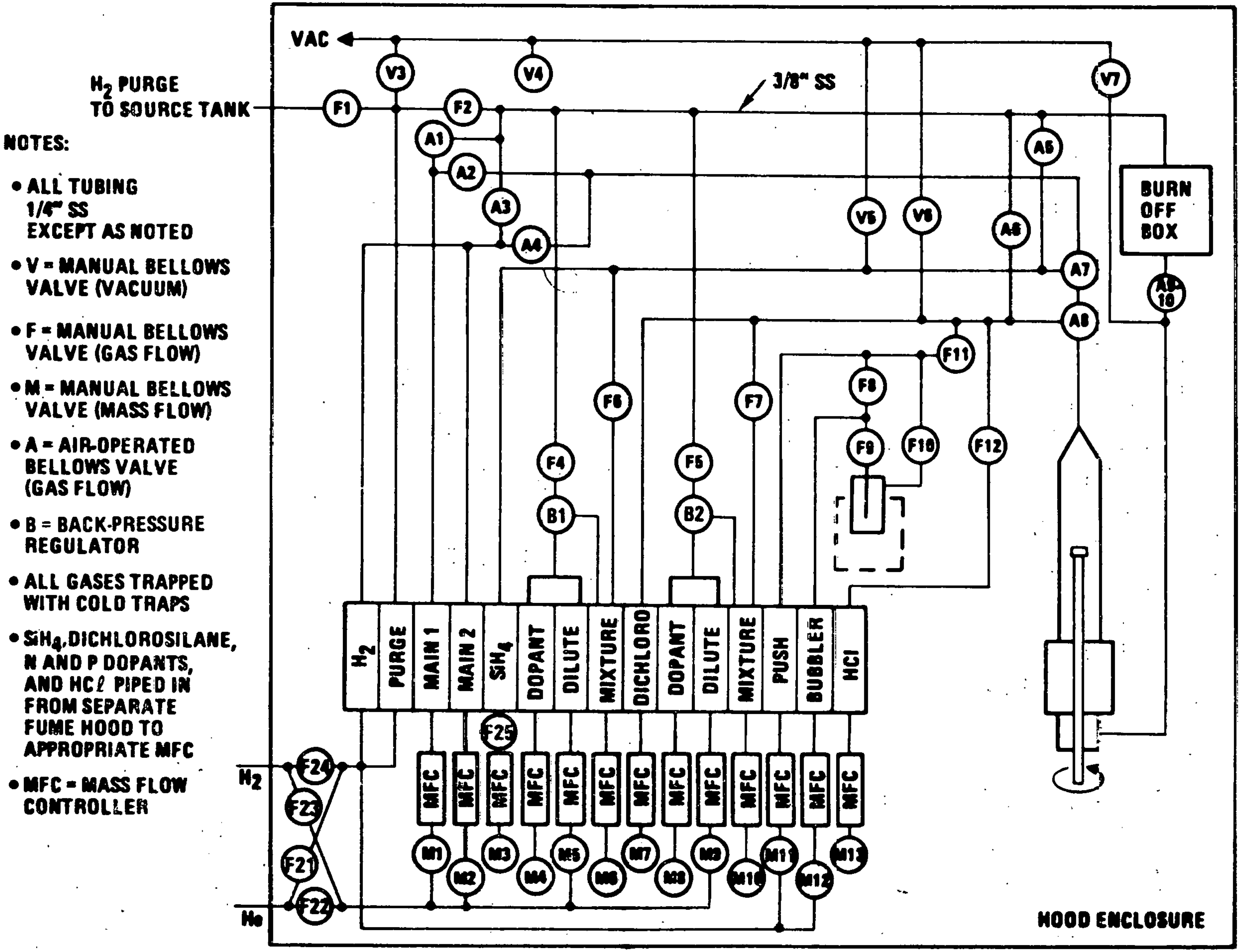
Chemical vapor deposition (CVD) of Si on potentially low-cost substrate materials, utilizing flow-through (open-tube) apparatus to transport appropriate Si compound by carrier gas to reactor chamber in which substrate is supported on rotating RF-heated pedestal. Pyrolysis reaction involving Si compound produces Si deposit. Properties of Si depend upon deposition temperature, growth rate, substrate properties, Si source compound, carrier gas, impurity doping compounds, and other factors.

Program Goals

Si Sheet Area (per Sample)	30 cm^2
Film Deposition Rate	5µm per Min.
Sheet Thickness	20 to 100µm
Si Sheet Crystal Structure	100µm Average Grain Size
Intragrain Dislocation Density	$<10^4$ per cm^2

TECHNICAL TASKS/ACTIVITIES

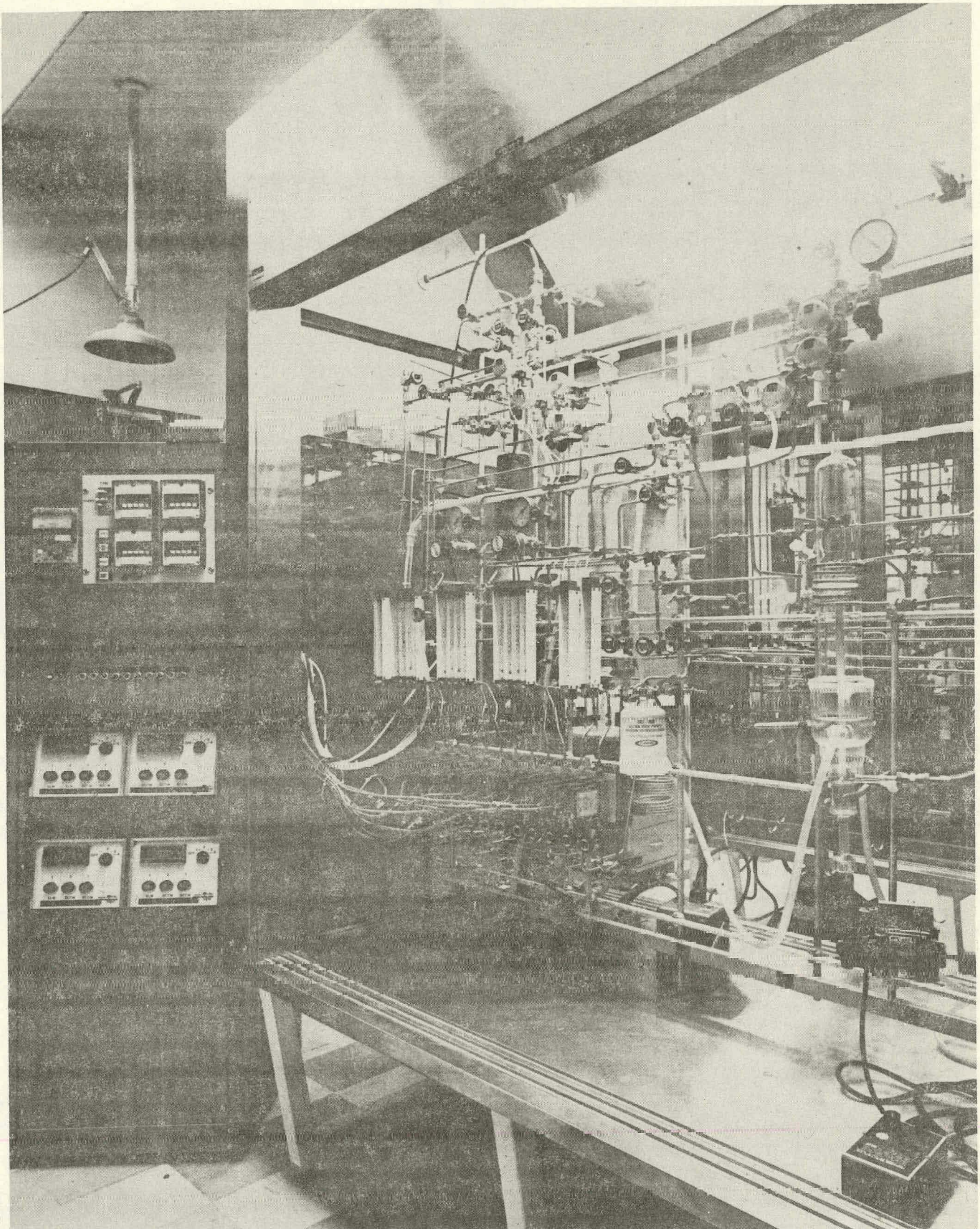
1. MODIFICATION AND TEST OF EXISTING CVD REACTOR SYSTEM
2. IDENTIFICATION/DEVELOPMENT OF SUITABLE SUBSTRATE MATERIALS
3. EXPERIMENTAL INVESTIGATION OF SI CVD PROCESS PARAMETERS
4. PREPARATION OF SI SHEET SAMPLES
5. EVALUATION OF SI SHEET MATERIAL PROPERTIES
6. FABRICATION AND EVALUATION OF SOLAR CELL STRUCTURES



NOTES:

- ALL TUBING 1/4" SS EXCEPT AS NOTED
- V = MANUAL BELLOWS VALVE (VACUUM)
- F = MANUAL BELLOWS VALVE (GAS FLOW)
- M = MANUAL BELLOWS VALVE (MASS FLOW)
- A = AIR-OPERATED BELLOWS VALVE (GAS FLOW)
- B = BACK-PRESSURE REGULATOR
- ALL GASES TRAPPED WITH COLD TRAPS
- SiH_4, DICHLOROSILANE, N AND P DOPANTS, AND HCℓ PIPED IN FROM SEPARATE FUME HOOD TO APPROPRIATE MFC
- MFC = MASS FLOW CONTROLLER

Figure 2-2. Schematic Diagram of Modified Si CVD Reactor System



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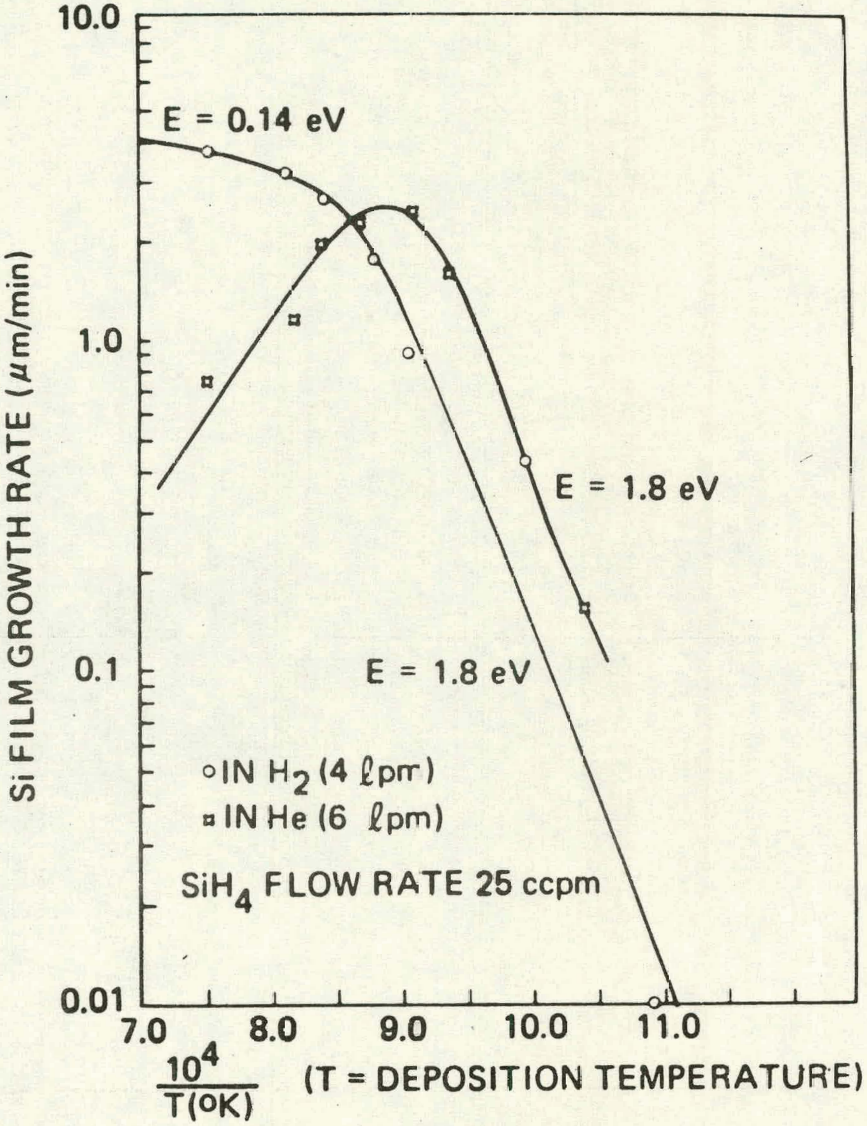
Si FILM DEPOSITION ON (01$\bar{1}$2) SAPPHIRE SUBSTRATES AS FUNCTION OF RECIPROCAL TEMPERATURE FOR SiH_4 PYROLYSIS IN H_2 AND IN He



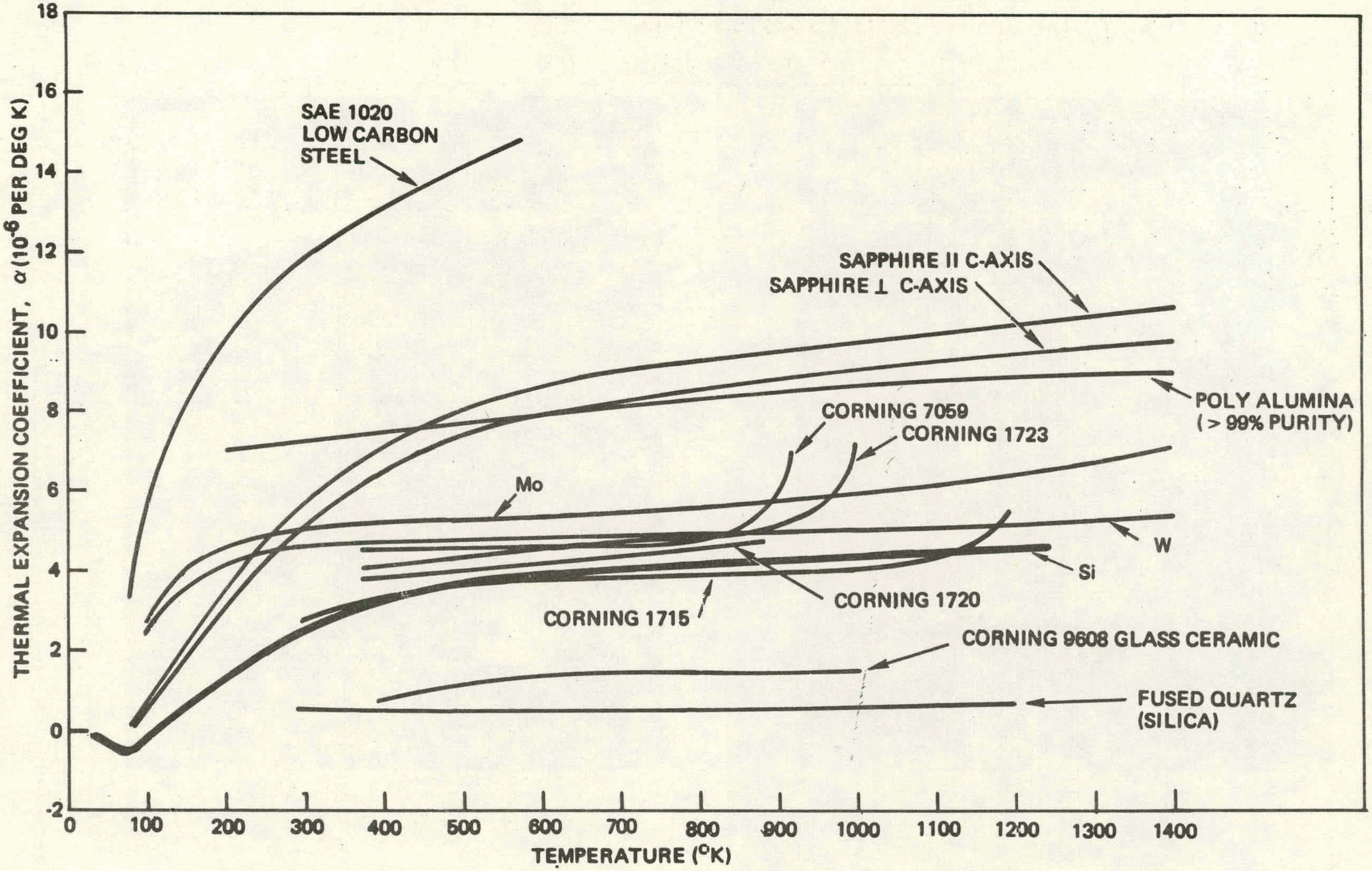
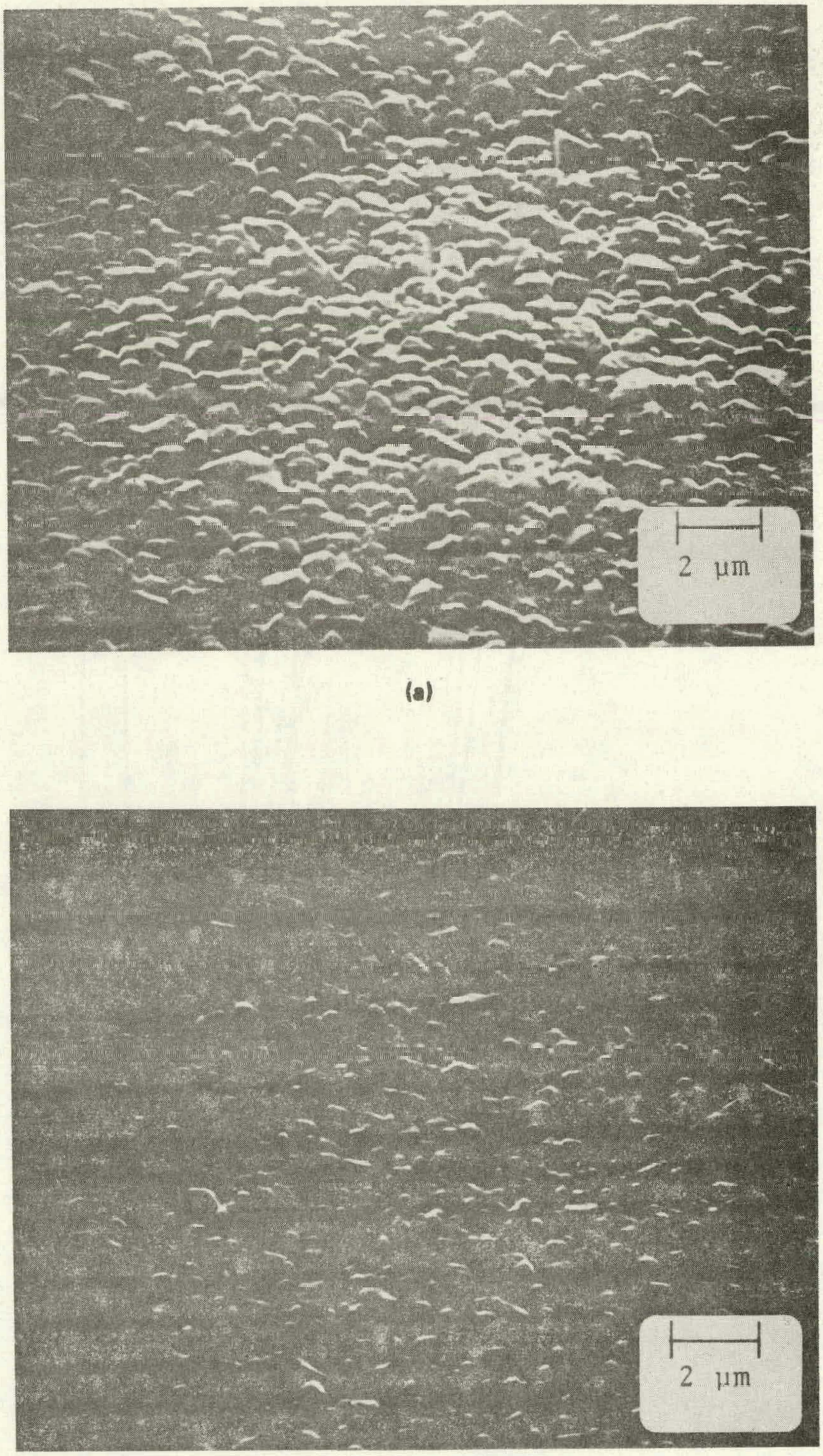


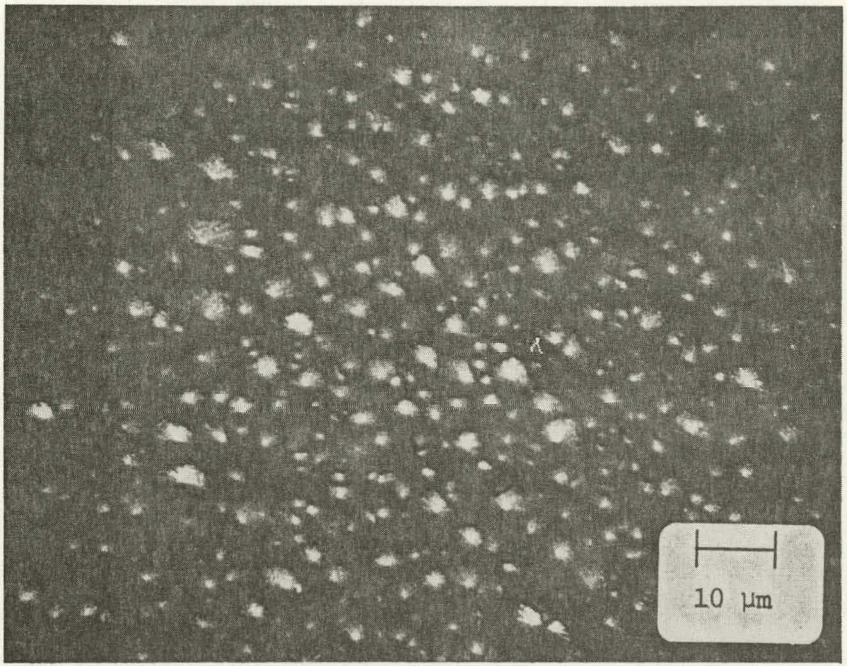
Figure 2-5. Linear Thermal Expansion Coefficients as a Function of Temperature for Si and Various Other Materials



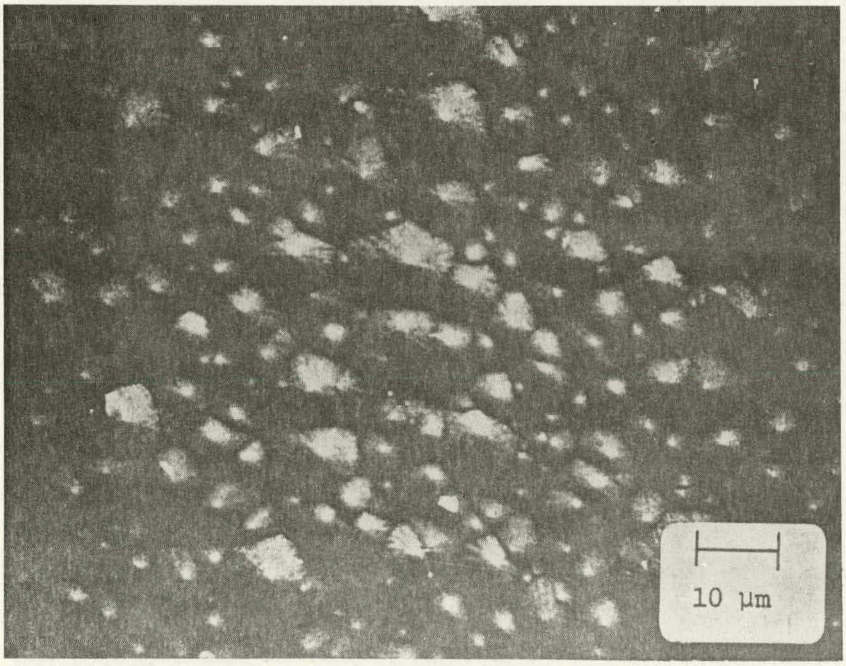
(a)

(b)

Figure 2-9. Surface Morphology of ASM805 Fired Alumina Substrate (3M Co.)
a) Rough Side, b) Smooth Side

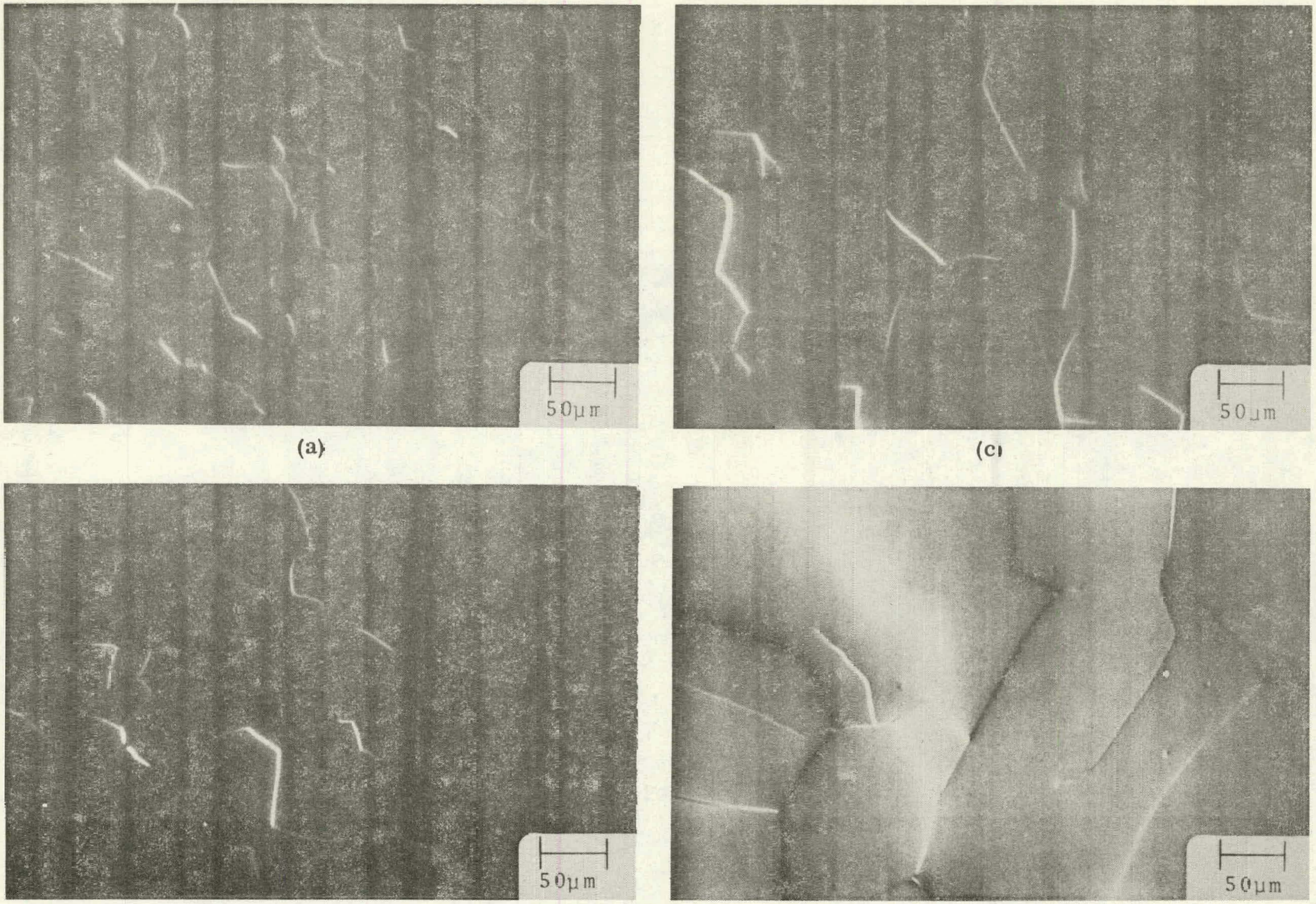


(a)



(b)

Figure 2-19. Rosette Surface Structures on CVD Si Films Grown on ASM805 Substrates in H_2 at ~1025°C at Approximately Equal Rates (>3μm/min). (a) Film Thickness ~ 20μm. (b) Film Thickness ~ 40 μm.



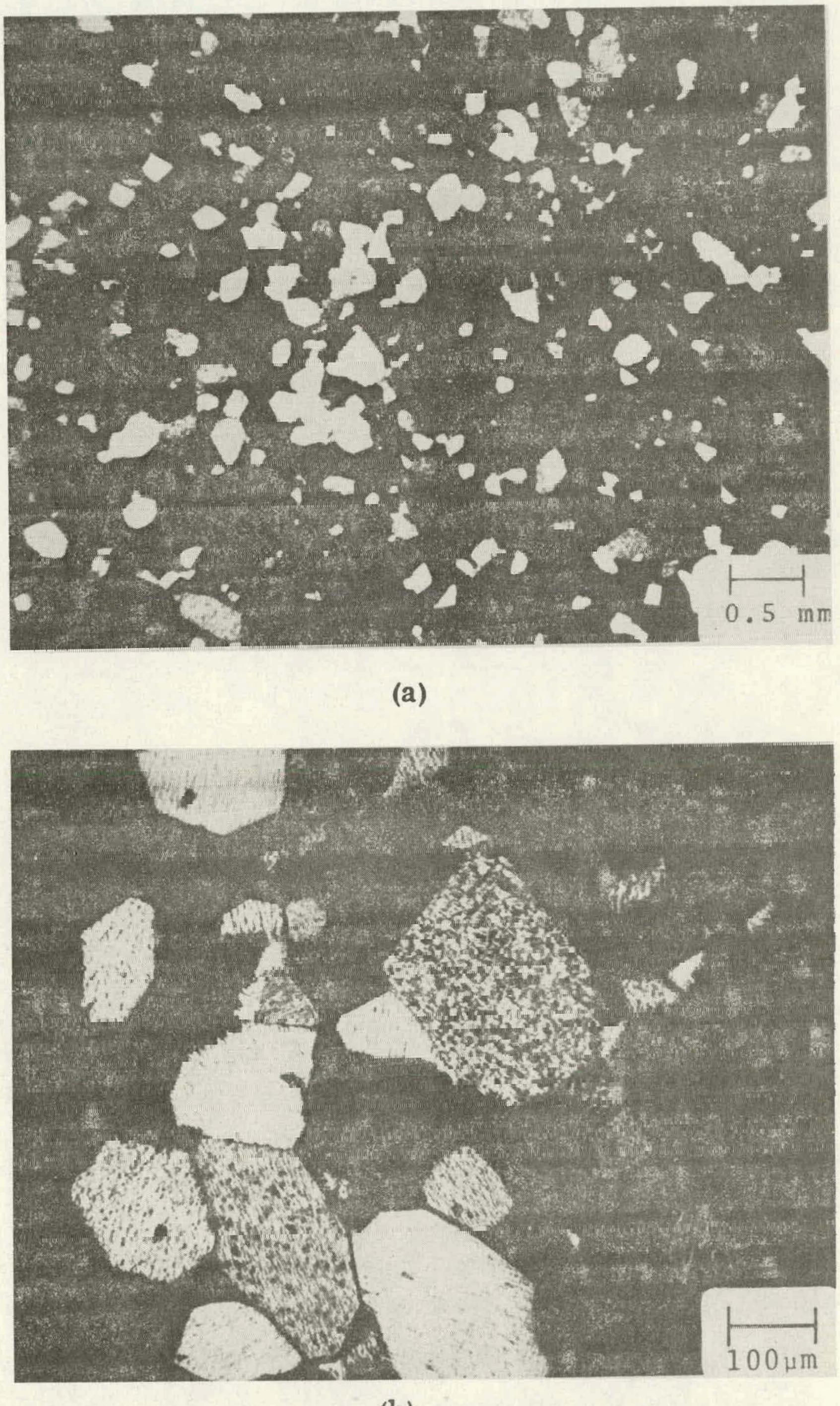
(a)

(c)

(b)

(d)

Figure 2-10. Nomarski Interference-contrast Photomicrographs of Surfaces of Polished Vistal Alumina Substrates of Four Different Firing Histories. (a) Vistal 1 (one firing at >1800°C for 6 hr); (b) Vistal 2 (two consecutive firings); (c) Vistal 3 (three consecutive firings); (d) Vistal 4 (four consecutive firings). (All photographs at normal incidence.)



(a)

(b)

Figure 2-15. Optical Photomicrographs of CVD Si Film on Polished Vistal 4 Polycrystalline Alumina Substrate, at Two Different Magnifications

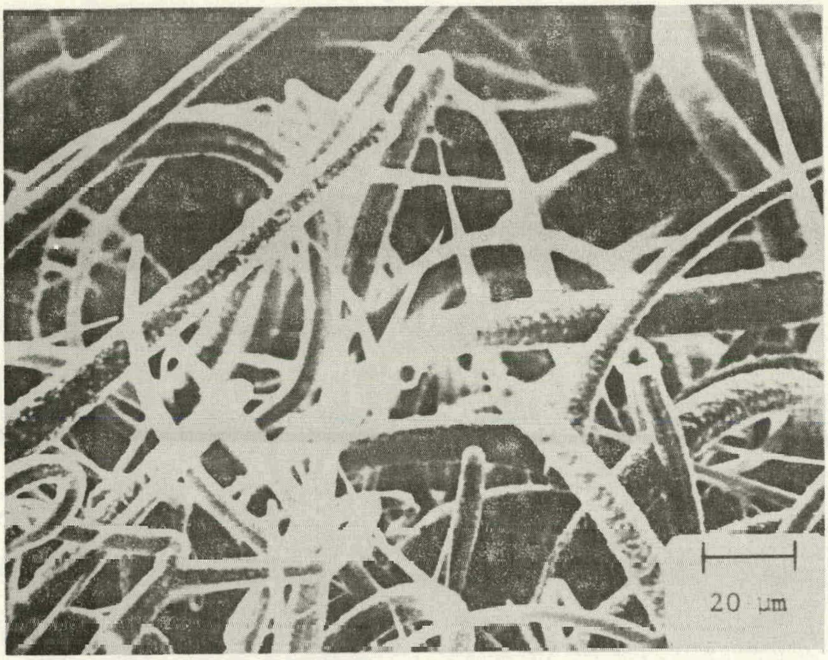


Figure 2-14. SEM Photograph of CVD Si Deposit on OI Glass GS211 at ~850°C in H_2 Atmosphere

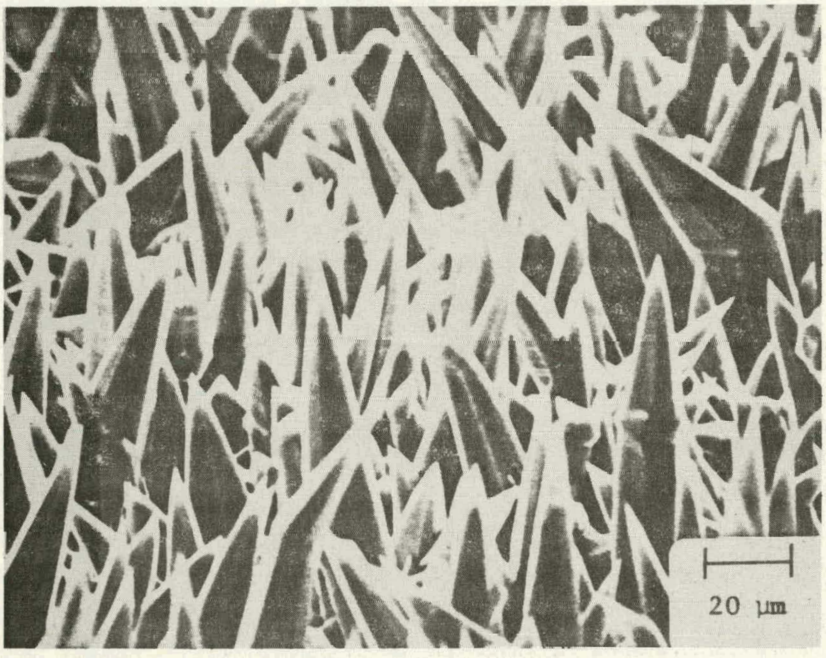


Figure 2-19. SEM Photograph of Whisker-like Deposit of Si on Zircon. Growth by SiH_4 Pyrolysis at 1025°C in H_2 Atmosphere.

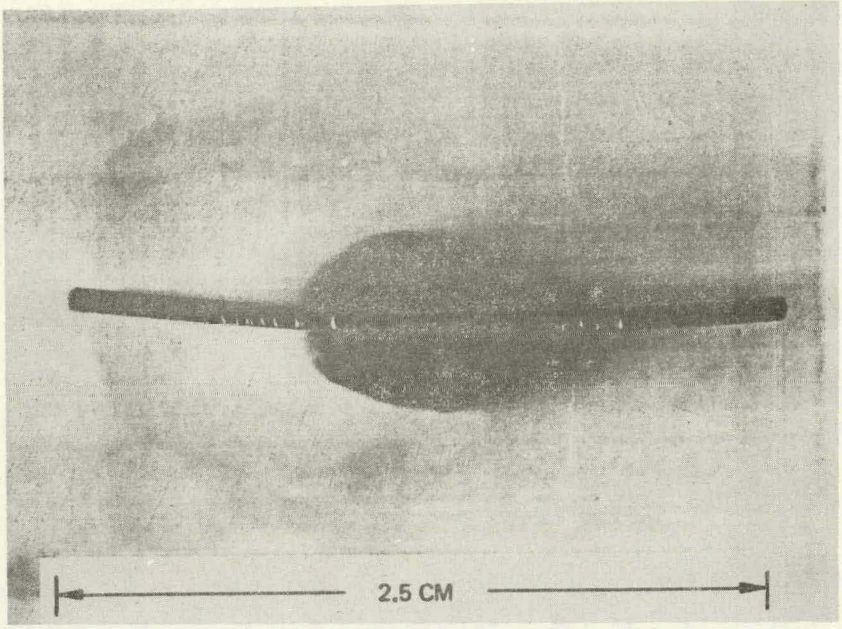


Figure 2-5. Edge View Showing Bowing of Composite of CVD Si on Code 7059 Glass After Deposition in He at 700°C. Si Film on Upper (Concave) Surface

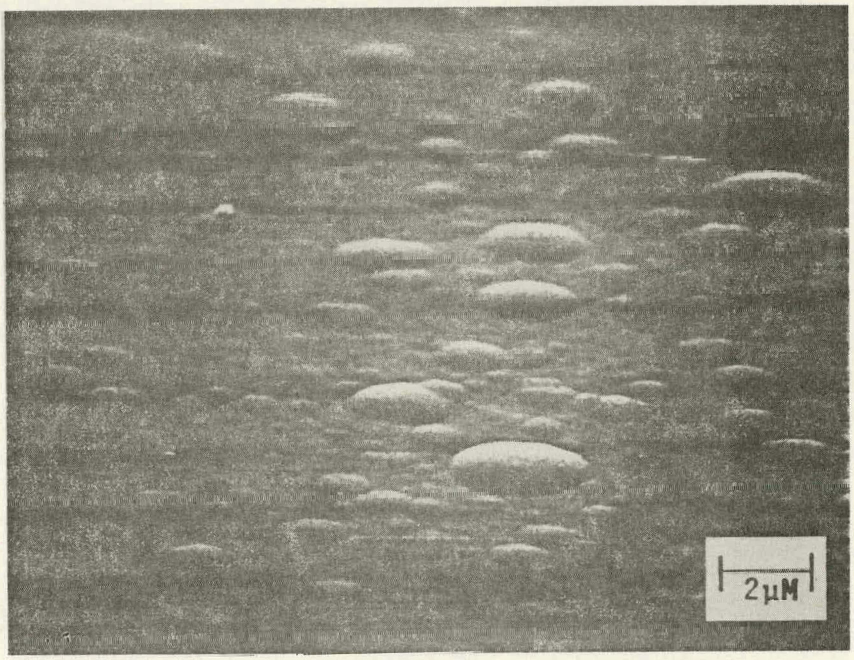


Figure 2-16. Bubbles Formed at Interface of CVD Si Film Grown on Corning Code 1723 Glass Substrate at ~650°C in He

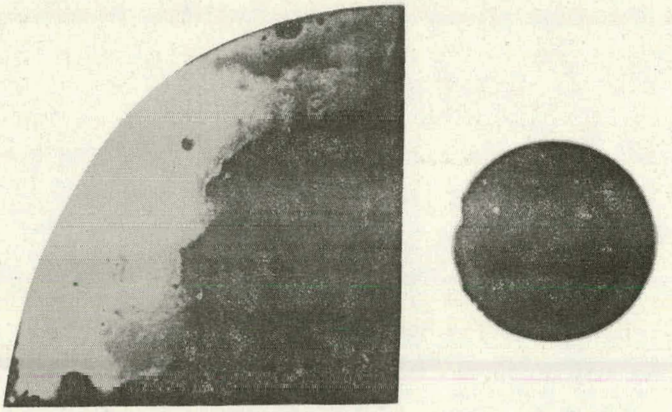


Figure 2-4. Evidence of Contamination of CVD Si Film Growth on Sapphire (Large Wafer) Caused by Nearby Glazed Alumina Substrate (Lead Borosilicate on ASM614) During Deposition in He at 827°C

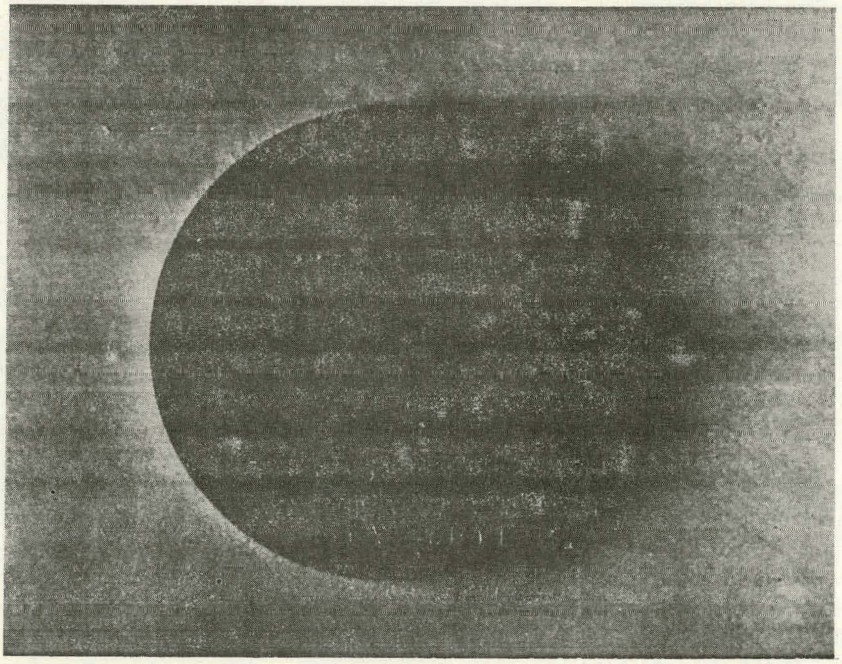
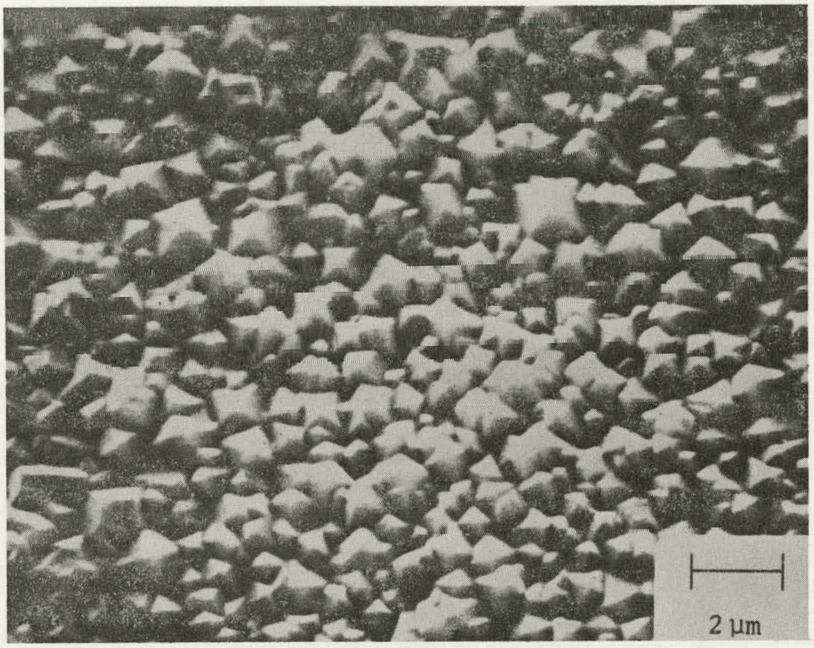
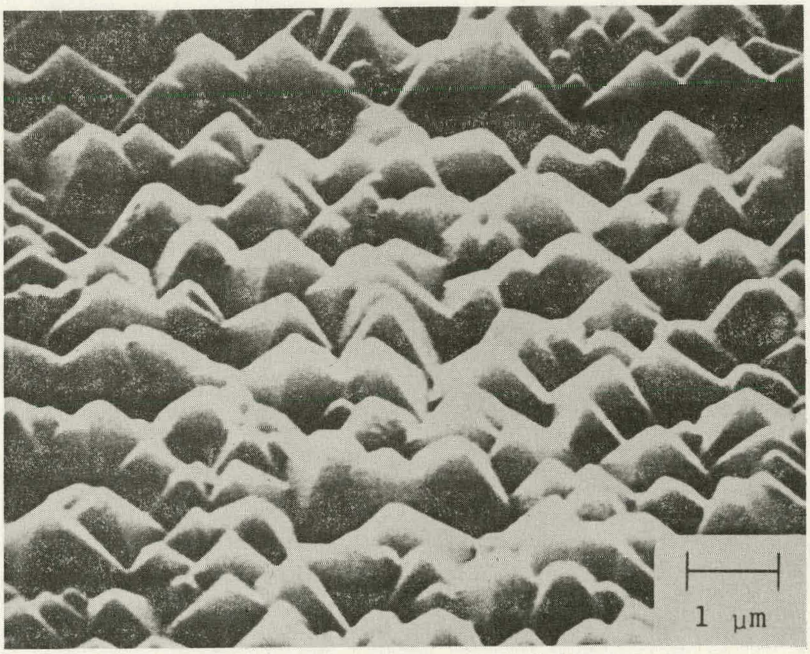


Figure 2-8. Wrinkled CVD Si Film Grown 14 μm Thick on Glazed Alumina Substrate (Lead Borosilicate Glaze 743 on A5M614) in He at 700°C



(a)



(b)

Figure 2-22. SEM Photographs of Surface of CVD Si Film Grown on Corning Code 1715 Glass by SiH_4 Pyrolysis in He at ~860°C.
a) View at Normal Incidence; b) View at 45 deg to Surface

Table 2-9. Electrical Properties of B-doped CVD Si Films Deposited by SiH_4 Pyrolysis in H_2 (4ℓpm) on Single-crystal and Polycrystalline Substrates of α Alumina ($A\ell_2O_3$)

SUBSTRATE MATERIAL AND SURFACE CONDITION	SiH_4 FLOW RATE (ccpm)	B_2H_6-IN-He FLOW RATE (ccpm)	DEPOS TEMP (°C)	APPROX FILM THICK (μm)	RESISTIVITY (ohm cm)		HOLE CONCENTRATION (cm^{-3})		HALL MOBILITY (cm^2/V-sec)	
					van der Pauw	Hall Bridge	van der Pauw	Hall Bridge	van der Pauw	Hall Bridge
(01$\bar{1}$2) sapphire* (polished)	10	8.1	1025	18	0.061	0 052	1.0×10^{18}	9.5×10^{17}	102	125
MRC Superstrate alumina* (as fired)	10	8.1	1025	20	0.76	–	5.0×10^{17}	–	16	–
MRC Superstrate alumina* (polished)	10	8.1	1025	20	0.86	–	4.8×10^{17}	–	15	–
(01$\bar{1}$2) sapphire† (polished)	10	500	1033	25	0.0050	0.012	3.3×10^{19}	1.7×10^{19}	37	31
MRC Superstrate alumina† (polished)	10	500	1033	25	0.0094	–	2.0×10^{19}	–	32	–
3M ASM805 Alumina† (as fired)	10	500	1033	25	0.0087	–	2.4×10^{19}	–	30	–

*These substrates used for simultaneous growth of Si

†These substrates used for simultaneous growth of Si

Table 2-11. B-doped CVD Si Sheet Samples Submitted to OCLI during Second Quarter for Solar Cell Processing and Measurement

SAMPLE NO.	SUBSTRATE MATERIAL AND THICKNESS (μm)	DEPOS. TEMP (°C)	CARRIER GAS AND FLOW RATE (lpm)	SiH_4 FLOW RATE (ccpm)	DOPANT GAS* FLOW RATE (ccpm)	FILM THICKNESS (μm)	AVE. GROWTH RATE (μm/min)	FILM RESISTIVITY (ohm-cm)	HOLE CONCENTRATION (cm^{-3})	HALL MOBILITY (cm^2/V-sec)	SAMPLE DIMENSIONS (cm) AND APPROX AREA (cm^2)	FILM STRUCTURE AND/OR SURFACE TEXTURE
OCLI-9	$(01\bar{1}2)$ Al_2O_3 375	1022	H_2 4	10	0.91	18	1.8	0.26†	1.3×10^{17}†	187†	1.0 x 1.1 1.1	Epitaxial
OCLI-10	$(01\bar{1}2)$ Al_2O_3 300	1025	H_2 4	10	9.1	18	1.8	0.070†	6.1×10^{17}†	145†	1.15 x 1.0 1.15	Epitaxial
OCLI-11	$(01\bar{1}2)$ Al_2O_3 300	1023	H_2 4	10	9.1	20	1.9	0.063†	6.8×10^{17}†	146†	1.0 x 0.9 0.9	Epitaxial
OCLI-12	$(01\bar{1}2)$ Al_2O_3 300	1025	H_2 4	10	9.1	19	1.9	0.052†	9.5×10^{17}†	125†	1.0 x 0.95 0.95	Epitaxial
OCLI-13	MRC Superstrate alumina (as fired) 700	1025	H_2 4	10	9.1	20	2.0	0.76**	5.0×10^{17}**	16**	1.3 x 1.2 1.6	Poly; preferred {110} oriented
OCLI-14	MRC Superstrate alumina (polished) 675	1025	H_2 4	10	9.1	20	2.0	0.86**	4.8×10^{17}**	15**	1.4 x 1.4 2.0	Poly; preferred {110} oriented

*Films B-doped from B_2H_6-in-He (46 ppm)

†Measured by Hall bridge method

**Measured by van der Pauw method

ELECTRONICS RESEARCH DIVISION

CHEMICAL VAPOR DEPOSITION GROWTH

SILICON SHEET GROWTH DEVELOPMENT

JPL CONTRACT NO. 954372

PROGRESS TO DATE

- CVD REACTOR SYSTEM MODIFICATIONS COMPLETED IN MID-APRIL
- SEVERAL CANDIDATE SUBSTRATE MATERIALS IDENTIFIED, CHARACTERIZED, AND TESTED IN EXPLORATORY CVD EXPERIMENTS IN H_2 AND IN HE IN 600-1100°C RANGE
    - POLYCRYSTALLINE FIRED ALUMINAS (Al_2O_3)
    - HIGH-TEMPERATURE GLASSES
    - GLASS-CERAMICS
- GROWTH RATE DATA OBTAINED FOR SiH_4 PYROLYSIS IN H_2 AND IN HE THROUGHOUT USEFUL TEMPERATURE RANGE
- VARIETY OF METHODS FOR CHARACTERIZING SUBSTRATES AND FILMS BEING APPLIED
    - PROFILOMETRY (SURFACE ROUGHNESS)
    - X-RAY DIFFRACTION LINE BROADENING (GRAIN SIZE)
    - X-RAY DIFFRACTION LINE INTENSITIES (PREFERRED ORIENTATION)
    - REFLECTION ELECTRON DIFFRACTION (SURFACE CRYSTAL STRUCTURE)
    - SCANNING ELECTRON MICROSCOPY (SURFACE TOPOGRAPHY, GRAIN SIZE)
    - CHEMICAL ETCHING (GRAIN BOUNDARY DELINEATION)
    - ELECTRICAL MEASUREMENTS (TRANSPORT PROPERTIES, MINORITY CARRIER LIFETIMES)
- SI FILM SAMPLES SUBMITTED TO OCLI FOR SOLAR CELL PROCESSING AND EVALUATION

PLANS FOR THE THIRD QUARTER

TASK 2. IDENTIFICATION/DEVELOPMENT OF SUITABLE SUBSTRATE MATERIALS

A. ADDITIONAL SUBSTRATE SCREENING
B. INTERACTION WITH POTENTIAL SUPPLIERS
C. COMPARISON OF SUBSTRATES FROM DIFFERENT MANUFACTURERS
D. INVESTIGATE EFFECTS OF SUBSTRATE SURFACE TREATMENTS

TASK 3. EXPERIMENTAL INVESTIGATION OF SI CVD PROCESS PARAMETERS

A. CVD PARAMETERS VS SUBSTRATE PROPERTIES
B. ADDITIONAL DOPING STUDIES
C. CONTINUE TWO-STEP GROWTH PROCESS STUDIES
D. ANNEALING EFFECTS ON FILM PROPERTIES
E. NUCLEATION COMPARISONS

TASK 4. PREPARATION OF SI SHEET SAMPLES

A. THICK P-TYPE FILMS FOR SOLAR CELL PROCESSING

TASK 5. EVALUATION OF SI SHEET MATERIAL PROPERTIES

A. ELECTRICAL MEASUREMENTS (HALL, VAN DER PAUW, SPREADING RESISTANCE, ETC)
B. X-RAY EVALUATION (ORIENTATION, GRAIN SIZE)
C. SEM (SURFACE STRUCTURE, ELECTRON CHANNELING PATTERNS, EDAX)
D. DIFFUSION LENGTH/LIFETIME MEASUREMENTS
E. THEORETICAL STUDIES OF CHARGE TRANSPORT MEASUREMENTS
F. PULSE-LASER SCRIBING OF HALL PATTERNS

TASK 6. FABRICATION AND EVALUATION OF SOLAR CELL STRUCTURES

A. EVALUATION OF FILMS BY OCLI

ULTRA VACUUM VAPOR DEPOSITION OF POLYCRYSTALLINE SILICON FILMS

Funding Agency

NASA LANGLEY RESEARCH CENTER

Planned Period of Performance

September 1976-June 1978

Planned Funding

$250K

Dr. R. T. Frost, Manager
Earth Orbit Applications Programs
General Electric Company
Space Sciences Laboratory
P.O. Box 8555
Philadelphia, Pa. 19101

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

ULTRA VACUUM VAPOR DEPOSITION OF POLYCRYSTALLINE SILICON FILMS

This report is on a program which has not yet begun and so covers only objectives, rationale and plans. The program has as its primary objective determination of the feasibility for vacuum vapor deposition of polycrystalline silicon films of adequate grain size and perfection for solar cell applications. Experimental studies will be conducted with various substrates in which the substrate temperature, deposition rate and vacuum level are varied. Of particular importance will be the method selected for surface preparation of substrate surfaces prior to deposition.

Consideration of the differential thermal expansion between silicon and inexpensive substrate materials indicates that a vapor deposition process will be practical only if the depositions can be carried out at relatively modest temperatures, in order to avoid excessive compressive strain in the polycrystalline material when cooled to room temperature. Although silicon atom surface mobilities are largely unknown, we speculate that film growth rates of the order of 10 microns per hour or less will allow time for silicon atom migration to kink sites provided silicon mobility is not unduly impeded by adsorbed residual gas atoms. To maintain film purity in the presence of these relatively low deposition rates, vacuum levels of the order of 10^{-10} torr or better are expected to be required. Such an ultra vacuum is also essential to prevent build-up of adsorbed gases on the substrate prior to deposition which will hopefully aid in reducing surface density of initial nucleation centers.

Limited experimental data indicates that ultra vacuum is a necessary condition for achievement of epitaxial growth by physical vapor deposition. Experiments by Turnbull were performed in which epitaxial growth of germanium on mica cleaved in the vacuum system was achieved but only amorphous films were deposited on mica surfaces with a small amount of adsorbed air. Jona has summarized the lowering of the epitaxial growth temperature for silicon vapor deposition as a function of vacuum level. The epitaxial temperatures were 1100, 830 and 550°C for vacuum levels of 10^{-5} torr, 10^{-8} torr and 10^{-10} torr, respectively. The results of Widmer at the latter pressure indicate that any practical large scale process will require pressure levels of 10^{-10} torr or lower in the presence of significant source and substrate outgassing. Practical considerations indicate that considerable superheating of the silicon source will be required to achieve practical rates on large areas and that the associated vacuum systems must transcend by orders of magnitude the capacities of the largest cryopumped system currently available.

Recent studies at the NASA Langley Research Center indicate that a molecular shield adjunct to the Space Shuttle project appears to be a feasible method for achieving the required large scale-up of vacuum system size, throughput, and heat rejection capability. Other NASA Space Processing studies of containerless melting and superheated evaporation indicate that the required scale-up of size for superheated sources can be easily achieved in the weightless space environment.

The figure shows calculated hydrogen and helium densities within a 3 meter diameter orbiting concave shield. The oxygen and nitrogen partial pressures will be orders of magnitude lower. A very preliminary cost analysis indicates orbital launch costs as the dominant element. Reasonable shuttle facility and flight cost assumptions indicate that costs compatible with ERDA goals may be possible, particularly for high frequency Shuttle launchings which will reduce costs per flight.

OBJECTIVES

- Determine feasibility for vacuum vapor deposition of silicon films suitable for solar cell applications on practical substrate materials.
- Study substrate material surface characteristics, cleaning and vacuum requirements required to form 10-50μ thick layers with acceptable grain size and defect character.
- Perform preliminary study of suitability of orbiting molecular shield adjunct to Space Shuttle for providing required ultra vacuum and superheated silicon sources to implement such a production scheme in an economical manner.

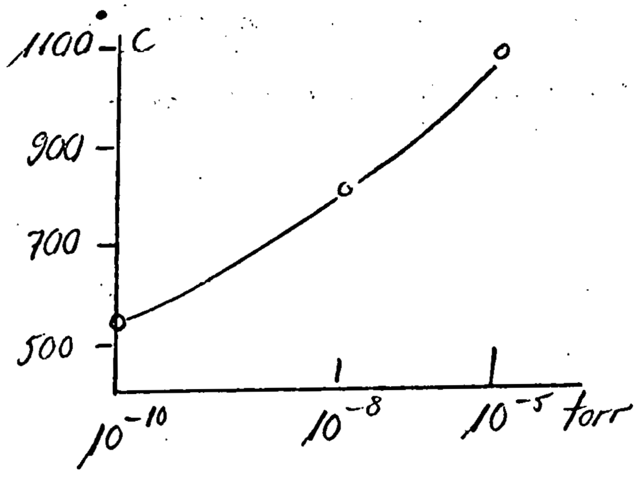
RATIONALE FOR VACUUM VAPOR DEPOSITION ON CONDUCTING SUBSTRATE

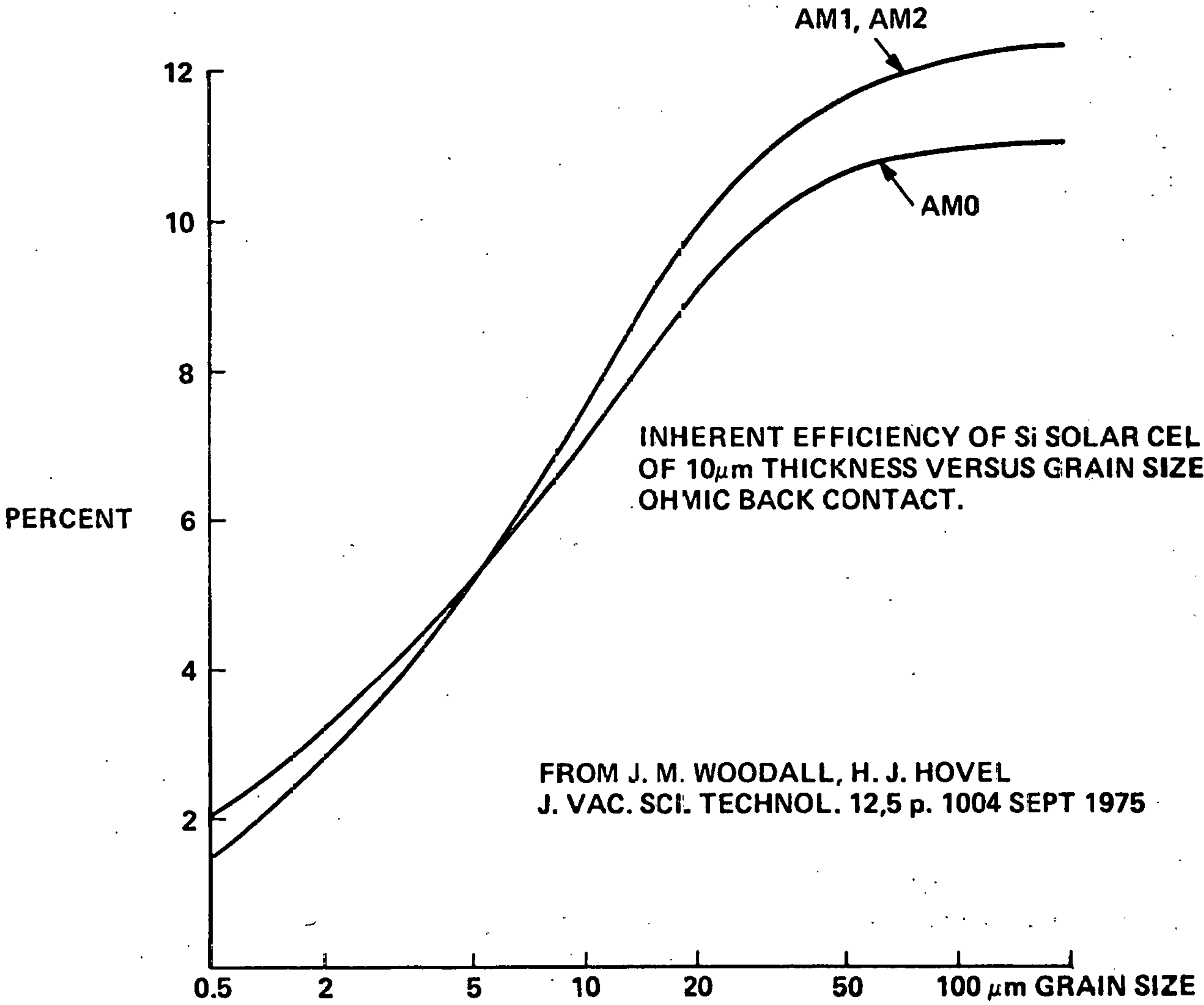
- Back contact automatically provided.
- Allows subsequent handling of thin polycrystalline material.
- Adapted to sequential vacuum deposition of junction, front contact, anti-reflection coating in same facility in continuous strip process.
- If relatively low deposition temperatures can suffice, differential thermal contraction problems associated with inexpensive substrates may be mitigated.

EVIDENCE FOR ULTRA HIGH VACUUM AS NECESSARY CONDITION FOR ACHIEVEMENT OF LARGE GRAIN SIZE

- Theoretical
  - High density nucleation centers due to particulate matter and adsorbed gases on substrate.
  - Role of adsorbed gases due to residual gases in inhibiting mobility of Si atoms arriving at substrate and subsequently migrating to kink sites.

- Experimental
  - Epitaxy of Ge on mica freshly cleaned in vacuum; amorphous growth when adsorbed gases are present.
  - Lowering of epitaxial temperature of Si on Si as vacuum level is improved to 10^{-10} torr; polycrystalline growth for T>250°C (Widmer).
  - Achievement of Si ordered structures on atomically clean metals at low deposition rates (Jona).



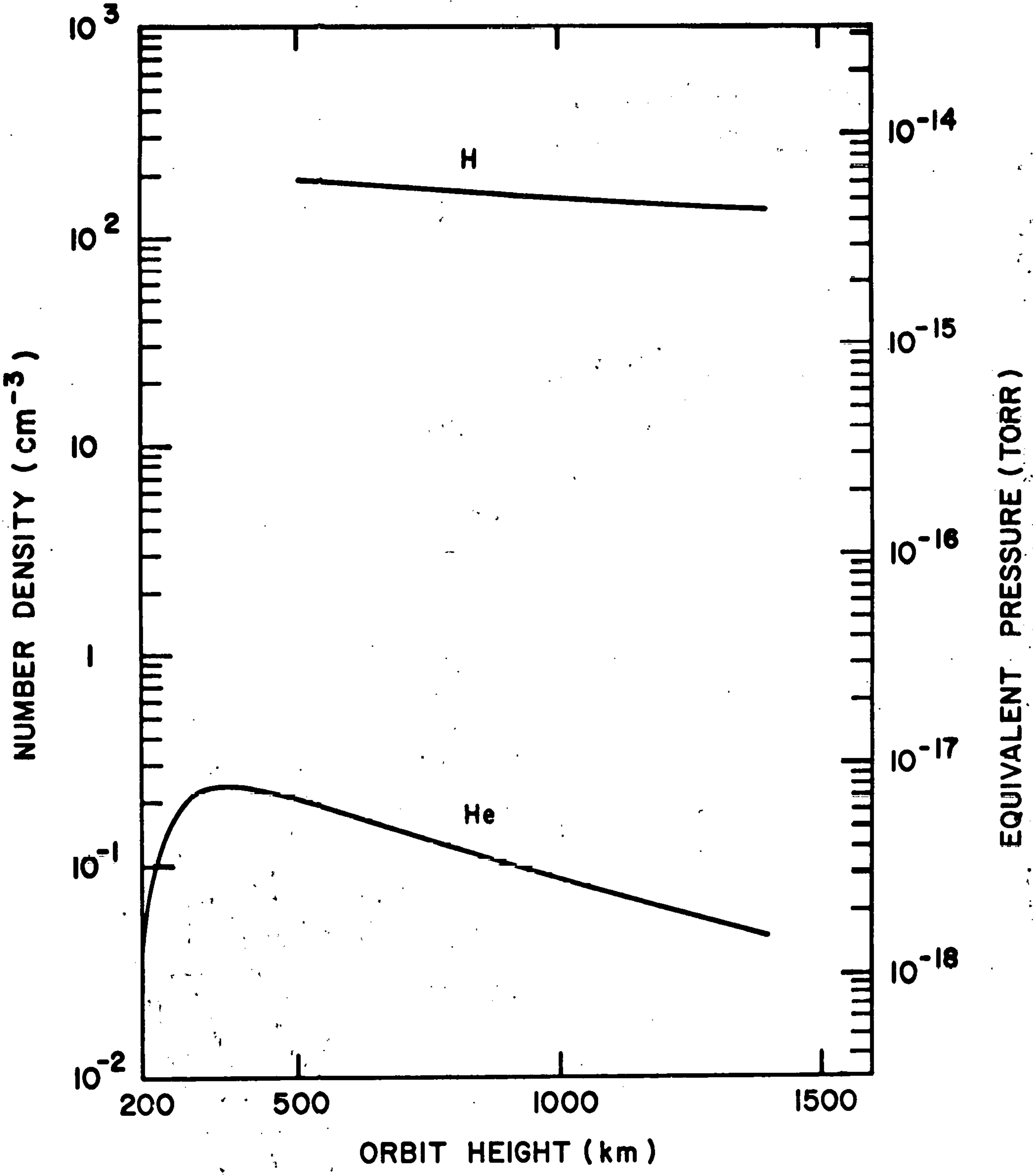


INHERENT EFFICIENCY OF Si SOLAR CELL OF 10μm THICKNESS VERSUS GRAIN SIZE. OHMIC BACK CONTACT.

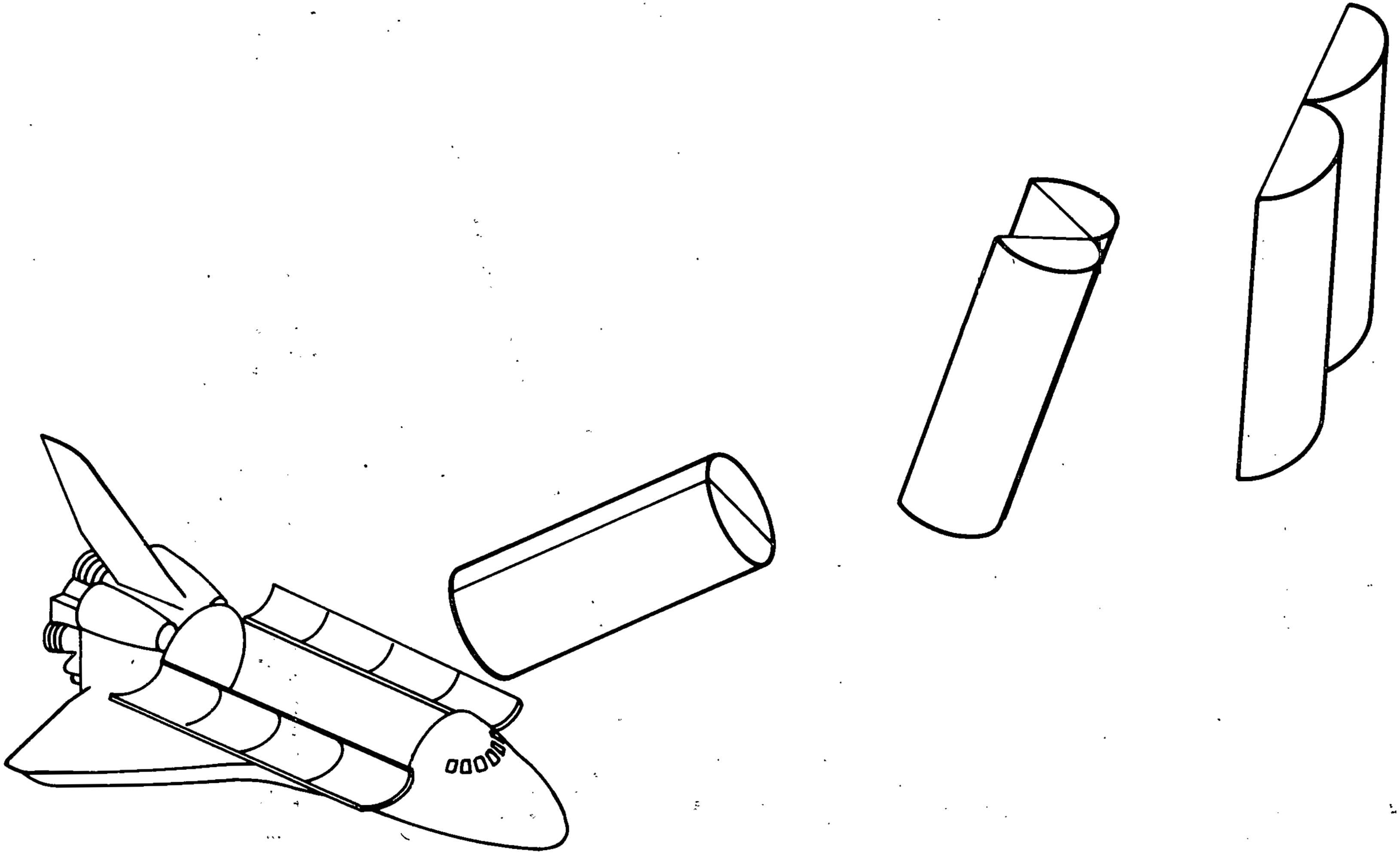
FROM J. M. WOODALL, H. J. HOVEL
J. VAC. SCI. TECHNOL. 12,5 p. 1004 SEPT 1975

Film Contamination by Residual Gas for Practicable Source and Substrate Arrangements Required for Production

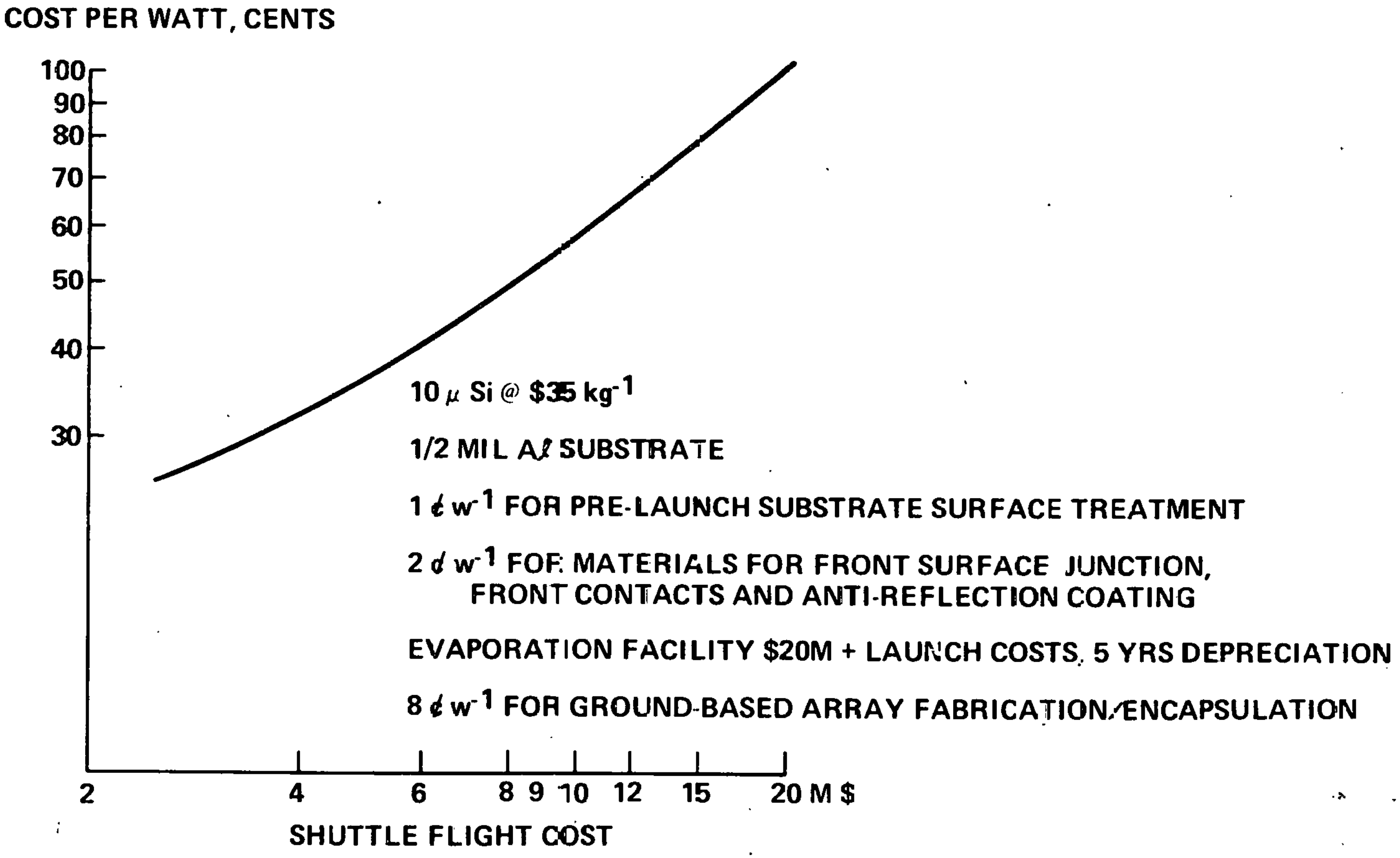
SOURCE TEMPERATURE C^{o}	AREA CM^{2}	DISTANCE TO SUBSTRATE CM	VACUUM LEVEL (TORR)	CONTAMINATION OF FILM FROM RESIDUAL GAS (COMPLETE STICKING)	
1724	1	50	10^{-6}	2.5×10^{-2}	TERRESTRIAL POSSIBILITIES
1724	1	50	10^{-10}	2.5×10^{-6}	
1888	1	50	10^{-11}	2.6×10^{-8}	
1724	10	50	10^{-13}	2.5×10^{-10}	EARTH ORBITAL FACILITY
2052	10	200	10^{-13}	4×10^{-13}	FILM PURITY LIMITED BY PURITY OF SOURCE MATERIAL
1888	100	200	10^{-14}	4×10^{-14}	


NUMBER DENSITY (cm^{-3})
10^3
10^2
10
1
10^{-1}
10^{-2}
H
He
200
500
1000
1500
ORBIT HEIGHT (km)
EQUIVALENT PRESSURE (TORR)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}

DEPLOYMENT OF MOLECULAR SHIELD FILM EVAPORATION FACILITY FROM SPACE SHUTTLE



COST PER ELECTRIC WATT GENERATING CAPACITY AS FUNCTION OF SHUTTLE FLIGHT COSTS.



10 μ Si @ \$35 kg^{-1}

1/2 MIL Aℓ SUBSTRATE

1 ¢ w^{-1} FOR PRE-LAUNCH SUBSTRATE SURFACE TREATMENT

2 ¢ w^{-1} FOR MATERIALS FOR FRONT SURFACE JUNCTION, FRONT CONTACTS AND ANTI-REFLECTION COATING

EVAPORATION FACILITY \$20M + LAUNCH COSTS, 5 YRS DEPRECIATION

8 ¢ w^{-1} FOR GROUND-BASED ARRAY FABRICATION/ENCAPSULATION

TASK DESCRIPTION

Preliminary source experiments to achieve practicable Si deposition rates free from contamination and source spitting.

Modification of vacuum deposition facilities for simultaneous depositions at various rates and substrate temperatures.

Study of minimum required substrate surface cleaning and preparation techniques required for growth of polycrystalline Si of sufficient grain size and freedom from defects.

Collection of systematic data on grain size and defect density of deposited Si as function of substrate temperature, deposition rate for oxygen partial pressures $< 10^{-12}$ torr, and total pressures $< 10^{-10}$ torr.

For Si films of adequate metallographic microstructure, formation of junctions and cells for tests of suitability for photovoltaic power generation.

SILICON THIN FILM CRYSTALLIZATION AND SOLAR CELL FABRICATION

NSF GRANT AER76-06096

SIMULATION PHYSICS, INC.

MARCH 1976 - JUNE 1977

$239,000

A. R. KIRKPATRICK
T. P. SHAUGHNESSY
M. BENKIKI

Abstract

Silicon Thin Film Crystallization and Solar Cell Fabrication

Doped amorphous silicon films have been electron beam evaporated onto temporary substrates and crystallized by several surface heating techniques including pulsed and dc electron beams, pulsed Nd: YAG laser, pulsed ruby laser and UV flashtube. These techniques have been assessed in terms of energy efficiency, substrate breakage and efficacy of grain growth. Concurrently, electrostatic bonding has been utilized to transfer these crystallized films onto metallized glass sheets for encapsulation and permanent mounting. Solar cell fabrication combining crystallization, ion implantation, and transfer permits low temperature deposition, avoids grain boundary effects, and allows the use of glass as a low cost, stable encapsulation material.

REQUIREMENTS

THIN FILM STRUCTURE

- LARGE GRAIN DIAMETERS
- COMPATIBLE WITH LOW COST, STABLE SUBSTRATE

DEVICE PROCESSING

- COMPATIBLE WITH SUBSTRATE
- MINIMIZE GRAIN BOUNDARY EFFECTS

OBJECTIVES

(1) DEVELOP METHODS TO INCREASE AVERAGE GRAIN DIAMETER

(2) DEVELOP FILM GROWTH AND DEVICE PROCESSING TECHNOLOGY WHICH PLACES FEW CONSTRAINTS UPON SUBSTRATE SELECTION.

(3) DEVELOP PROCESSING WHICH AVOIDS GRAIN BOUNDARY EFFECTS.

TECHNICAL APPROACH

- STRUCTURAL MODIFICATION OF THIN FILMS BY RECRYSTALLIZATION.
- LOW TEMPERATURE CELL FABRICATION TO LIMIT GRAIN BOUNDARY EFFECTS AND AVOID SUBSTRATE INCOMPATIBILITY PROBLEMS.

TECHNIQUES

- TEMPORARY SUBSTRATES FOR SILICON FILMS
- RECRYSTALLIZATION
- ION IMPLANTATION
- PULSED ELECTRON ANNEALING OF IMPLANT DAMAGE
- ELECTROSTATIC BONDING TO GLASS SHEETS

CELL FABRICATION SEQUENCE (N/P CELL)

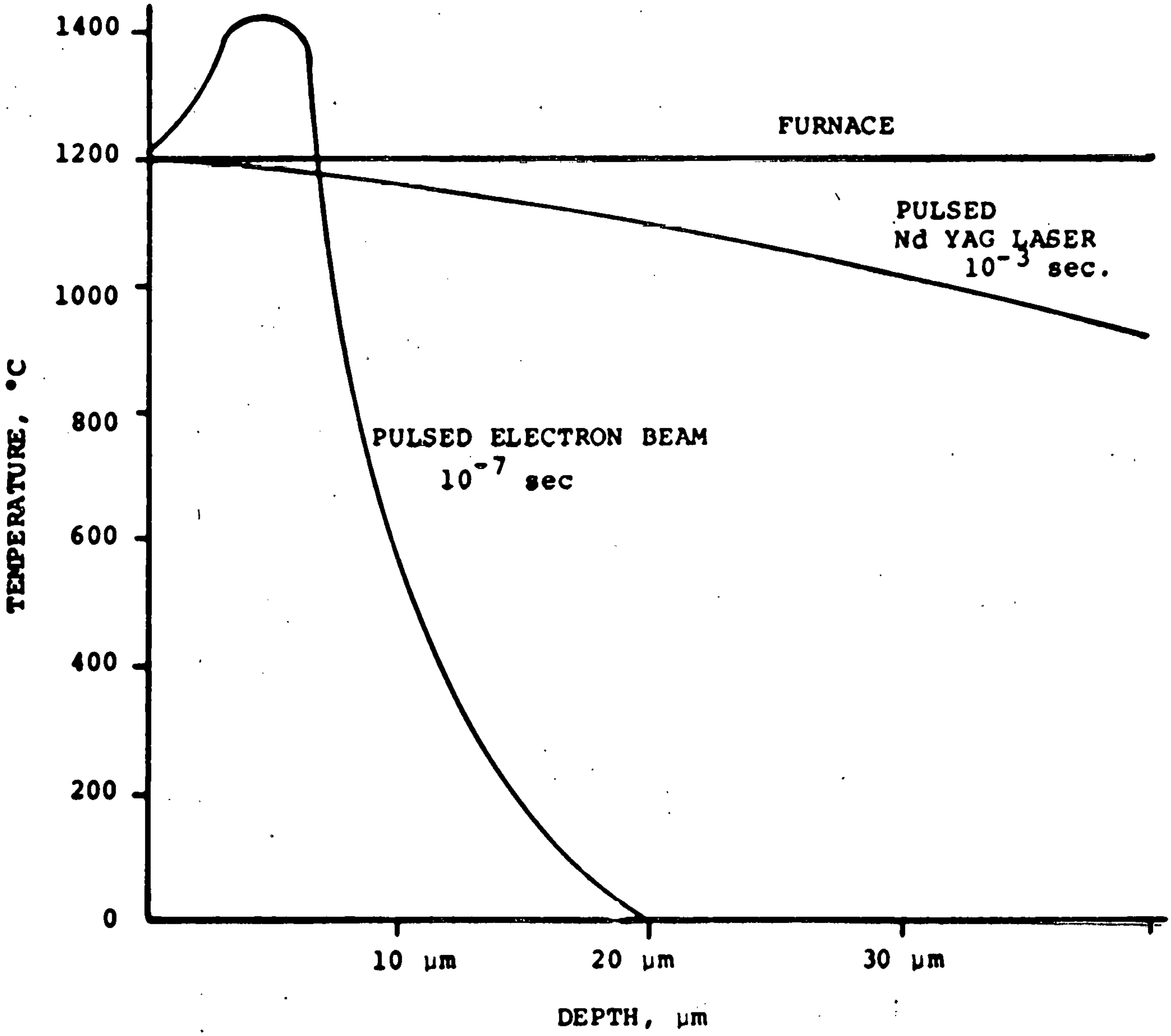
1. DEPOSIT SILICON FILM ONTO GRAPHITE COATED SILICON TEMPORARY SUBSTRATE
2. RECRYSTALLIZE
3. ION IMPLANT PHOSPHORUS INTO FILM SURFACE
4. ANNEAL IMPLANT WITH PULSED ELECTRON BEAM
5. INTEGRALLY ATTACH FILM SURFACE TO METALLIZED GLASS BY ELECTROSTATIC BONDING
6. SEPARATE FILM-GRAPHITE INTERFACE
7. ION IMPLANT BORON INTO NEW FILM SURFACE
8. ANNEAL IMPLANT WITH PULSED ELECTRON BEAM
9. APPLY BACK CONTACT METALLIZATION

ADVANTAGES

- CELL INTEGRALLY ATTACHED TO GLASS SHEET
- PROCESSING OF BOTH SURFACES OF SILICON FILM
- ION IMPLANTATION WITH ELECTRON BEAM ANNEALING AVOIDS GRAIN EDGE DIFFUSION EFFECTS
- CONTACT GRID METAL DEPOSITED ON GLASS SHOULD REDUCE MIGRATION ACROSS JUNCTION

RECRYSTALLIZATION METHODS

CATEGORY	PROCESS TIME	METHOD	POWER DENSITY WATTS/CM^2	% SOURCE EFFICIENCY	APPROXIMATE GROSS ENERGY CONSUMPTION IN JOULES/CM^2
SLOW	HOURS - MINUTES	RESISTANCE AND RF FURNACE			10^5
FAST SCAN	1 sec to 10^{-4} sec	SCANNED Nd:YAG LASER	10^5	1	$10^3 - 10^7$
		SCANNED DC ELECTRON BEAM	10^3	25	$10 - 10^3$
INTERMEDIATE PULSE	10^{-3} sec	PULSED RUBY LASER	10^5	0.1	10^5
		PULSED Nd:YAG LASER	10^5	1	10^4
		UV FLASHTUBE	10^4	10	10^4
FAST PULSE	10^{-7} sec	PULSED ELECTRON BEAM	2.5×10^7	50	10^1



PREDICTED TEMPERATURE PROFILE

TRANSFER TECHNOLOGY

- SUBSTRATE, FILM, AND METALLIZED GLASS POSITIONED TOGETHER AT 500°C.
- FILM ELECTROSTATICALLY BONDED TO GLASS.
- SUBSTRATE IS RELEASED FOR SUBSEQUENT REUSE.

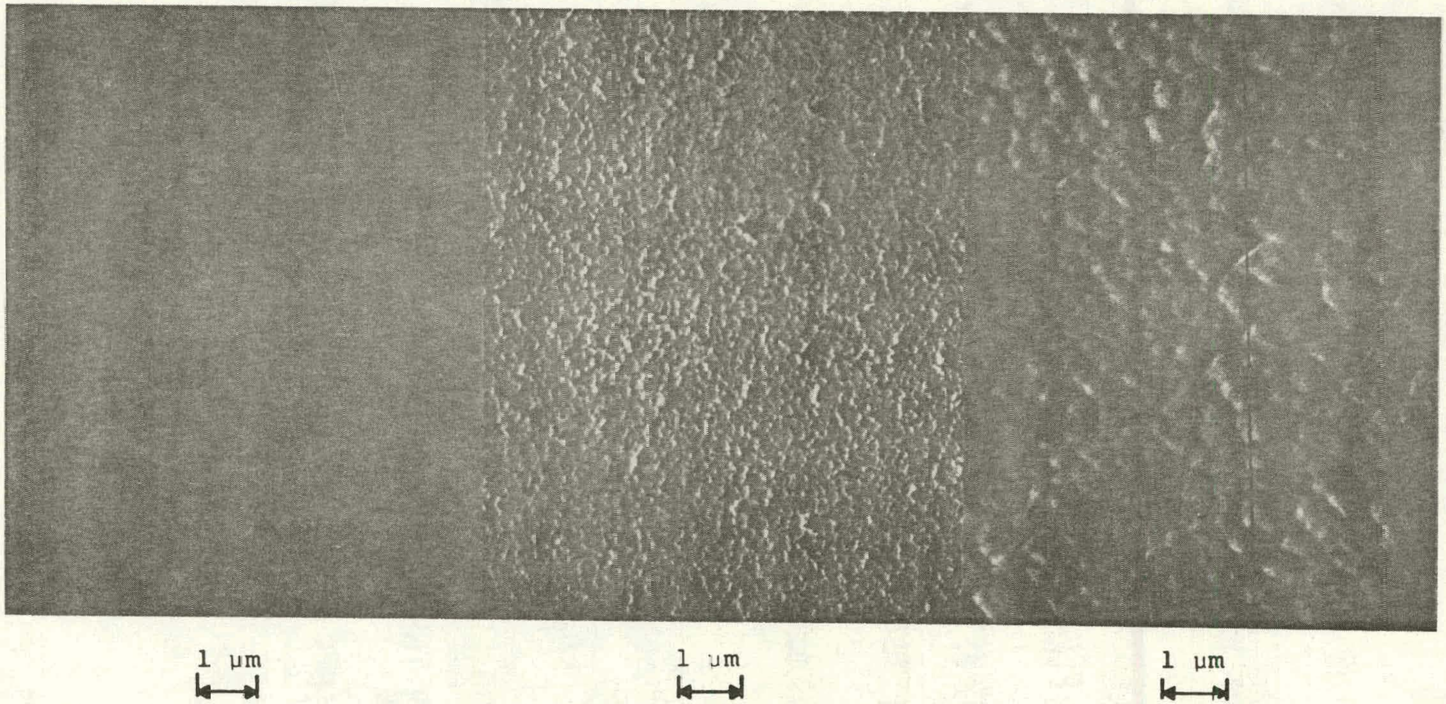
PROGRAM STATUS

- FIVE MONTHS INTO A SIXTEEN MONTH EFFORT.
- DOPED AMORPHOUS AND POLYCRYSTALLINE FILMS DEPOSITED BY ELECTRON BEAM EVAPORATION.
- RECRYSTALLIZATIONS DEMONSTRATED FOR SEVERAL METHODS:

SLOW	RESISTANCE FURNACE
MEDIUM	DC ELECTRON BEAM PULSED LASER UV FLASHTUBE
FAST	PULSED ELECTRON BEAM

- GOOD ELECTRICAL ACTIVATION AFTER RECRYSTALLIZATION FOR THE ABOVE METHODS.
- THIN FILM TRANSFER FROM TEMPORARY SUBSTRATE TO GLASS DEMONSTRATED.

SILICON THIN FILMS (5μm)



AS DEPOSITED

PULSED ELECTRON BEAM
PROCESSED 100 μsec

PULSED RUBY LASER
PROCESSED 1 msec

SUMMARY OF KEY RESULTS

- FABRICATION OF DOPED SILICON FILMS AT LOW TEMPERATURES ON TEMPORARY SUBSTRATES WITH RELEASE INTERFACE.
- RECRYSTALLIZATIONS OF FILMS USING PULSED AND SCAN METHODS TO GRAIN SIZES OF APPROXIMATELY ONE MICRON.
- THIN FILM TRANSFER FROM TEMPORARY SUBSTRATE TO METALLIZED GLASS EITHER BEFORE OR AFTER PULSE PROCESSING.

MAJOR PROBLEMS

- GRAIN SIZE INADEQUATE
- PULSED ENERGY SOURCES PRODUCE NON-UNIFORM TREATMENT OF FILM.
- DEPTH OF PROCESSING WITH PULSED ELECTRON BEAM INSUFFICIENT.

PLANNED FURTHER DEVELOPMENT

- FABRICATION:
  - OPTIMIZATION OF DOPING LEVEL, DOPING UNIFORMITY, AND INTERFACE THICKNESS.
- PULSED ELECTRON BEAM PROCESSING:
  - DEVELOP BEAM CHARACTERISTICS TO ACHIEVE DEPTH AND UNIFORMITY.
  - OPTIMIZE MULTIPLE SHOT PROCESSING.
- PULSED LASER PROCESSING:
  - OPTIMIZE MULTIPLE SHOT PROCESSING.
- TRANSFER TECHNOLOGY
  - DEMONSTRATE TRANSFER OF LARGE AREA FILMS.
  - TRANSFER IN INERT ARGON ATMOSPHERE OR VACUUM AMBIENT.

AMORPHOUS SILICON SOLAR CELLS

THIN FILMS OF SILICON ON LOW COST SUBSTRATES

Funding Agency: ERDA

Contract E(04-3) - 1286

Period of Grant: July 1, 1976 - Feb. 28, 1977
Value: $185,000

David E. Carlson
Principal Investigator
RCA Laboratories, Princeton, N.J. 08540

Presented at the National Solar Photovoltaic Program Review Meeting
August 3-6, 1976
University of Maine at Orono
Orono, Maine 04473

I. Objective

The project objective is to develop a low cost solar cell using discharge-produced amorphous silicon (a-Si).

II. Previous Activities

The unusual properties of discharge-produced a-Si prompted us to initiate a research program in 1974 to study the potential of this material for low cost, thin film solar cells. Our early experiments showed that photovoltaic devices could be made with a-Si using either gas discharge doping to make p-n or p-i-n junctions or by using evaporated metal contacts to form Schottky barrier junctions on a-Si. Schottky barrier cells were found to exhibit better collection efficiencies at short wavelengths ($\lambda < 5000$ Å) and better fill factors than p-n or p-i-n cells.

Low cost substrate materials such as aluminum and steel sheet have been used to fabricate good quality devices. Ohmic contacts are made to the substrate by depositing ∿500 Å of phosphorous-doped a-Si.

Good quality devices were made using only ∿1 μm of undoped a-Si; the large optical absorption coefficient of a-Si in the visible wavelength range allows the use of such thin films (see visual aid #4). These films were deposited using a d.c. glow discharge in SiH_4, a technique that readily scales up for large area depositions (see visual aid #5).

III. Summary of Prior Results

We have achieved conversion efficiencies of 4.3% (AM1) using Pt Schottky barriers in conjunction with antireflection coatings of Si_3N_4 and TiO_2 (see visual aid and #6). Considerable improvement in efficiency should still be possible since we estimate the theoretical limit to be ∿15%.

The Schottky barrier cells exhibit near-ideal diode behavior with diode quality factors close to unity (see visual aid #7). Pt Schottky barrier heights of ∿1.1 eV have been determined from capacitance-voltage measurements and V_{oc} - j_{sc} measurements. The exceptional quality of the a-Si diodes has been confirmed by the observation of electroluminescence at 77°K.

IV. Future Plans

Our program will use two approaches to improve the performance of a-Si solar cells. First, we will attempt to empirically optimize the fabrication procedure by carefully varying the fabrication parameters. The second approach will involve a detailed investigation of material and device properties, and the data will be analyzed to determine the parameters that influence device efficiency so that the cells can be tailored for maximum performance.

We plan to optimize the deposition conditions by choosing the best substrate material for making a low resistance contact to the a-Si. The ohmic contact to the substrate will be further optimized by studying different dopants and concentration profiles. Other fabrication parameters that will be investigated are deposition rate, SiH_4 pressure, substrate temperature and film thickness. Different annealing treatments will also be evaluated. A detailed investigation of Schottky barriers on a-Si will be initiated near the end of the contract period.

The characterization measurements that will be performed on a-Si films are resistivity (vs. temperature), optical absorption and photoluminescence. Contact studies will be made on doped and undoped films. The measurements to be performed on a-Si cells are illuminated and dark I-V, capacitance-voltage, collection efficiency (vs. wavelength, temperature, bias), light pulse experiments (to determine transit times), thermally stimulated currents (to measure trap densities), electroluminescence, and life tests. Compositional profiles will also be used to evaluate devices (Auger electron spectroscopy and secondary ion mass spectrometry).

Amorphous Silicon Cells

(Thin Films of Silicon on Low Cost Substrates)
Contract E (04-3) - 1286

RCA Laboratories, Princeton, N. J. 08540

Period of Grant: July 1, 1976 - Feb. 28, 1977
Value: $185,000

Principal Investigator: David E. Carlson

Visual Aid #1

Project Objective: to develop a low cost solar cell using discharge-produced amorphous silicon.

Visual Aid #2

Planned Activity to Date

I. Investigation of Discharge-Produced Amorphous Si as a Potential Solar Cell Material.

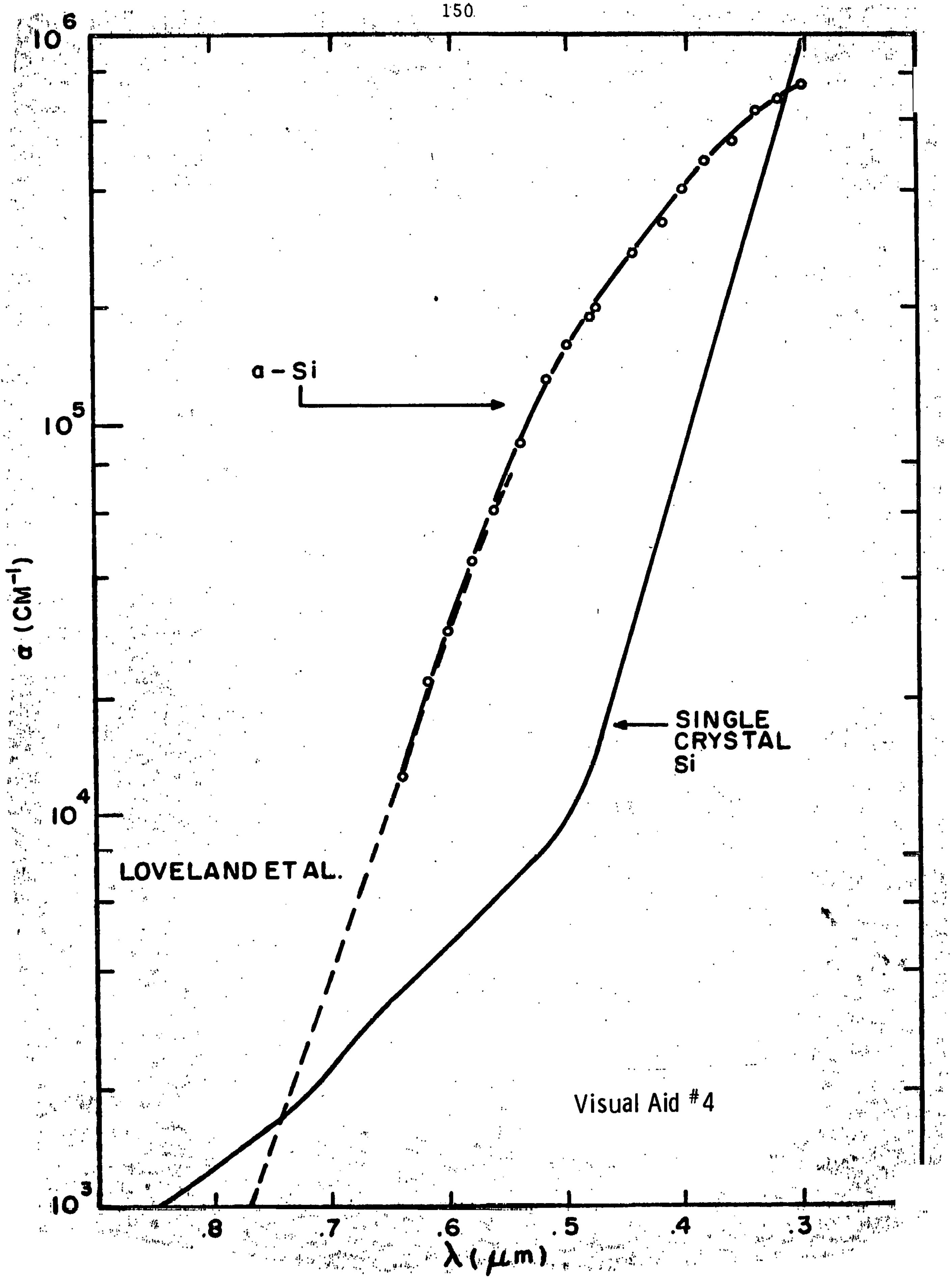
II. Selection of Best Solar Cell Structure
   A. Schottky barrier cell

III. Selection of Good Substrate Materials
   A. Most conductive materials; e.g., Aℓ, steel, etc.

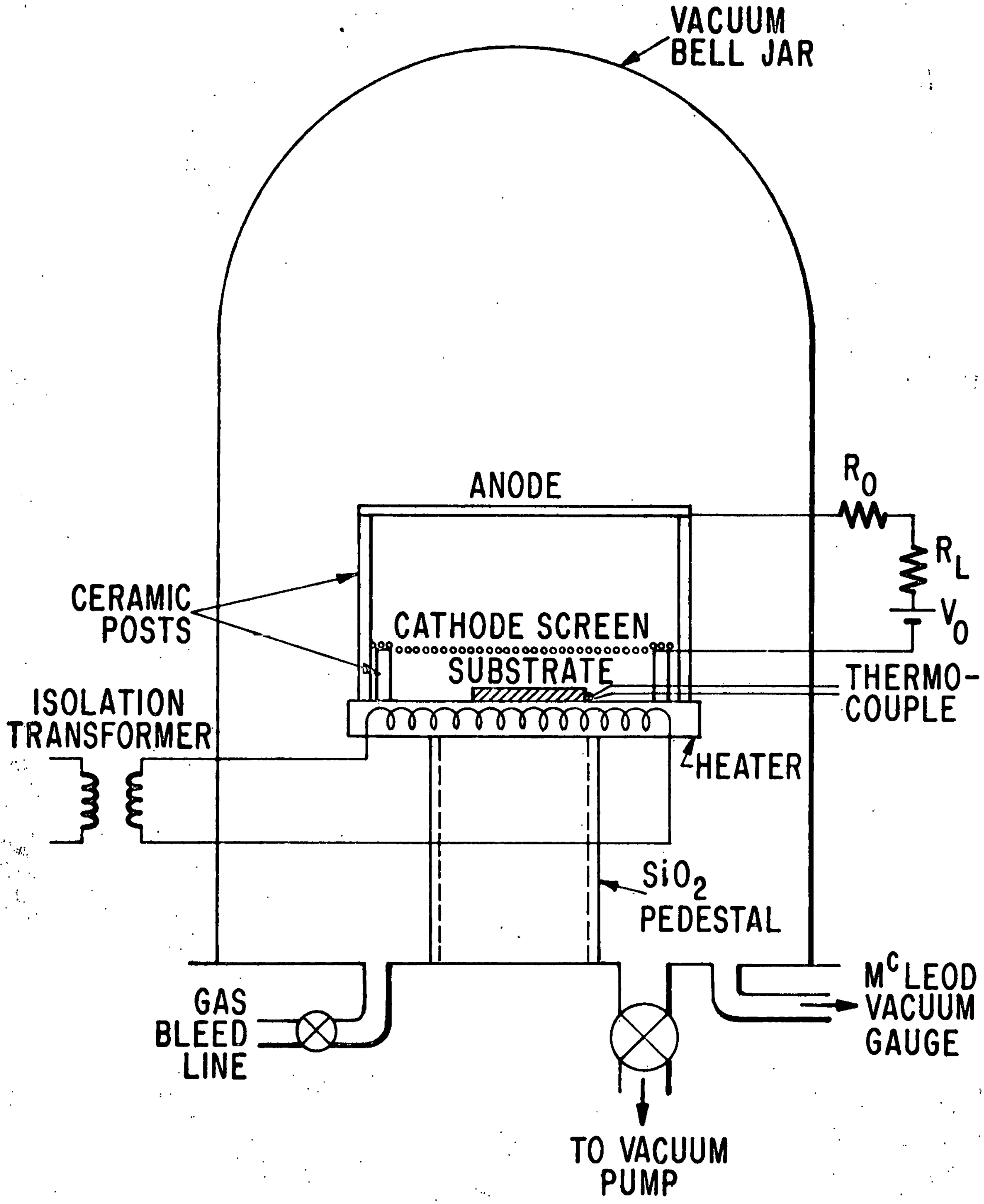
IV. Optimization of Deposition Conditions
   A. Doped layer using ∼1% PH_3 in SiH_4
   B. Thickness of a-Si on order of 1 μm

V. Characterization of Material and Cells
   A. Electrical (I-V, Q.E., C-V, etc.)
   B. Optical absorption

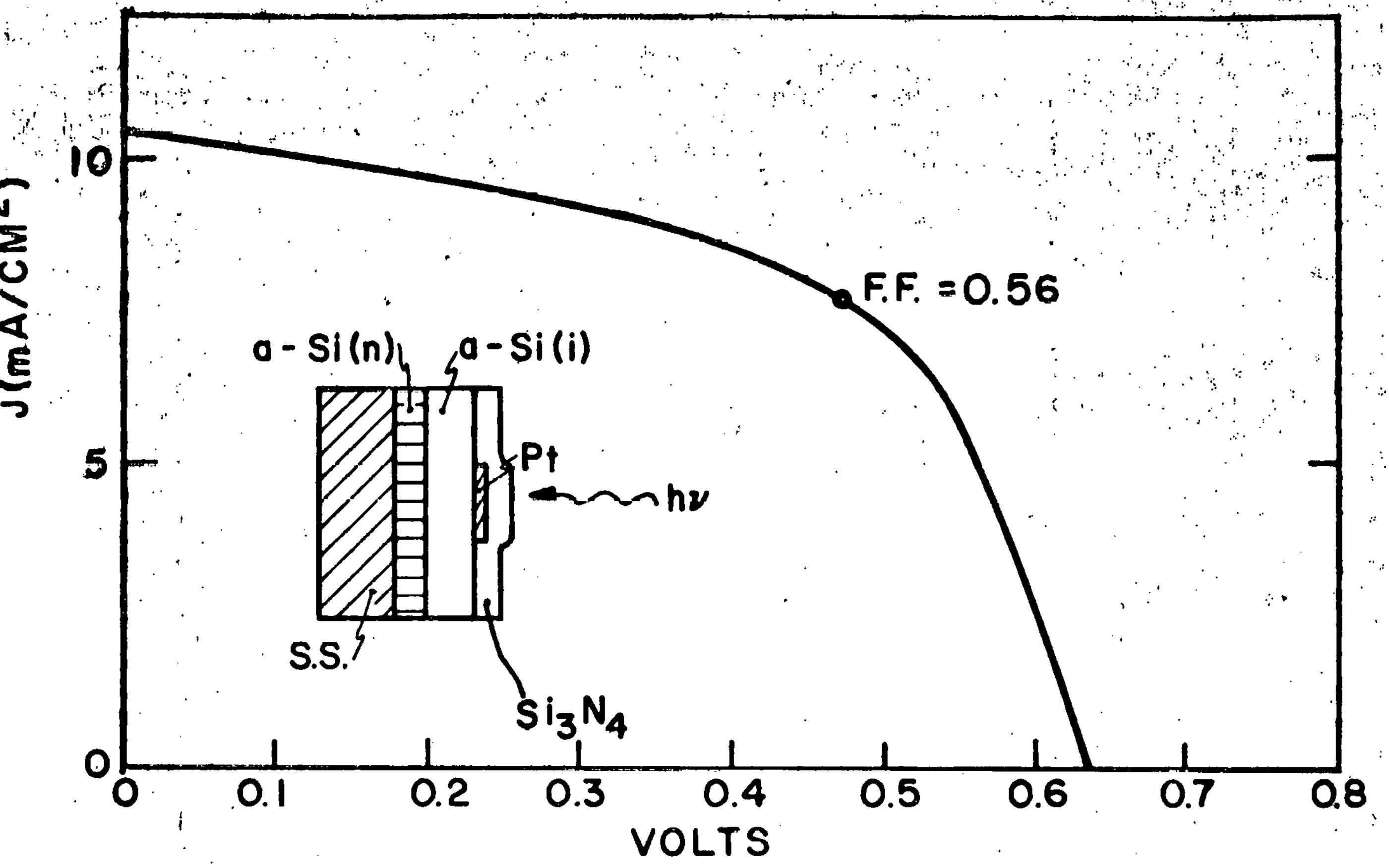
Visual Aid #3


10^6
10^5
10^4
10^3
α (CM^{-1})
.8
.7
.6
.5
.4
.3
λ (μm)
a - Si
SINGLE CRYSTAL Si
LOVELAND ET AL.

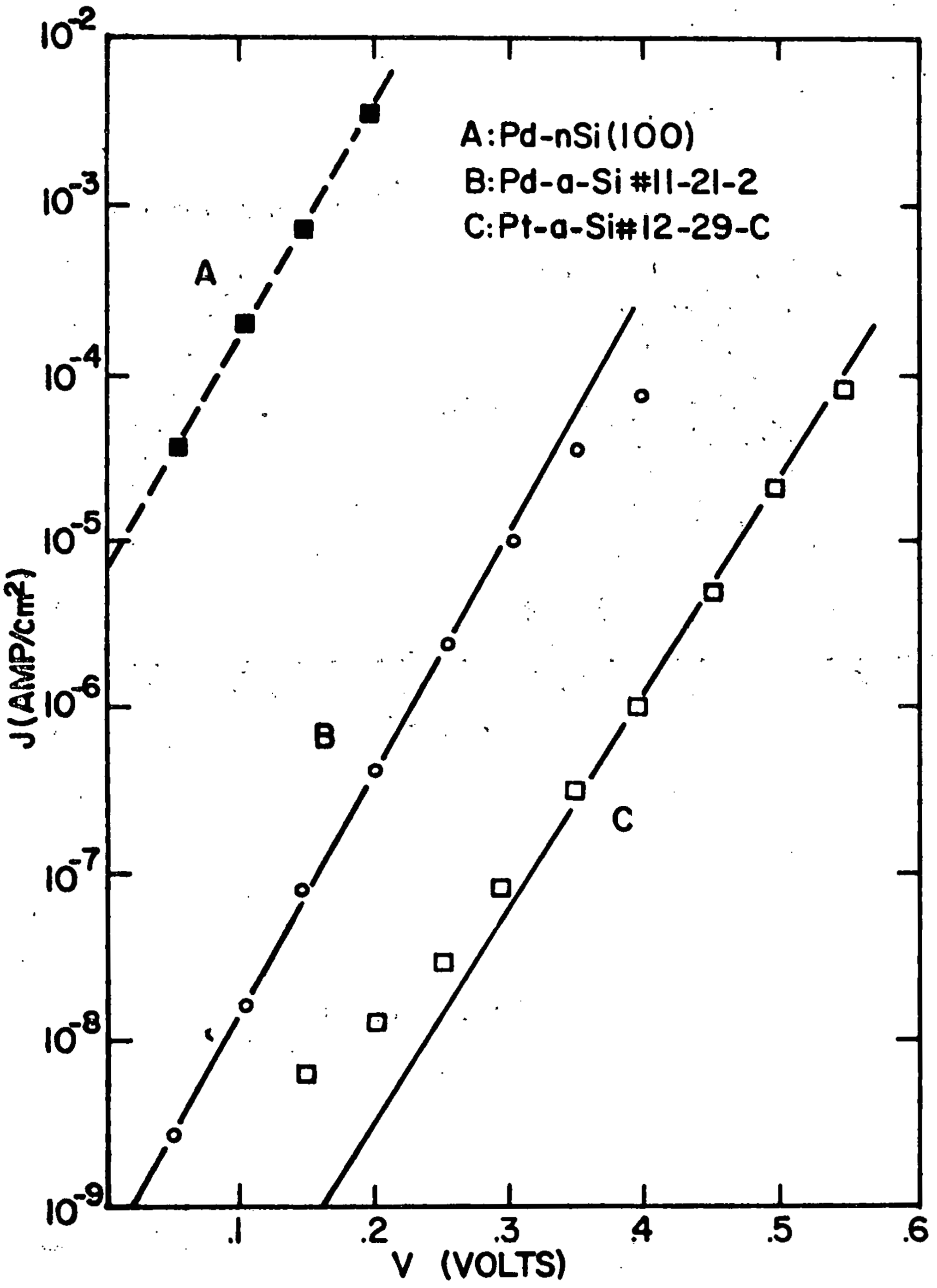
Visual Aid #4


VACUUM BELL JAR
ANODE
R_0
R_L
V_0
CERAMIC POSTS
CATHODE SCREEN
SUBSTRATE
THERMO-COUPLE
ISOLATION TRANSFORMER
HEATER
SiO_2 PEDESTAL
GAS BLEED LINE
M^cLEOD VACUUM GAUGE
TO VACUUM PUMP

Visual Aid #5


J(mA/CM²)
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
VOLTS
F.F. =0.56
a - Si(n)
a - Si(i)
Pt
hν
S.S.
Si₃N₄

Visual Aid #6


A:Pd-nSi(100)
B:Pd-a-Si #11-21-2
C:Pt-a-Si#12-29-C
A
B
C
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
J (AMP/cm^2)
.1
.2
.3
.4
.5
.6
V (VOLTS)

Visual Aid #7

Summary of Prior Results

I. Conversion efficiency of 4.3% (AM1)
(estimated maximum efficiency is ∼15%).

II. Near-ideal diode behavior, $\beta' \simeq 1.0$, $\beta \simeq 1.1$.

III. Schottky barrier heights ≃ 1.1 eV.

IV. Electroluminescence (77°K).

Visual Aid #8

Planned Activity to March 1977

I. Optimize Deposition Conditions
  A. Choose best substrate materials
  B. Select best dopant and profiles
  C. Optimize deposition rate, pressure and temperature
  D. Evaluate effect of annealing treatments

II. Optimize Device Structure
  A. Choose best film thickness
  B. Start optimization of Schottky barrier
  C. Evaluate different anti-reflection coatings

Visual Aid #9

Planned Activity to March 1977

III. Characterize Material and Devices

- A. Film ~~thickness~~ PROPERTIES
  - 1. Resistivity vs. temperature
  - 2. Optical absorption
  - 3. Photoluminescence
- B. Contact Studies on doped and undoped films
- C. Device Measurements
  - 1. Illuminated and dark I-V
  - 2. Capacitance - voltage
  - 3. Collection efficiency vs. wavelength, temperature, bias
  - 4. Light pulse experiments (transit times)
  - 5. Thermally stimulated currents (trap densities)
  - 6. Electroluminescence
  - 7. Life tests
- D. Compositional Profiles of Devices

Visual Aid #10

National Solar Photovoltaic Program Review Meeting
August 3-6, 1976
University of Maine at Orono

SESSION III - Polycrystalline Silicon
Materials and Devices

Paper 7

STUDIES OF BASIC MECHANISMS INFLUENCING SOLAR CELL EFFICIENCY FOR TERRESTRIAL APPLICATIONS

F. A. Lindholm
AND
C. T. Sah

CONTENTS

University of Florida 1853

University of Florida College of Engineering
We Build
1910

National Solar Photovoltaic Program Review Meeting
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STUDIES OF BASIC MECHANISMS INFLUENCING SOLAR CELL EFFICIENCY FOR TERRESTRIAL APPLICATIONS

F. A. LINDHOLM
AND
C. T. SAH

CONTENTS

1. GENERAL INFORMATION

(A) PROJECT TITLE AND CONTRACT NUMBER

STUDIES OF BASIC MECHANISMS INFLUENCING SOLAR CELL EFFICIENCY FOR TERRESTRIAL APPLICATIONS
ERDA CONTRACT NO. E-(40-1)-5134

(B) PERFORMING ORGANIZATION

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF FLORIDA, GAINESVILLE

(C) CONTRACT DURATION AND PERIOD

18 MONTHS (01 JUNE 1976 TO 30 NOVEMBER 1977)

PRINCIPAL INVESTIGATOR

FRED A. LINDHOLM
PROFESSOR OF ELECTRICAL ENGINEERING

CONSULTANT

C. TANG SAH

2. DEFINITION OF OVERALL OBJECTIVES

TO DISCOVER AND DELINEATE THE BASIC MECHANISMS INFLUENCING SOLAR CELL EFFICIENCY AND TO PROVIDE MATHEMATICAL MODELS WHICH INCORPORATE THESE MECHANISMS INTO THE ENGINEERING DESIGN OF SOLAR CELLS.

(A) EFFECTS OF DIFFUSED EMITTER ON EFFICIENCY
(B) PROCESS VARIATIONS ON EFFICIENCY

3. PLANNED ACTIVITIES

(A) THEORETICAL

- (1) Distorted Band Edges
- (2) Recombination Rates and Effective Lifetimes
- (3) Longitudinal and Transverse Inhomogeneities

(B) EXPERIMENTAL

- (1) SOLAR CELL JUNCTION TYPES
  - (a) Single-crystal Silicon (In-house, Sandia)
  - (b) Polycrystalline Films (Sample-avaialbe)
    Si & Compound Semiconductors
- (2) EXPERIMENTAL PARAMETERS
  - (a) Energy Levels of Recombination Centers
  - (b) Density of Recombination Centers
  - (c) Electron and Hole Thermal Emission and Capture Rates at Recombination Centers
  - (d) Recombination Lifetimes in Emitter and Base
  - (e) Charge Stored in Emitter and Base
- (3) MEASUREMENT TECHNIQUES [1]
  - (a) Thermally Stimulated Capacitance (TSCAP) [2]
    High-Frequency Capacitance vs Temperature Change
  - (b) Voltage Stimulated Capacitance (VSCAP)#
    High-Frequency Capacitance vs Time after bias voltage change.
  - (c) Light Stimulated Capacitance (LSCAP)#
    High-Frequency Capacitance vs time after illumination

Coined by C. T. Sah for this presentation.

4. DESCRIPTION OF PROGRESS MADE

(A) DIFFUSED SILICON P+/N DIODES MADE

- •High (1200C) and Low (875C) Boron Diffusion
- •10^{14} to 10^{17} Phos/cm^3 CZ Silicon Substrates

(B) MAJORITY AND MINORITY CARRIER TRAPS DETERMINED

- •TSCAP and VSCAP Methods (N_{TT}, e_n^t, e_p^t), LSCAP in progress.

(C) CONTRIBUTIONS FROM EMITTER AND BASE SEPARATED[3]

- •Lifetimes in Emitter and Base
- •Charge Stored in Emitter and Base
- •Parameter Measurement Methods

- OCVD	Open Circuit Voltage Decay
- JCR	Junction Current Recovery Lifetime
- I vs V (T)	Dark DC Current-Voltage-Temperature Charact.
- I_{SC} vs V_{OC}	Short-Circuit Current vs Open-Circuit Voltage
- Y vs V (T)	Admittance ($Y=G+j\omega C$) vs Voltage & Temperature

5. KEY RESULTS

(A) DIFFUSED SILICON P+/N DIODES ARE MADE; N+/P IN PROGRESS.

(B) RECOMBINATION LEVELS ARE DETERMINED.

(C) NEW METHODS OF SEPARATING THE EMITTER AND BASE RECOMBINATION CURRENTS [illegible] DEMONSTRATED. (Major Result)
ARE

6. PLANNED ACTIVITY - MILESTONE CHART

(A) EFFECTS OF DIFFUSED EMITTER

0	3	6	9	12	15	18 MONTHS
Device Run 1	Measurements 1st Order Interpretatn.	Computer-Aided* Refined Analysis				
		Device Run 2	Measurements 1st Order Interpretatn.	Computer-Aided* Refined Analysis		

(B) EFFECTS OF PROCESS VARIATIONS

0	3	6	9	12	15	18 MONTHS
				Fabrication Runs Varying T, Impurity Profiles; Evaluate Ion Implanted Devices* Thin Film Devices		

*In collaboration with Jerry Fossum of Sandia.

7. REFERENCES

1. The measurement techniques are recently summarized in
   - C. T. Sah, "Detection of Recombination Centers in Semiconductors from the Transient Response of the Space Charge Layer Capacitance," Invited Tutorial Paper, Procedding of National Workshop on Low Cost Polycrystalline Silicon Solar Cells, May 18, 1976
   - C. T. Sah, "Bulk and Interface Imperfections in Semiconductors," Sherman Fairchild Lecture given at Lehigh University on November 7, 1973; to be published in the October, November or December issue of Solid-State Electronics.

2. C. T. Sah and J. W. Walker, "Thermally Stimulated Capacitance (TSCAP) in p-n Junctions," Applied Physics Letters, v20, 193-196, 01 March 1972

3. The detailed theory and measurements will be presented in
   - F. A. Lindholm and C. T. Sah
     Normal Models in Semiconductor p-n Junction Devices for Material Parameter Determination
     Journal of Applied Physics, September 1976
   - Lindholm, Neugroschel, Sah, Godlewski and Brandhorst
     Methodology for Experimentally-Based Determination of Gap Shrinkage and Effect Lifetimes in Emitter and Base of pn Junction Solar Cells
     To be presented at the 12-th Photovoltaic Specialist Conference, November 8-9, 1976
   - Lindholm, Neugroschel and Sah
     Invited paper to be presented at the IEEE International Electron Devices Conference, December, 1975

ENERGY BEAM DEPOSITION OF SILICON

ERDA - SAN FRANCISCO
Grant or Contract Number E(04-3)-1287

July 1, 1976 - June 30, 1977
237,000

A. Baghdadi, R.W. Gurtler

Motorola Inc.
Semiconductor Group
Solar Energy Department
4039 East Raymond Street
Phoenix, Arizona

Presented at
National Solar Photovoltaic Review Meeting
August 3 - 6, 1976
University of Maine, Orono
Orono, Maine

ENERGY BEAM DEPOSITION OF SILICON

This research program is aimed at developing a new method for chemical vapor deposition (CVD).

An Energy Beam, Fig. 1, will be used to deposit polycrystalline silicon in ribbon form, Figure 2. The Energy Beam method could be a rapid and efficient method of CVD, since it directly couples an RF field to a stream of gas. Two approaches to the substrate problem are as follows (Figure 3):

1. Permanent Substrate: Must search for inexpensive substrate material.
2. Temporary Substrate: Poly ribbon is "peeled-off" from the substrate before solar cell processing.

Grain size enhancement will be attempted using Motorola's Ribbon-to-Ribbon (RTR) crystal growth technique, Figures 4, 5. Ribbon-to-Ribbon is somewhat like a float-zone crystal growth method in which polycrystalline ribbon is used as feedstock. It can be applied to the objectives of this program in a number of ways. Figures 6 - 8.

Various silicon-bearing gases will be investigated as sources for the deposition of polycrystalline silicon films, Figure 9. In order to achieve the highest possible growth rates, we will use a multiple nozzle manifold, Figure 10. The nozzle configuration will be designed to produce a relatively flat ribbon.

Decomposition of the silicon bearing gas can occur at the substrate due to thermal decomposition, or in the plasma due to RF excitation. If plasma dissociation is important, it may be optimized by the proper choice of carrier gases, flow rates, and concentrations.

CONCLUSION

We are investigating the possibilities of developing a rapid, efficient chemical vapor deposition method for silicon using an Energy Beam. By subsequently using the RTR crystal growth process, we expect to develop a method for producing inexpensive silicon of sufficient quality to manufacture 10% efficient solar cells.

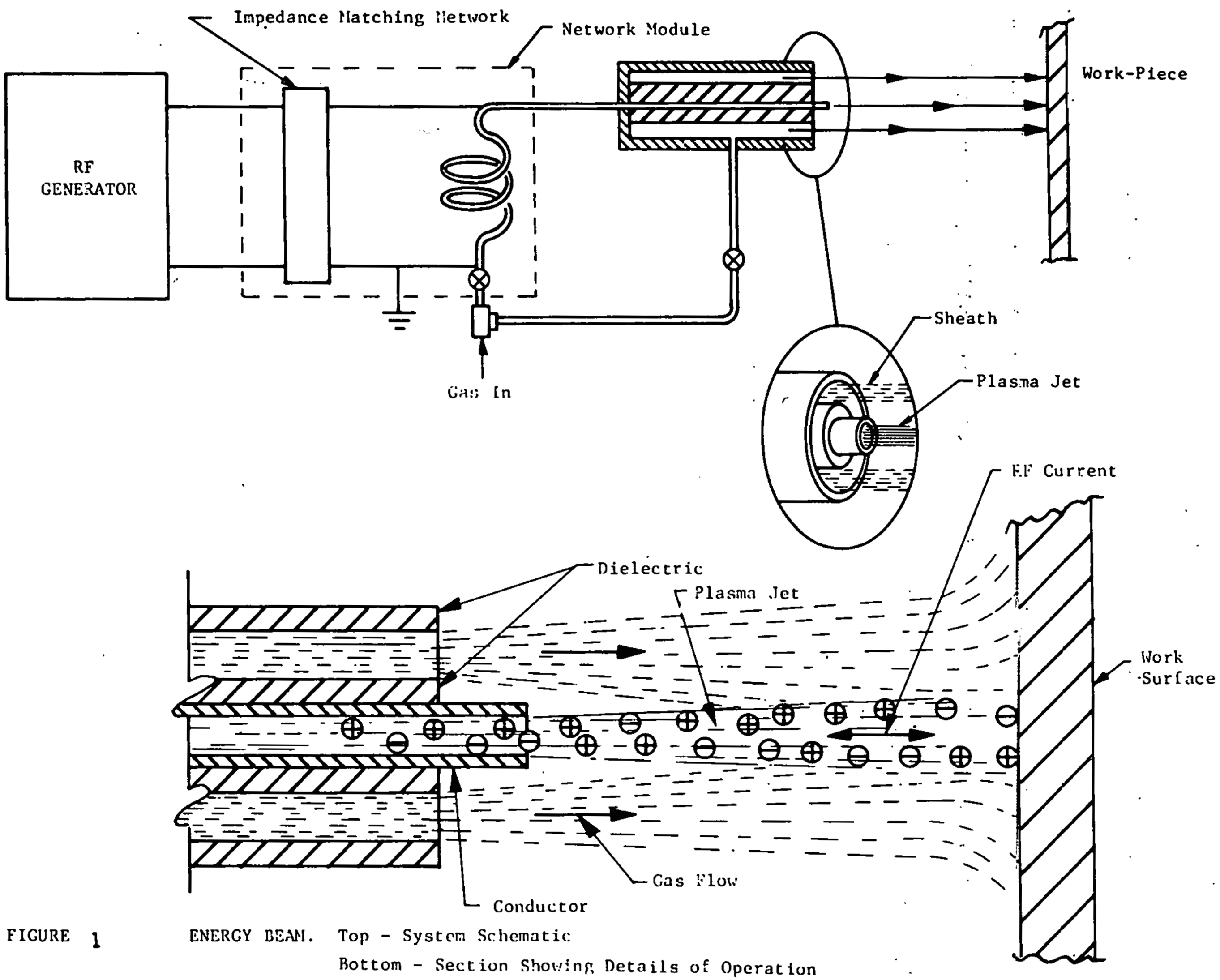
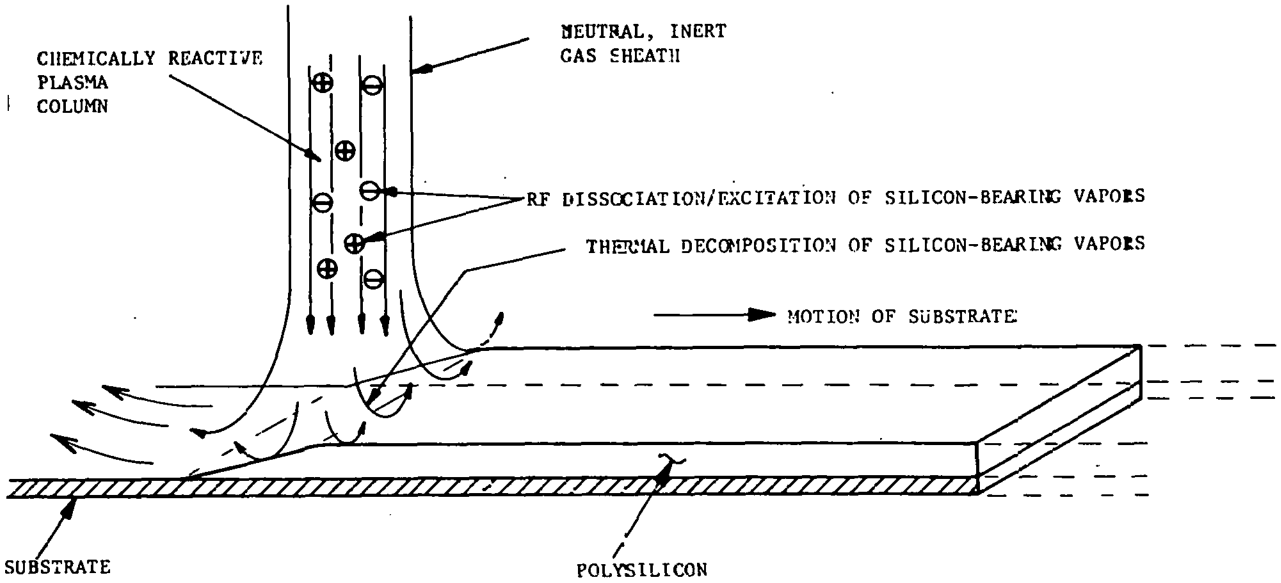


FIGURE 1 ENERGY BEAM. Top - System Schematic
Bottom - Section Showing Details of Operation

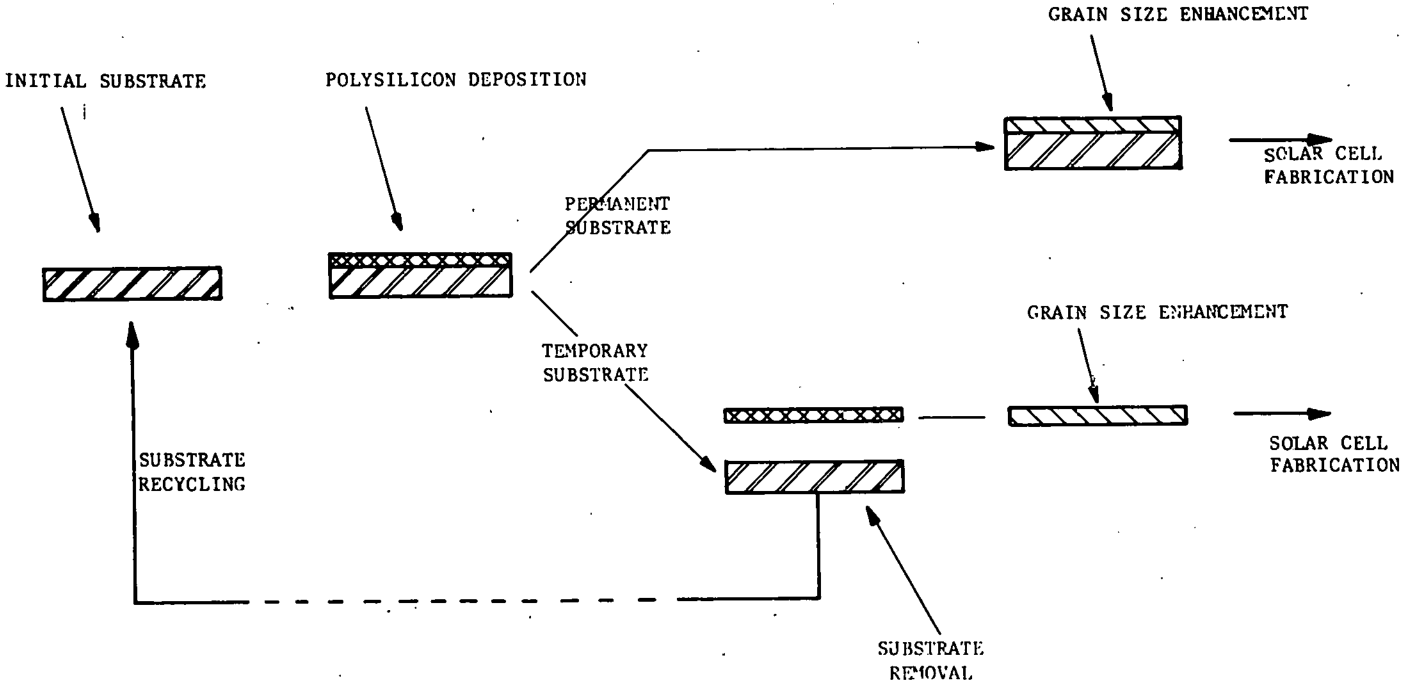


SCHEMATIC OF POLYCRYSTALLINE SILICON FILM DEPOSITION

ONTO A SUBSTRATE BY MEANS OF AN ENERGY BEAM INTO

WHICH IS INTRODUCED ONE OR MORE SILICON-BEARING VAPORS.

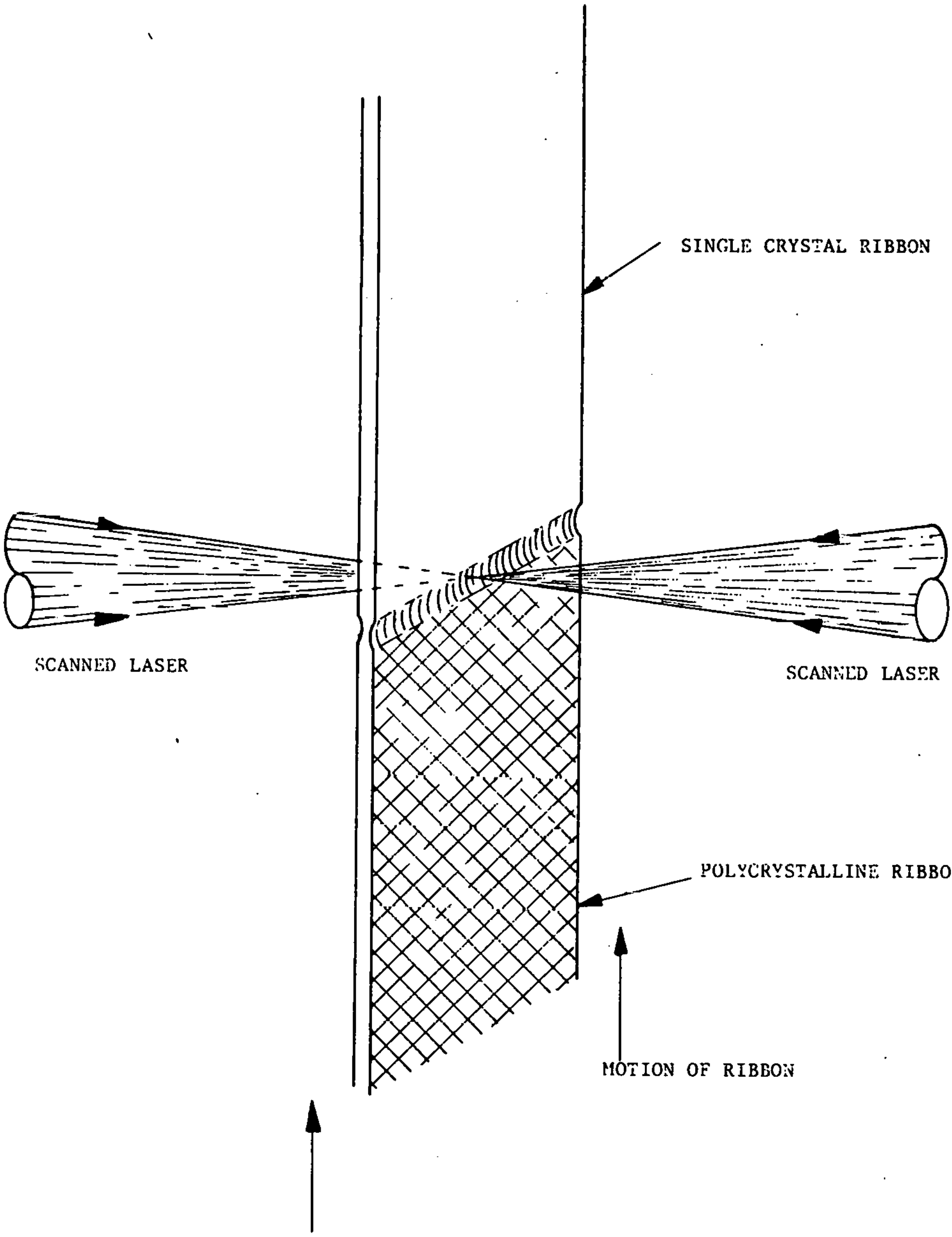
FIGURE 2



DIFFERENTIATION OF TWO POLYCRYSTALLINE THIN FILM PROCESSES

TOP: Permanent Substrate (PS) Process
BOTTOM: Temporary Substrate (TS) Process

FIGURE 3



RIBBON-TO-RIBBON (RTR) PROCESS FOR GROWING SINGLE CRYSTAL
SILICON RIBBON FROM POLYCRYSTALLINE FEEDSTOCK

FIGURE 4

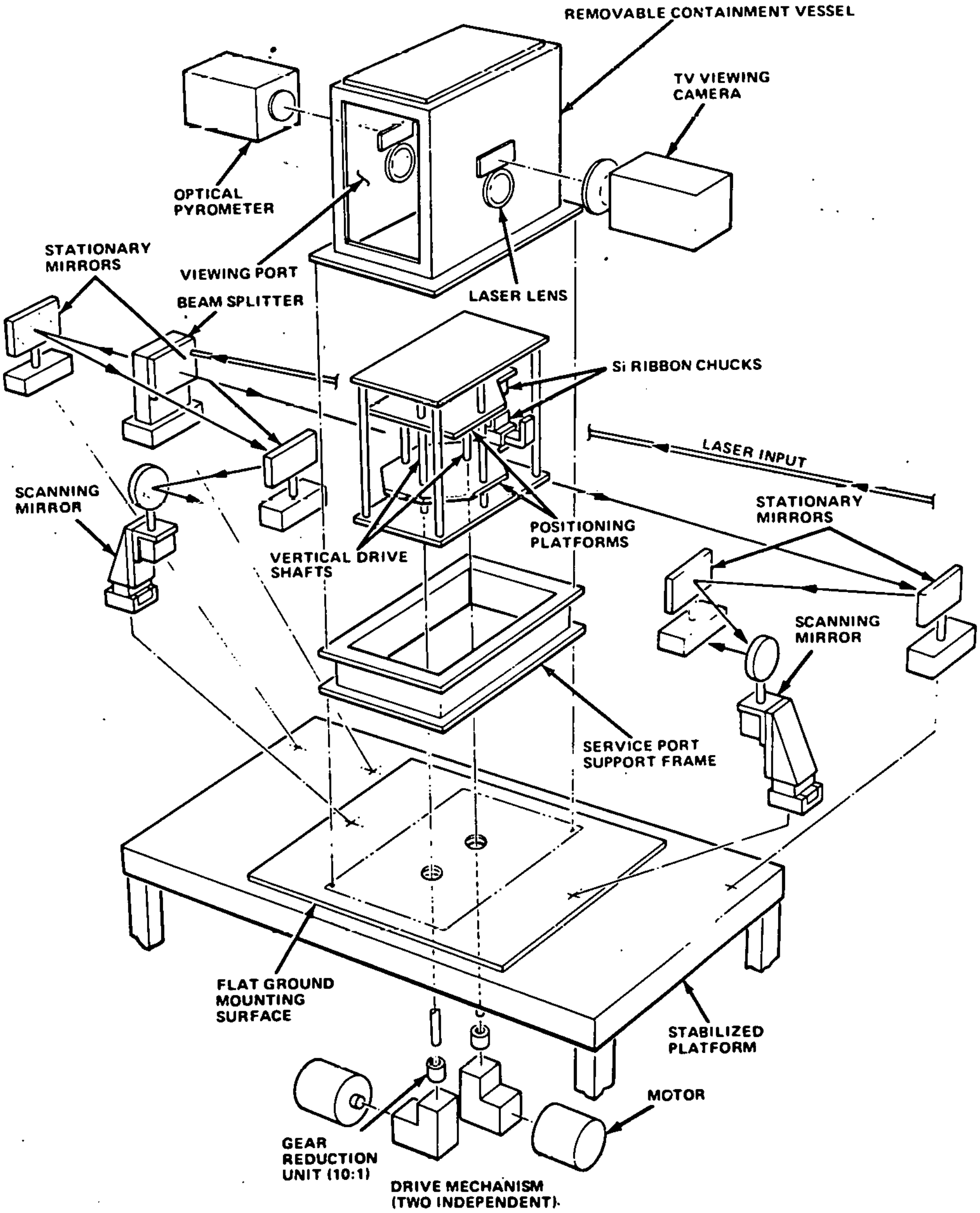
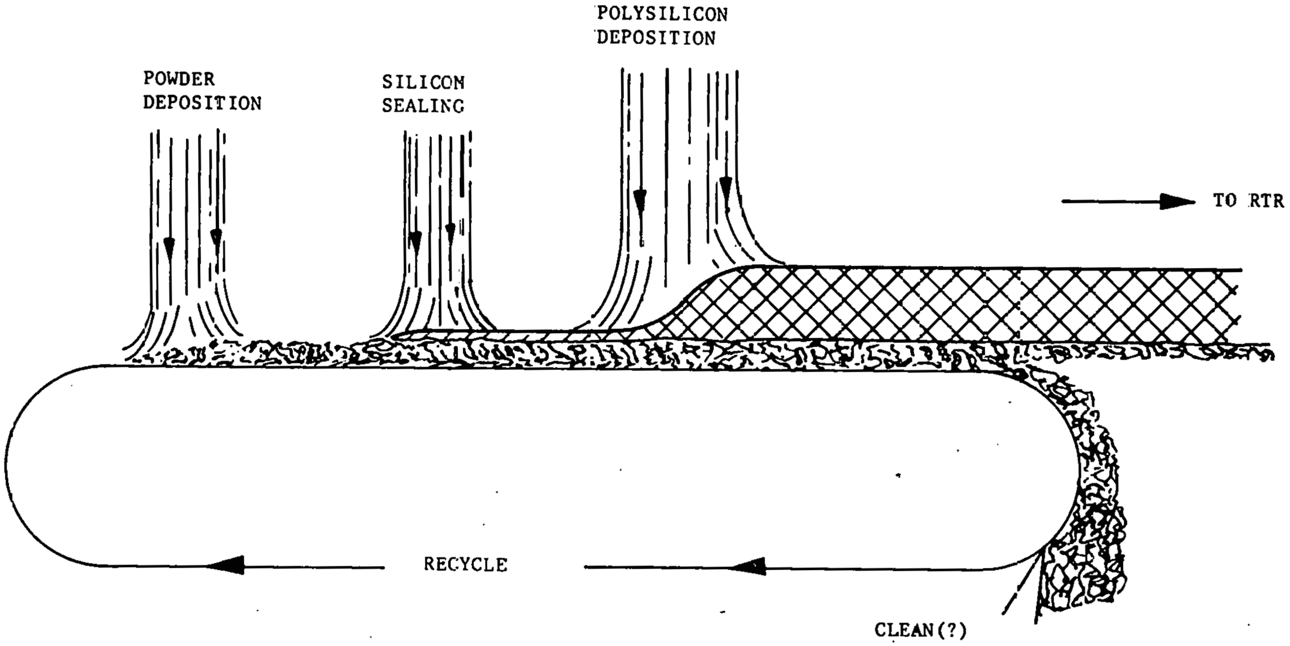
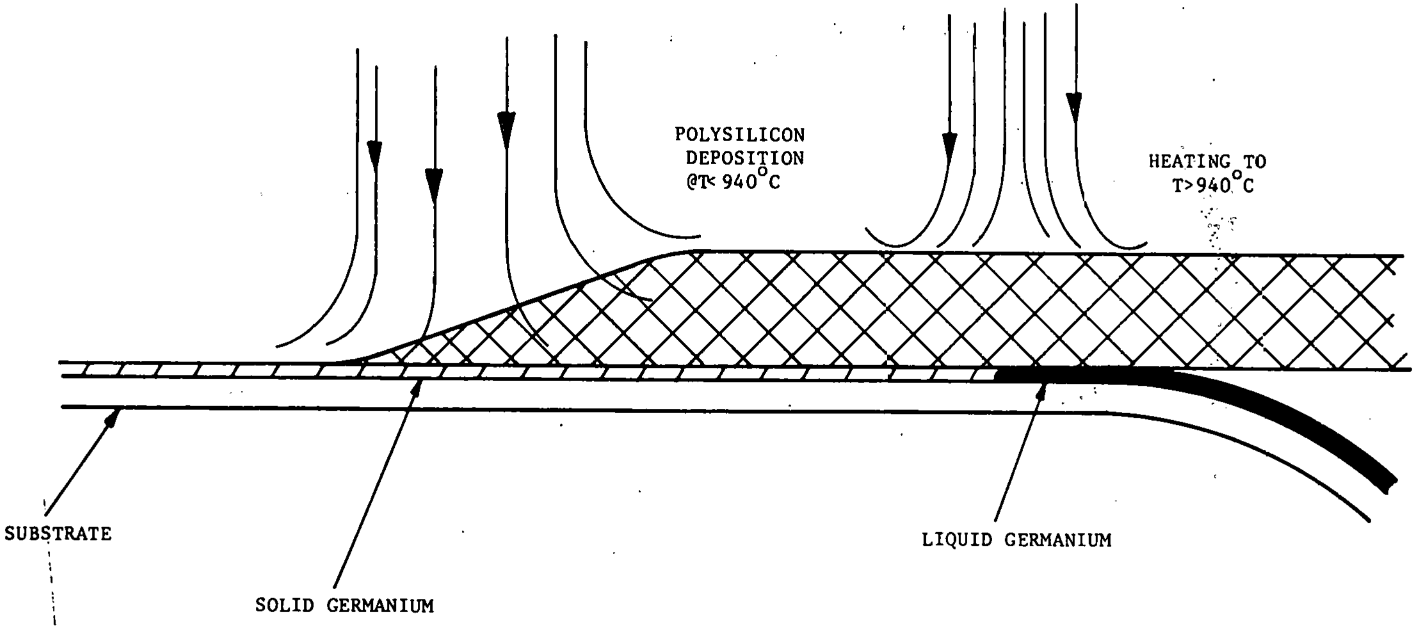


FIGURE 5 EXPLODED VIEW OF EXPERIMENTAL RTR GROWTH APPARATUS



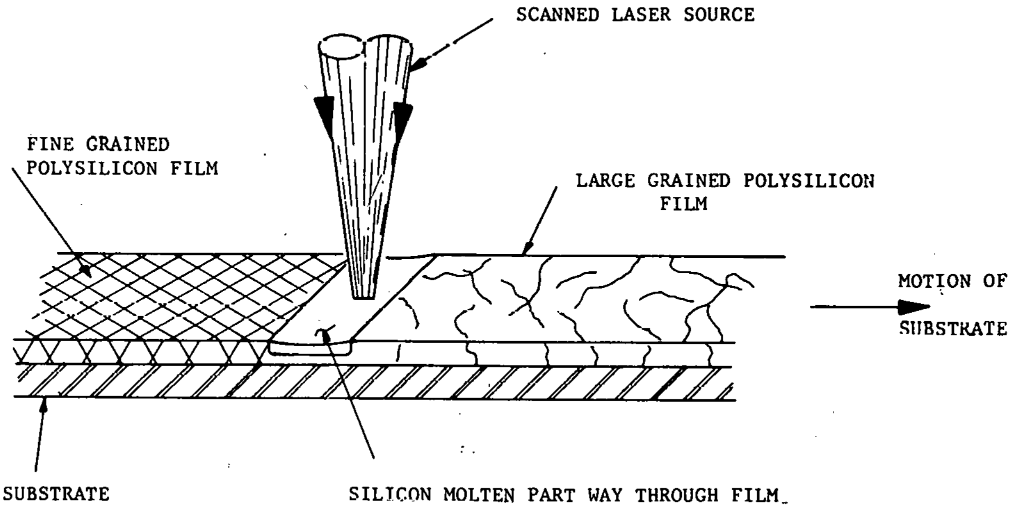
SILICON POWDER USED TO PRODUCE SELF-SUPPORTING POLYCRYSTALLINE SILICON FILM BY A TEMPORARY SUBSTRATE PROCESS

FIGURE 6



LIQUID SUBSTRATE TECHNIQUE TO PRODUCE A SELF-SUPPORTING POLYCRYSTALLINE SILICON FILM. IN THIS EXAMPLE, GERMANIUM IS USED AS THE LIQUID SEPARATION LAYER.

FIGURE 7



RTR PROCESSS MODIFIED TO ENHANCE GRAIN SIZE IN SILICON FILM ON A PERMANENT SUBSTRATE

FIGURE 8

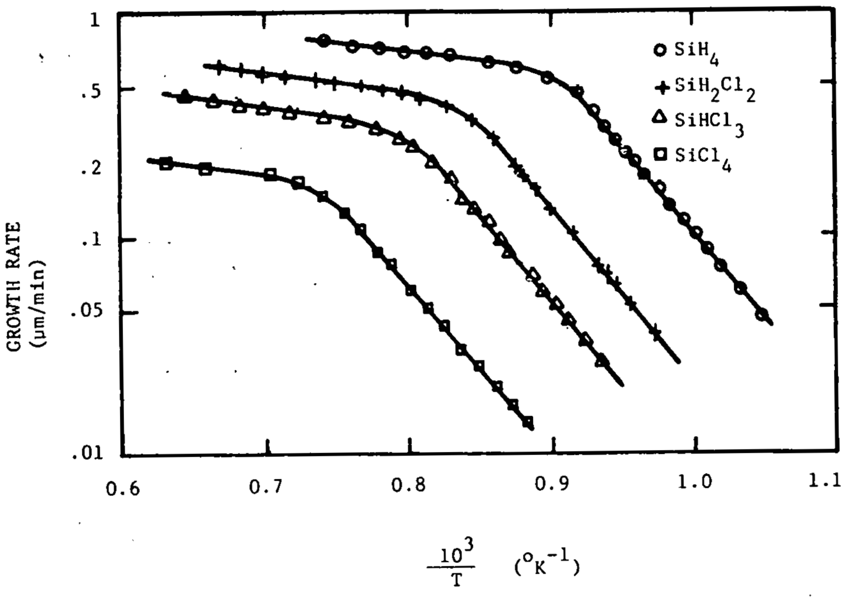
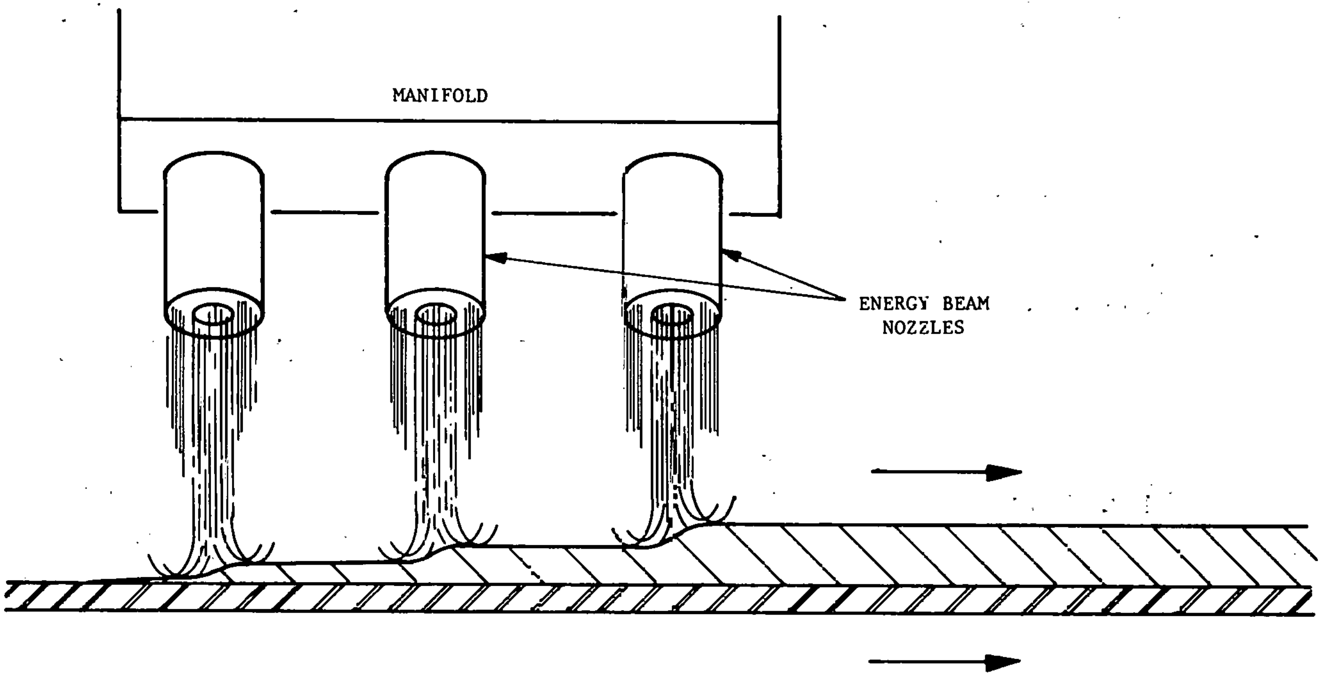


FIGURE 9 Temperature dependence of the growth rate of polycrystalline silicon, starting from nearly equal concentrations (about 0.1%) of SiH_4, SiH_2Cl_2, $SiHCl_3$ and $SiCl_4$ in hydrogen).



SILICON FILM DEPOSITION VIA THE ENERGY BEAM

UTILIZING MULTIPLE NOZZLES FROM A COMMON MANIFOLD

FIGURE 10

CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS
ERDA/SANDIA

CONTRACT NUMBER: E(29-2) - 3686
PERIOD OF CONTRACT: JUNE 1975 - SEPTEMBER 1976
VALUE: $581K

PRINCIPAL INVESTIGATOR: A. KIRPICH
ADVANCED ENERGY PROGRAMS
GENERAL ELECTRIC SPACE DIVISION
VALLEY FORGE, PA.

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3 THROUGH 6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

STUDY OBJECTIVES

- PREPARE CONCEPTUAL DESIGNS FOR THREE APPLICATIONS:
  - SINGLE FAMILY RESIDENCE
  - CENTRAL POWER PLANT
  - INTERMEDIATE SIZE SYSTEM
- DETERMINE PERFORMANCE IN SELECTED REGIONS
- PERFORM ECONOMIC ANALYSIS
- IDENTIFY TECHNOLOGY NEEDS
- IDENTIFY SIGNIFICANT BARRIER ISSUES

PART I

ON-SITE RESIDENCE RESULTS

ASSUMPTIONS FOR ON-SITE RESIDENCE STUDIES

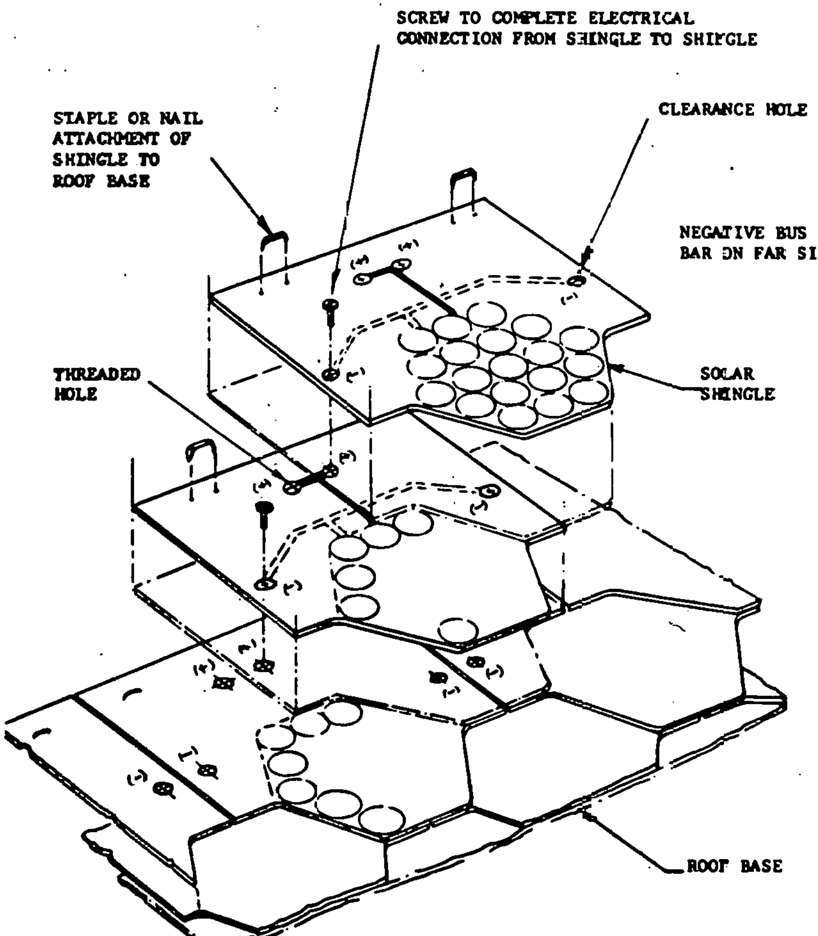
- SILICON SOLAR CELLS
- ROOF-MOUNTED PLANAR SOLAR ARRAY
- ALL-ELECTRIC RESIDENCE
  - FIXED PROFILE DIVERSIFIED LOAD (LIGHTS, APPLIANCES, ETC.)
  - VARIABLE WEATHER-DEPENDENT HEATING AND COOLING LOAD
- AC DISTRIBUTION
- UNINTERRUPTIBLE UTILITY TIE-IN
- NO POWER FEEDBACK TO UTILITY WITH ENERGY STORAGE
- POWER FEEDBACK WITHOUT ENERGY STORAGE
- LOCATIONS: CLEVELAND, PHOENIX, MIAMI

3

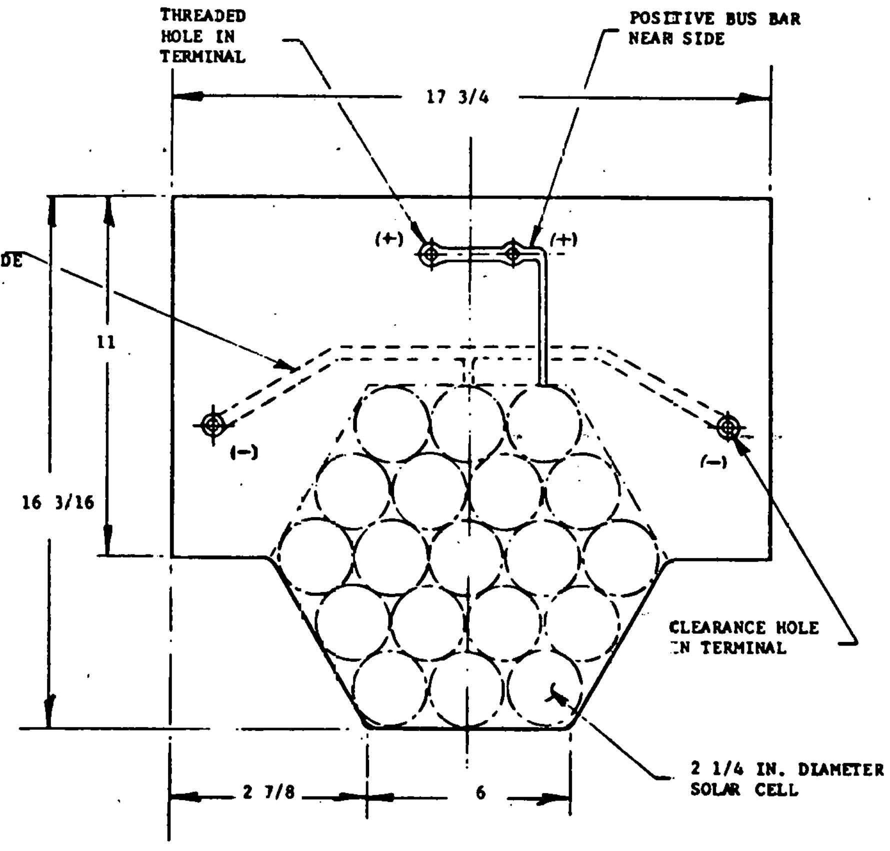
ON-SITE RESIDENCE
SYSTEM CHARACTERISTICS

PARAMETER	SYSTEM WITH BATTERIES	SYSTEM WITHOUT BATTERIES
SOLAR ARRAY		
CONFIGURATION	SHINGLE MODULES	SAME
CELL TYPE	SILICON, 5.72 cm DIA, 13.4%	
SERIES CELLS	513	
PARALLEL CELLS	64	
ROOF AREA, m^2	109	
CELL AREA, m^2	84	
ROOF AZIMUTH	0^o (DUE SOUTH)	
ROOF SLOPE	CLEVELAND 37^o PHOENIX 22^o MIAMI 17^o	
BATTERY		NONE
TYPE	LEAD ACID	
SERIES CELLS	96	
CAPACITY	250 a-h (48 KWH)	
WEIGHT	2232 Kg	
INVERTER	8 KW	13 KW

SOLAR SHINGLE DESIGN

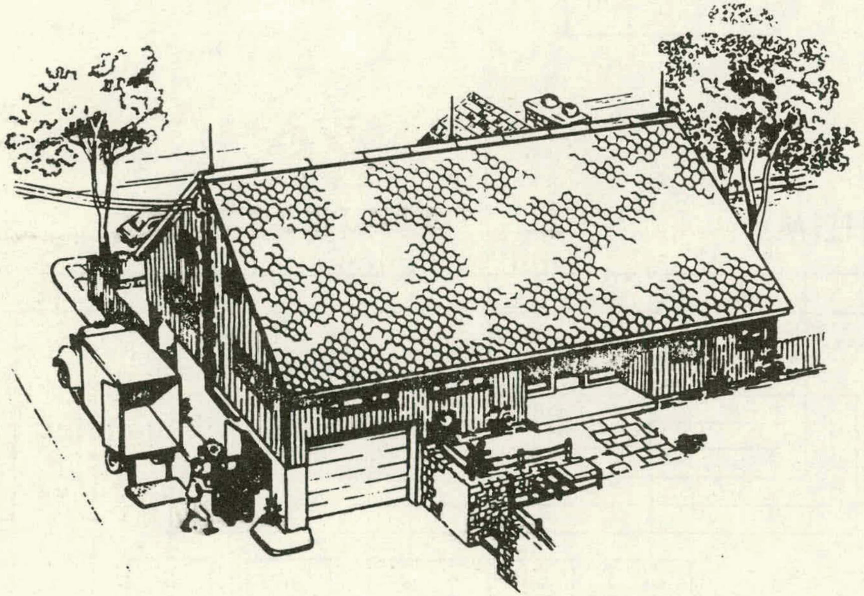


EXPLODED VIEW OF SHINGLE ASSEMBLY

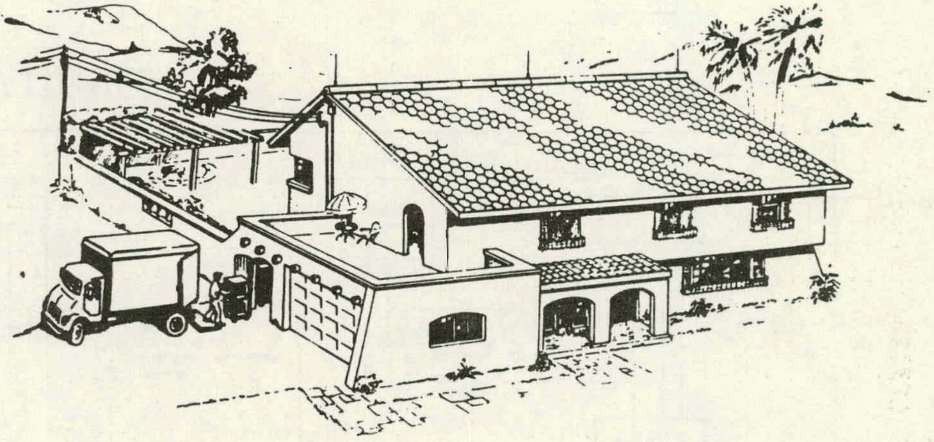


DETAIL OF SOLAR SHINGLE
(19 CELL TYPE)

ARCHITECTURAL CONCEPT

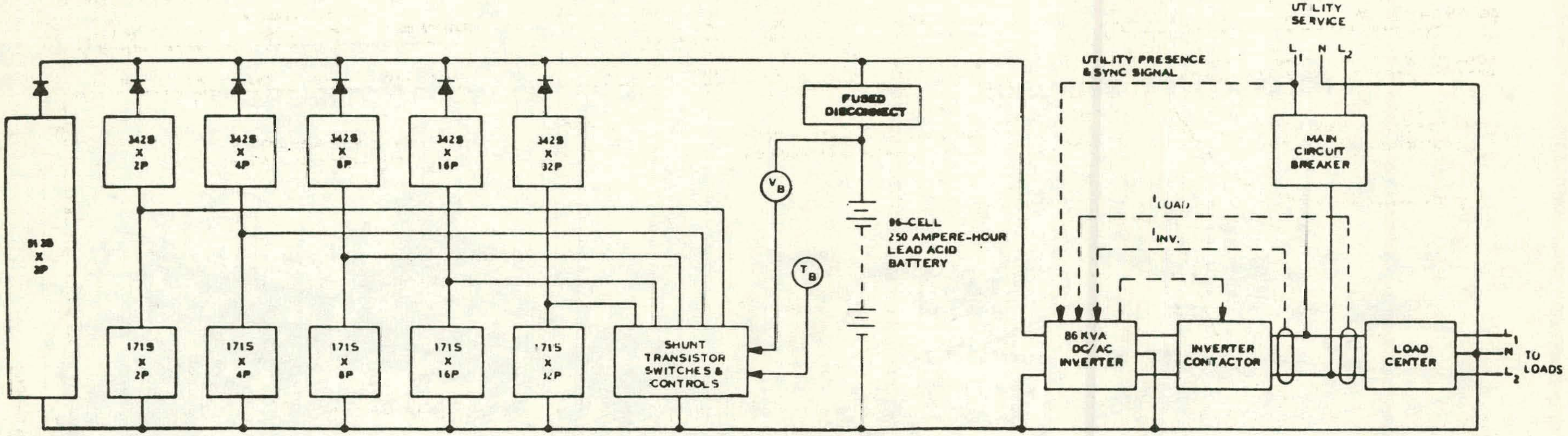


NORTHERN U.S. LOCATION

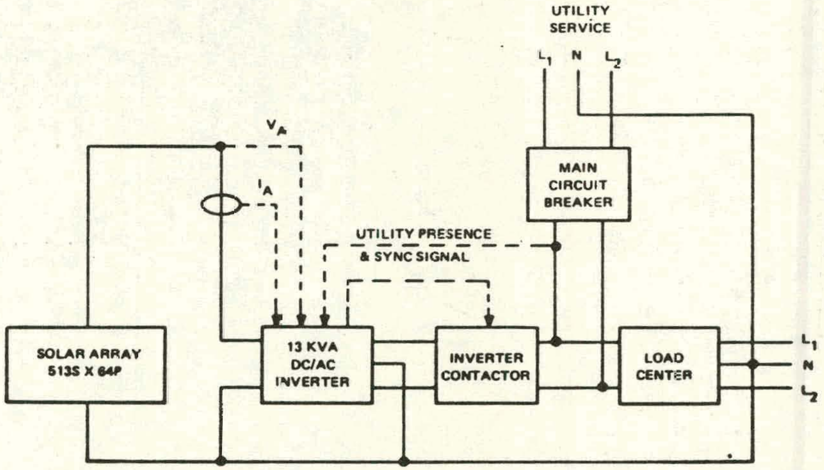


SOUTHERN U.S. LOCATION

SYSTEM SCHEMATIC

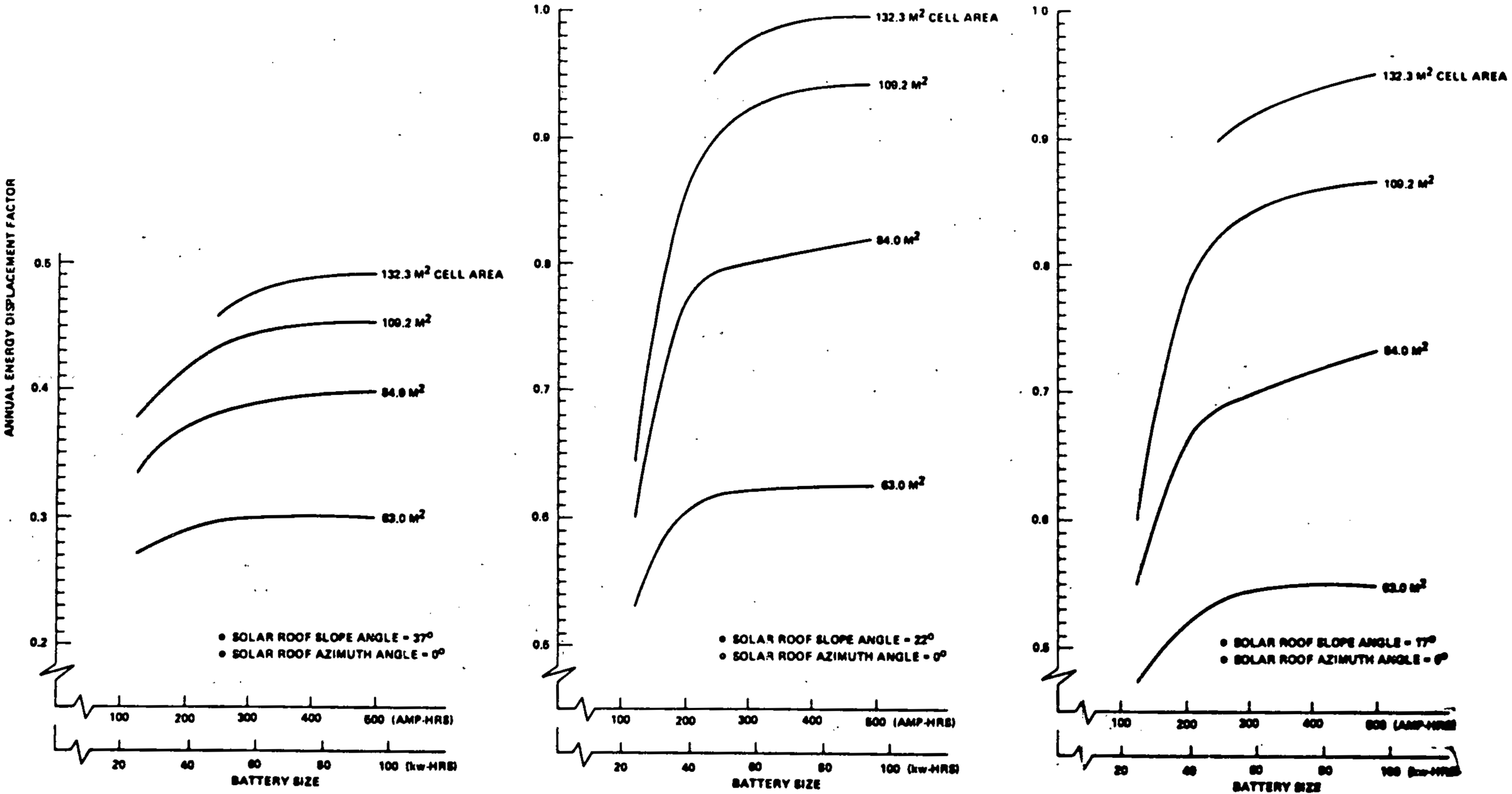


WITH BATTERIES



WITHOUT BATTERIES

PERFORMANCE SENSITIVITY TO ARRAY AND BATTERY SIZE

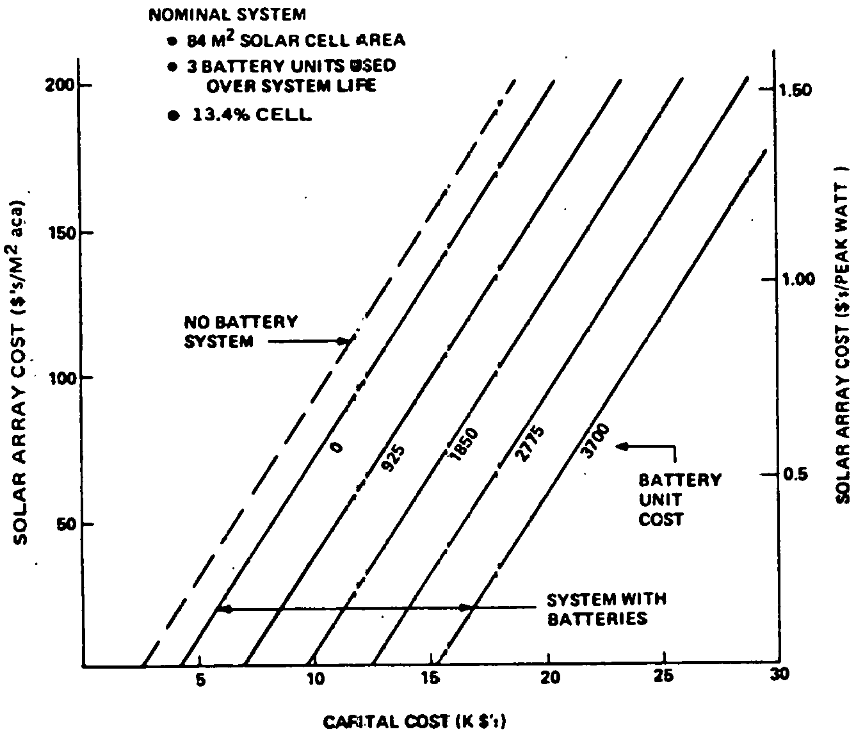


(a) CLEVELAND, OHIO

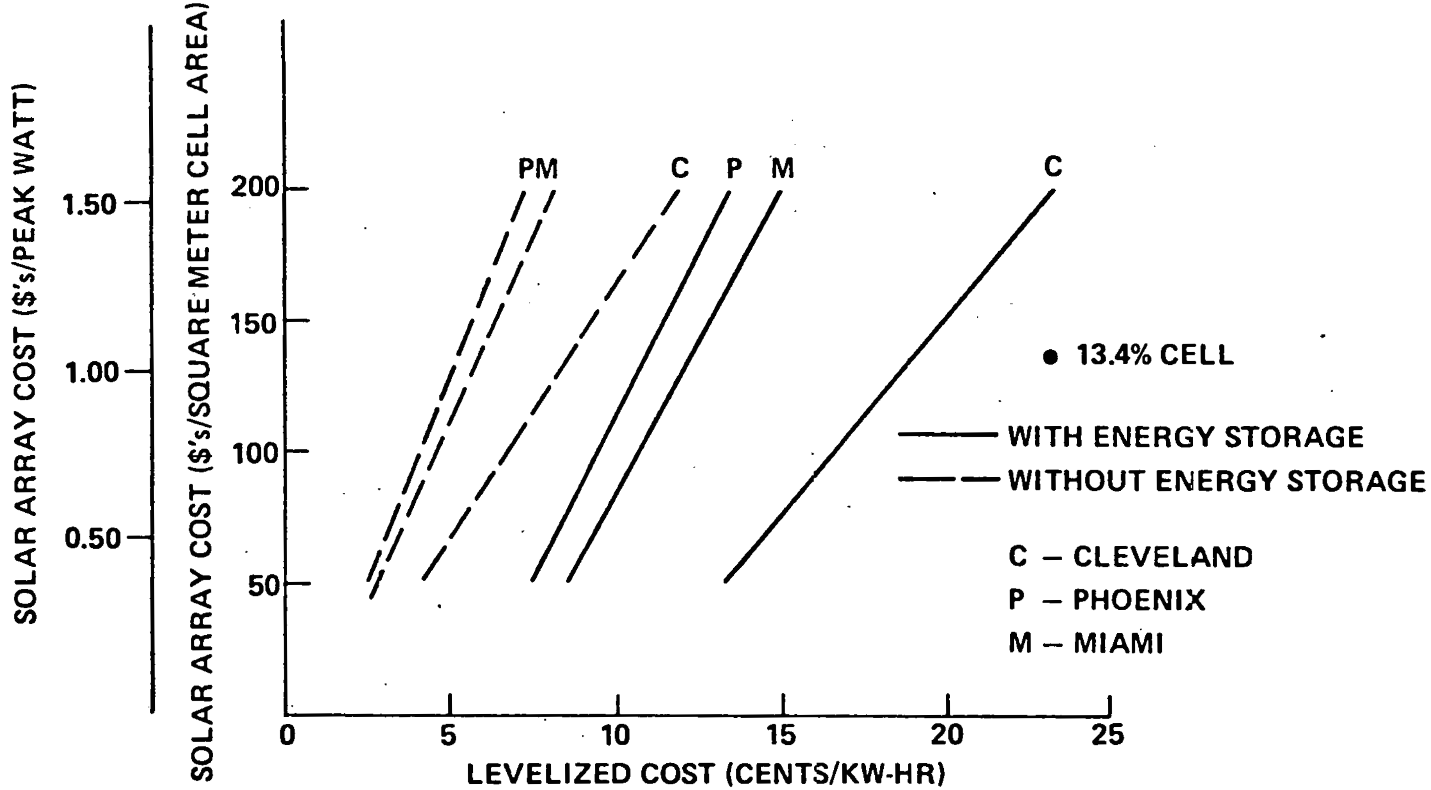
(b) PHOENIX, ARIZONA

(c) MIAMI, FLORIDA

CAPITAL COSTS FOR NOMINAL SYSTEMS



COMPARISON OF LEVELIZED COST



MAJOR CONCLUSIONS ON-SITE RESIDENCE STUDY

- MAX. ARRAY COST TO GET $.05/KWH
  - 45¢/PK WATT - CLEVELAND
  - 90¢/PK WATT - PHOENIX
- NO STORAGE WITH UTILITY FEEDBACK
  MOST COST-EFFECTIVE
- ± 15 DEGREES ACCEPTABLE FROM OPTIMUM SLOPE AND AZIMUTH
- AC OUTPUT LEAST COMPLICATED
- PRINCIPAL BARRIER CONCERNS FEEDBACK
  - FURTHER STUDY REQUIRED

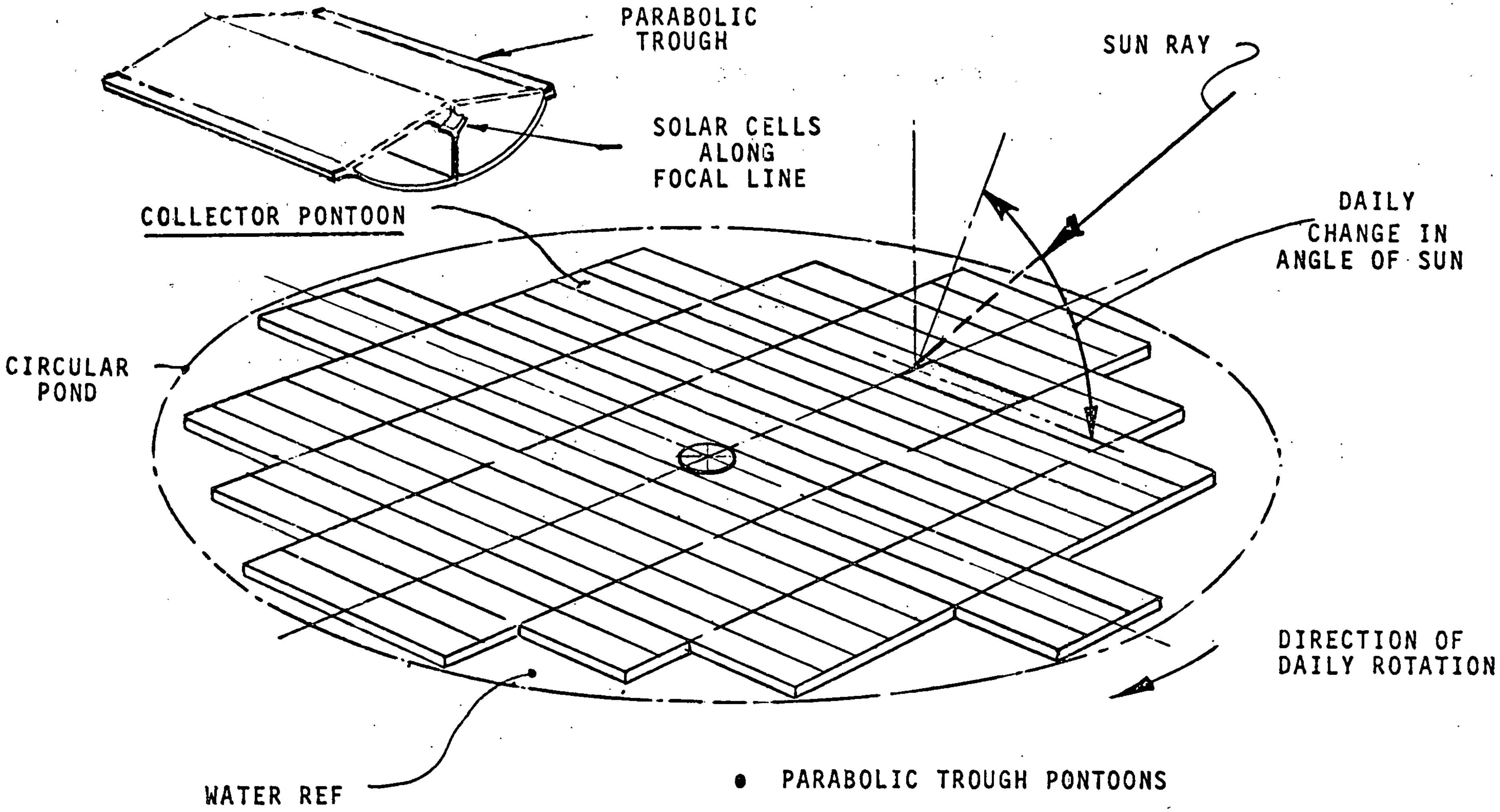
PART II

CENTRAL POWER PLANT RESULTS

ASSUMPTIONS FOR CENTRAL POWER PLANT STUDIES

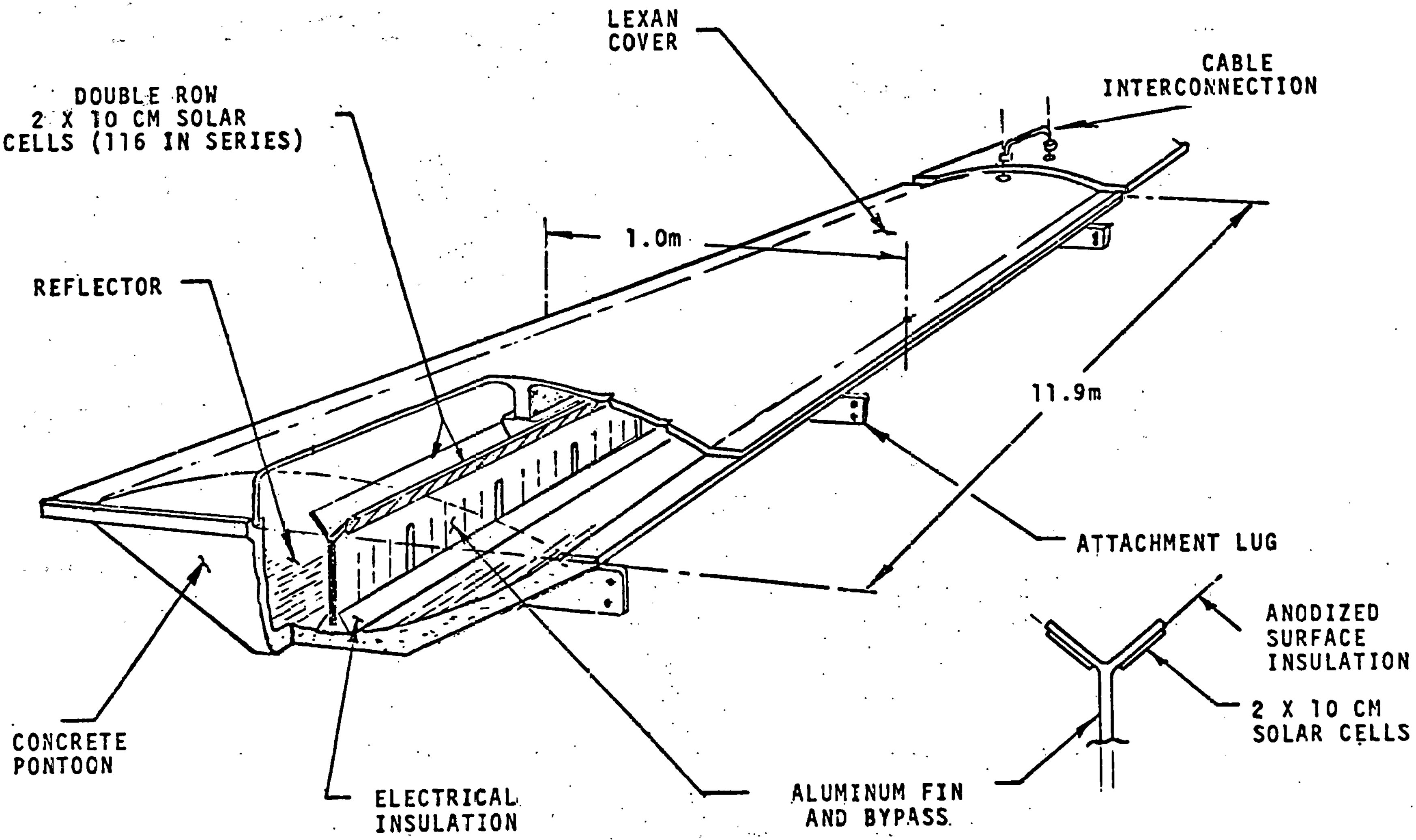
- PLANT LOCATED IN PHOENIX REGION
- PLANT FEEDS UTILITY GRID AT 345 KV
- NO ENERGY STORAGE - VARYING PLANT OUTPUT HANDLED BY DYNAMIC ADJUSTMENT OF OTHER GENERATION UNITS
- LINE COMMUTATION FOR DC/AC CONVERSION
- THREE CONCEPTS ANALYZED
  - 25 TO 1 CONCENTRATOR, SOLAR AZIMUTH TRACKER
  - 3.6 TO 1 CONCENTRATOR, SEASONAL TILT ADJUSTMENT
  - TILTED FLAT-PLATE ARRAY

SOLAR AZIMUTH TRACKER - CONCEPT NO. 1

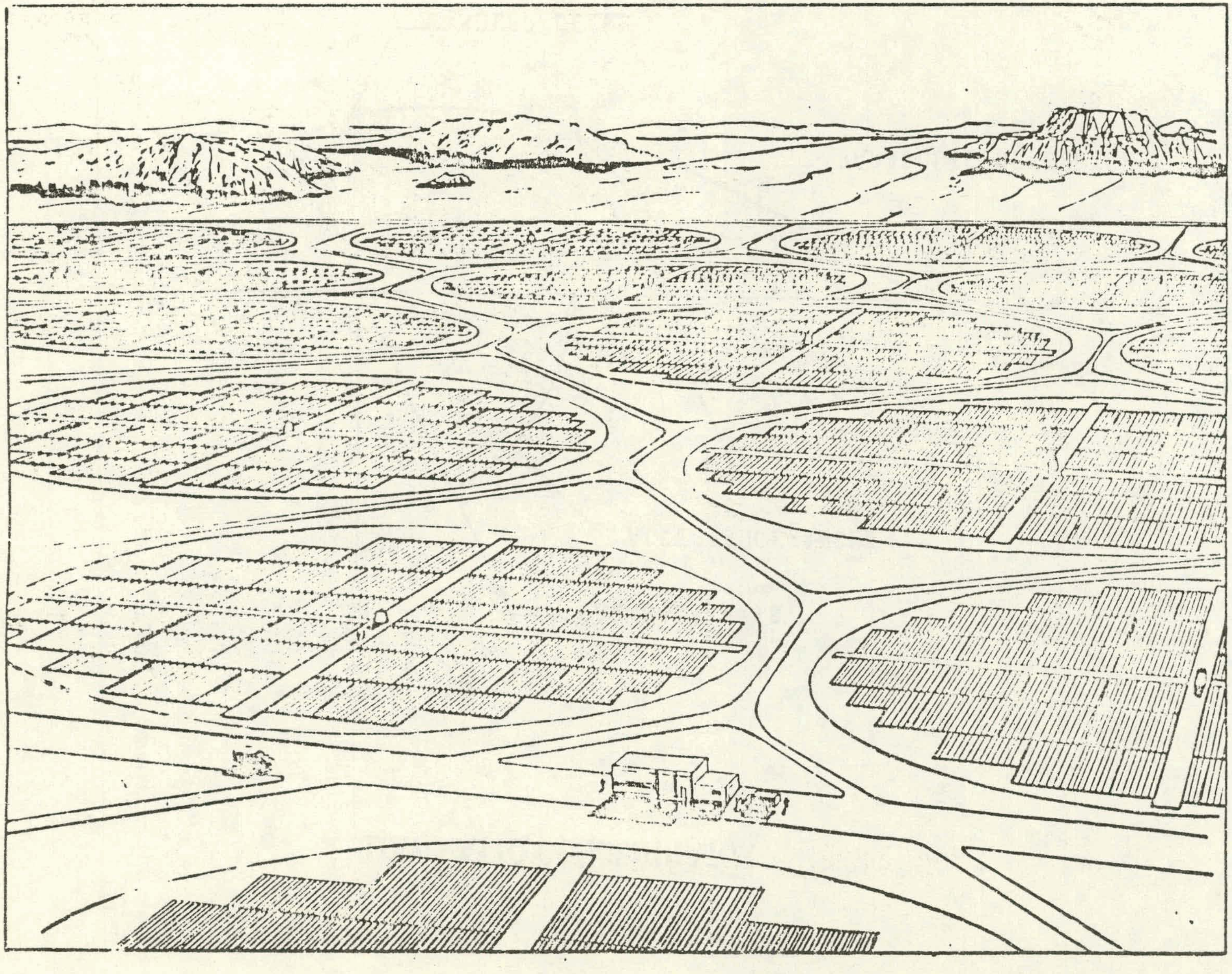


- PARABOLIC TROUGH PONTOONS
- FLOATING ARRAY FORMED BY INTERCONNECTED PONTOONS
- ARRAY DISC ROTATED TO PLACE SUN IN VERTICAL PLANE THROUGH PONTOON AXIS

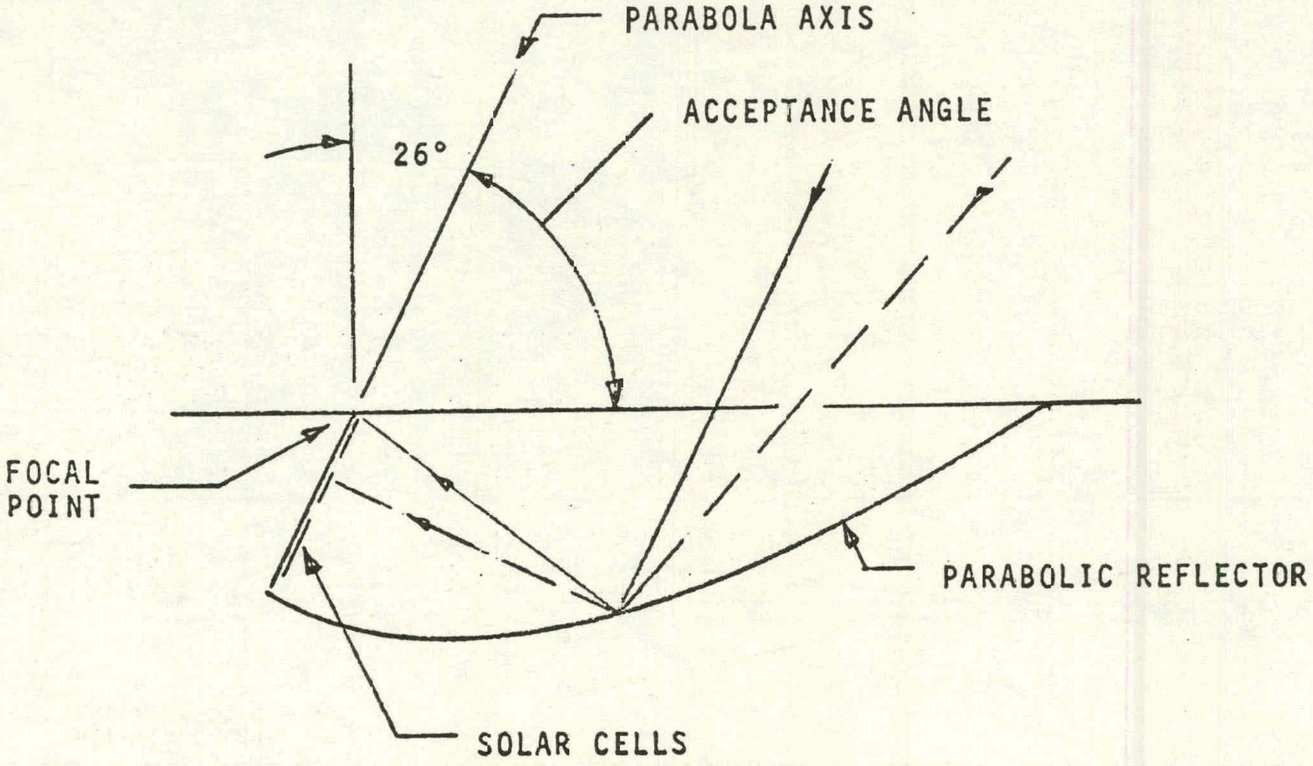
PONTOON CONCENTRATOR - CONCEPT NO. 1



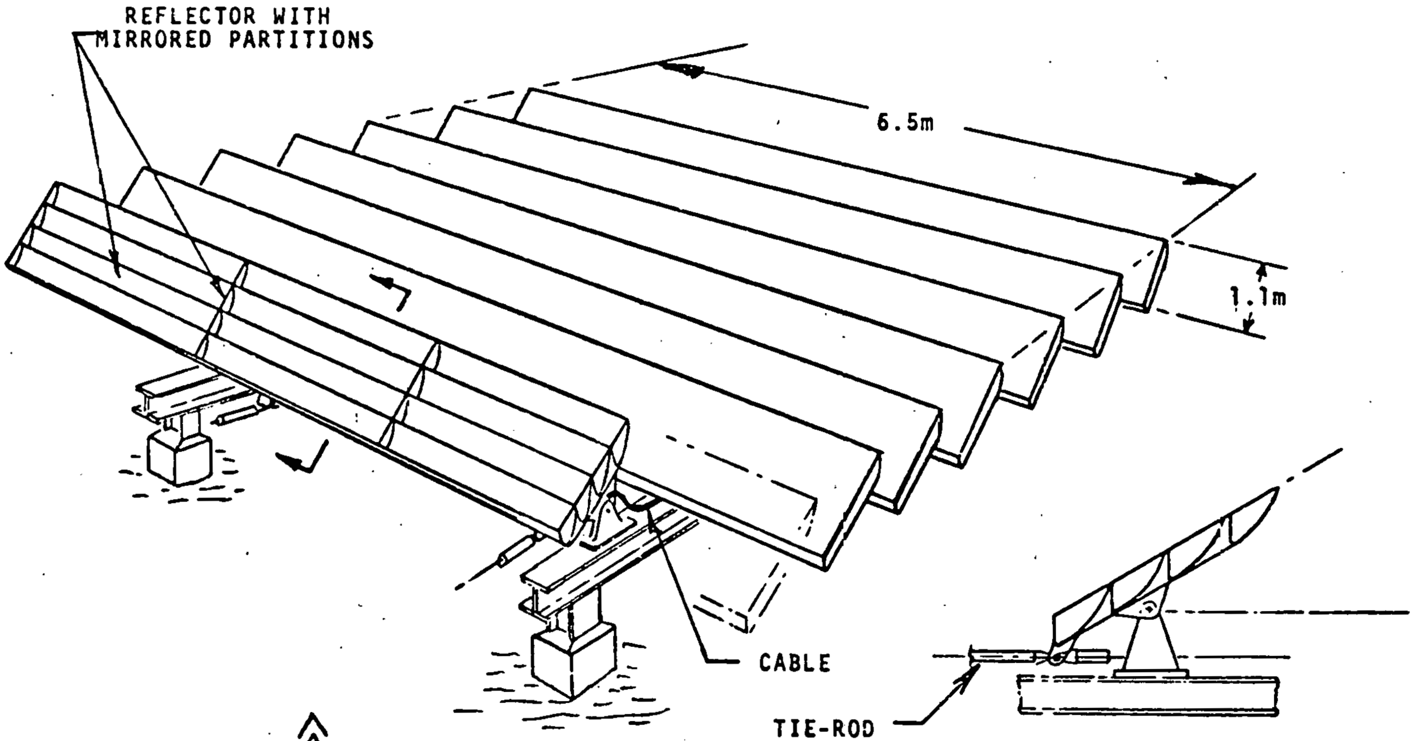
SOLAR AZIMUTH TRACKING POWER PLANT

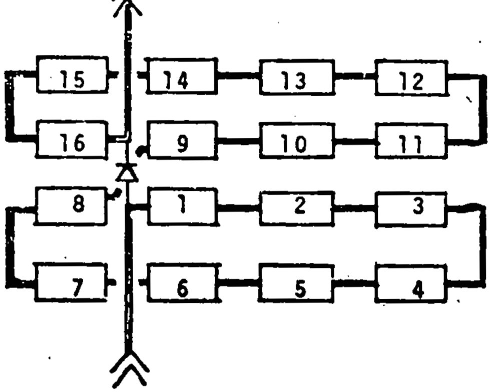


LOW-RATIO CONCENTRATOR



LOW-RATIO CONCENTRATOR SOLAR ARRAY - CONCEPT NO. 2





PANEL:
16 SERIES COMPARTMENTS
25 X 160 cm COMPARTMENT APERTURE
1000 cm^2 COMPARTMENT CELL AREA
75 KG

FIXED PANEL SOLAR ARRAY - CONCEPT NO. 3

- CONSIDERED FOR COMPARATIVE PURPOSES WITH CONCEPTS 1 AND 2 USING RESIDENCE RESULTS FOR PHOENIX
- EAST-WEST ROWS TILTED AT 22°
- ROW SPACING: 1.7 X PANEL WIDTH
- OVERALL PANEL AREA: 12.9×10^6 M^2
- OVERALL CELL AREA: 10.1×10^6 M^2
  (PACKING FACTOR = 78%)
- LAND AREA: 24 KM^2
- PERFORMANCE: SAME AS CONCEPT NO. 1 USING 13.4% EFFICIENT CELL
  (100 MW/CM^2, 28°C, AM2)

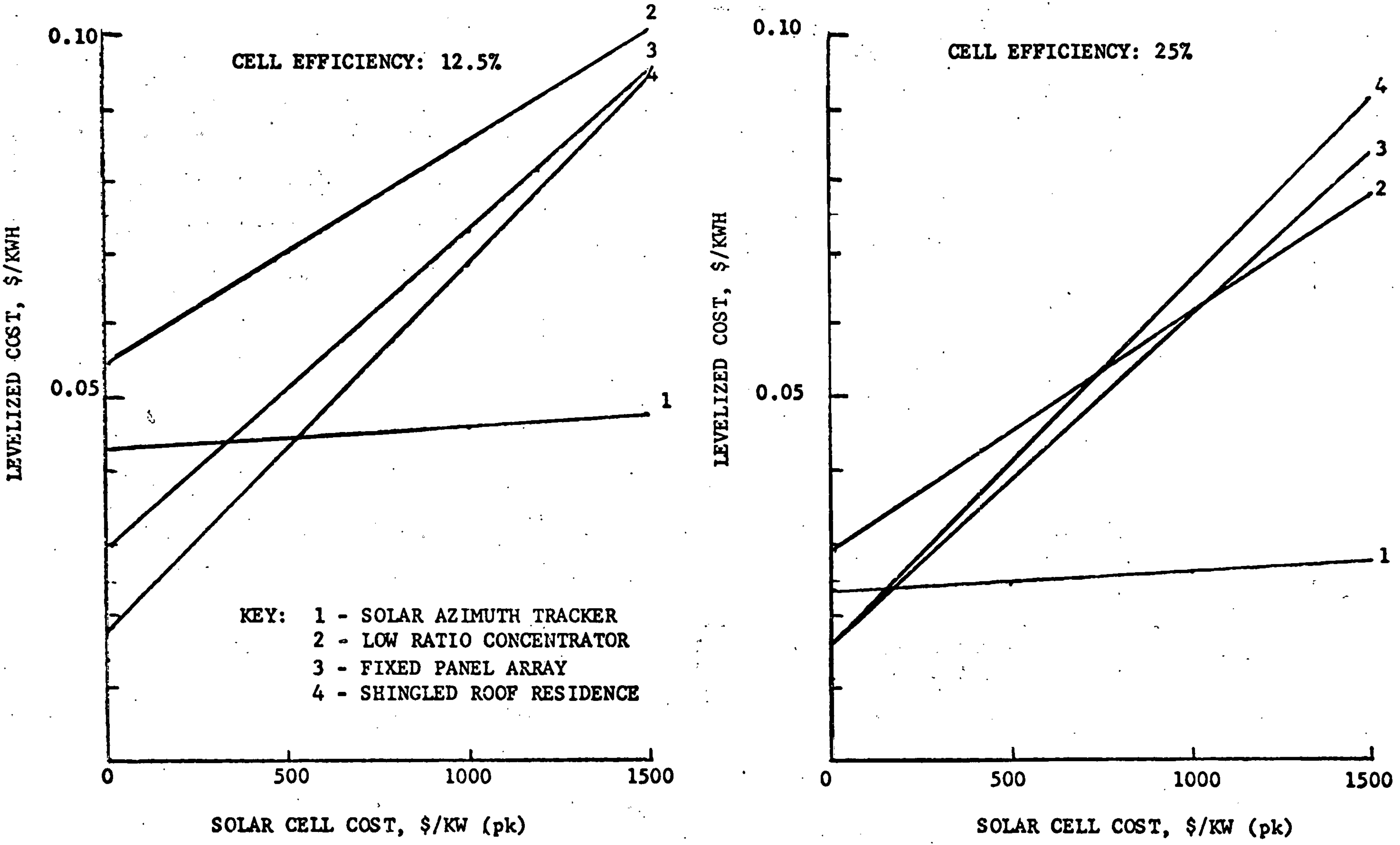
SIZE COMPARISON OF CONCEPTS

CONCEPT	1	2	3
DESCRIPTION	SOLAR AZIMUTH TRACKER	LOW-RATIO CONCENTRATOR	FIXED PANEL ARRAY
NOMINAL CELL	11.8%	13.4%	13.4%
CELL AREA	1.0 KM^2	7.3 KM^2	10.1 KM^2
COLLECTOR AREA	25.0 KM^2	32.6 KM^2	12.9 KM^2
LAND AREA	50.0 KM^2	39.3 KM^2	24 KM^2
ANNUAL PERFORMANCE	2.83 X 10^6 MHW	2.83 X 10^6 MHW	2.83 X 10^6 MHW

CENTRAL POWER PLANT CAPITAL COSTS
(IN MILLIONS OF $)

COST ELEMENT	CONCEPT NO. 1 SOLAR AZIMUTH TRACKER		CONCEPT NO. 2 LOW-RATIO CONCENTRATOR		CONCEPT NO. 3 FIXED PANEL ARRAY	
ARRAY SYSTEM						
LAND (@ $500 HECTARE)	$ 2.5		$ 2.0		$ 1.2	
SITE PREPARATION DEVELOPMENT	116.1		18.5		12.4	
SOLAR CELLS (@$50/m^2)	50.0		365.0		505.0	
SOLAR COLLECTORS	852.9		789.3		302.6	
MISC (SUPPORT, ARRAY CABLING, ETC.)	133.4		346.8		231.2	
SUBTOTAL		1154.9		1521.6		1052.4
ELECTRICAL PLANT SYSTEM						
CONVERTER STATIONS (50) BLDG. EQUIP.	105.6		105.6		105.6	
TRANSFORMER STATIONS (5) BLDG. EQUIP.	15.0		15.0		15.0	
SWITCHING STATION (1) BLDG. EQUIP.	6.5		6.5		6.5	
PLANT CONTROL CENTER BLDG. EQUIP.	2.5		2.5		2.5	
UNDERGROUND CABLING & CONDUIT	11.3		11.3		11.3	
TOWERS & FIXTURES, SWITCHING STATION	1.0		1.0		1.0	
YARDWORK	0.8		0.8		0.8	
SUBTOTAL		142.7		142.7		142.7
TOTAL (MAJOR COMPONENTS, LABOR MATERIAL)		1297.6		1664.3		1195.1

COMPARISON OF LEVELIZED COSTS



MAJOR CONCLUSIONS
CENTRAL POWER PLANT STUDY

- TO ACHIEVE ECONOMIC PARITY -

  HIGH CONCENTRATION: 1-2 \$/PK WATT
  @ 20% CELL EFFICIENCY

  FLAT-PLATE: 0.20 \$/PK WATT
  @ 20% CELL EFFICIENCY

  LOW CONCENTRATION: NOT ACHIEVABLE
- HIGH CONCENTRATION PROVIDES BEST CHANCE FOR MEETING ECONOMIC GOALS
- LOW CONCENTRATION DISAPPOINTING
- FOR CONCENTRACTORS, HIGHER CELL EFFICIENCY MORE IMPORTANT THAN CELL COSTS

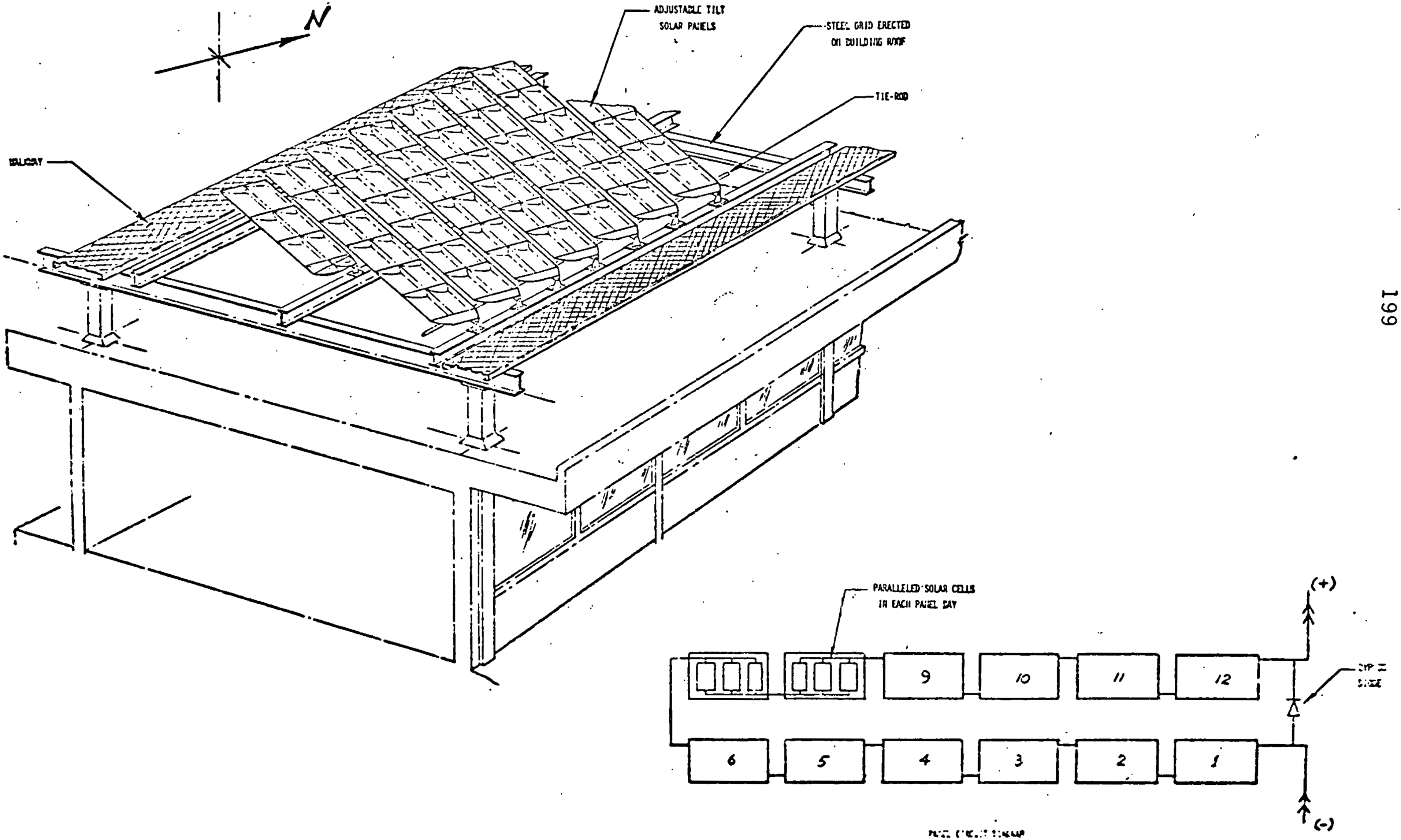
PART III

INTERMEDIATE SCHOOL SYSTEM APPLICATION

ASSUMPTIONS FOR INTERMEDIATE SCHOOL SYSTEM STUDY

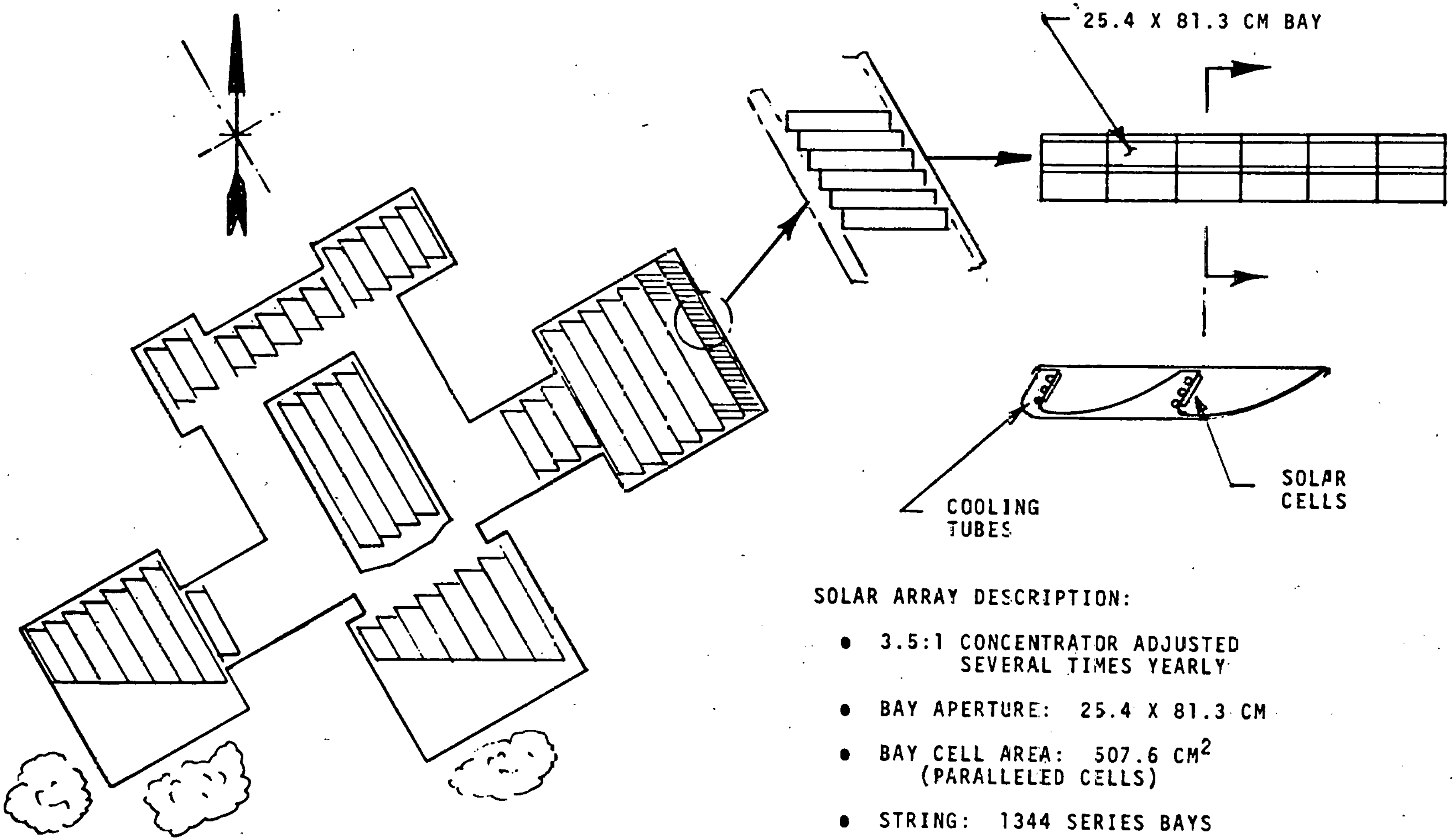
- BUILDING - VALLEY FORGE JUNIOR HIGH SCHOOLS
  - 1200 STUDENTS
  - SINGLE STORY
  - ROOF AREA - 10,000 M^2
- 1963 WASH, D.C. WEATHER DATA TAPE
- UTILITY OWNS SYSTEM
- NO ELECTRICAL ENERGY STORAGE
- PV OUTPUT FED TO UTILITY GRID
- THERMAL OUTPUT USED FOR BUILDING HEATING & COOLING
- UTILITY SELLS THERMAL ENERGY AT CURRENT-YEAR
  - OIL PRICES
- RETROFIT APPLICATION

SCHOOL SOLAR ARRAY CONCEPT



PANEL CIRCUIT DIAGRAM

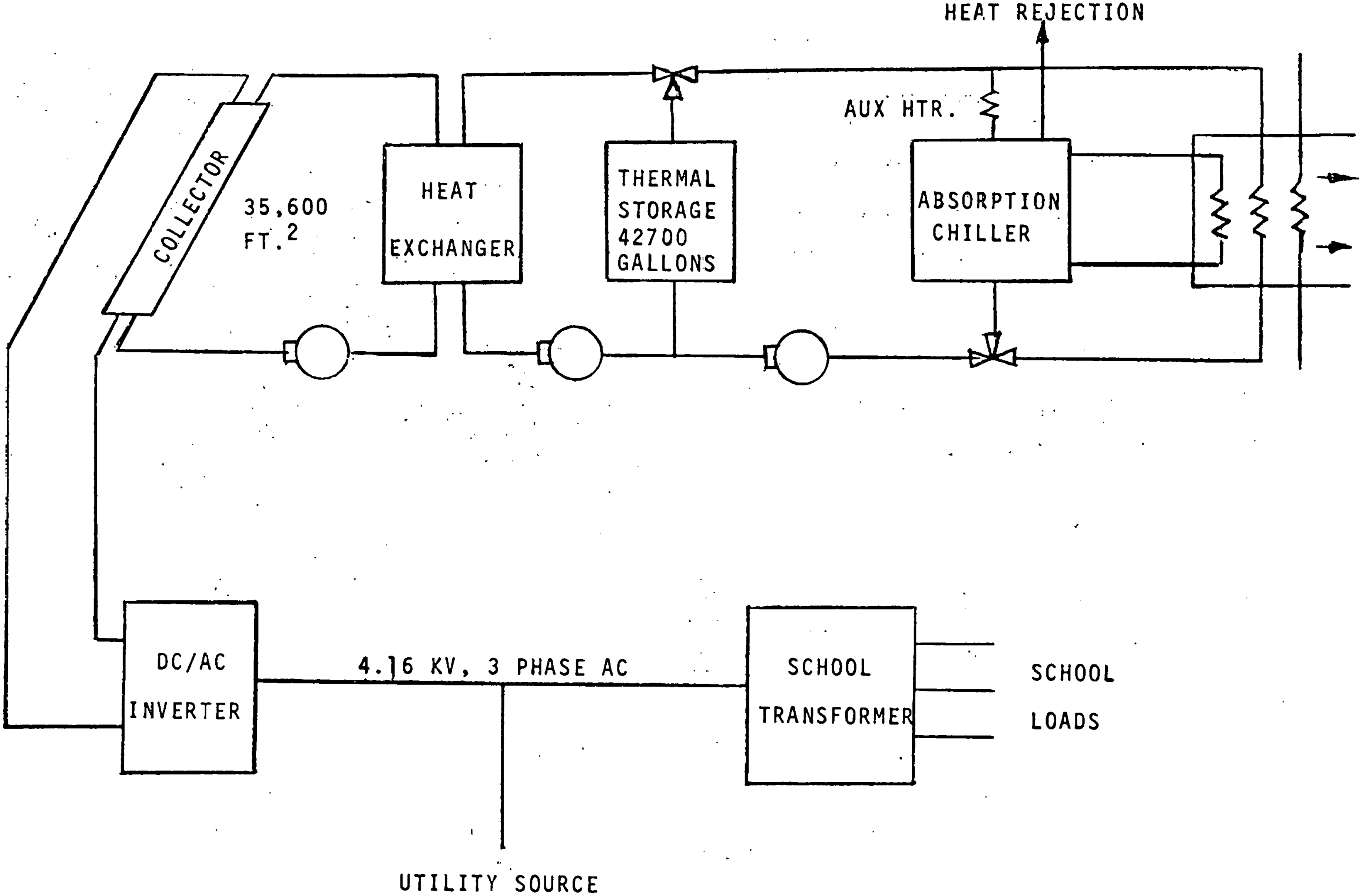
SCHOOL SOLAR ARRAY LAYOUT



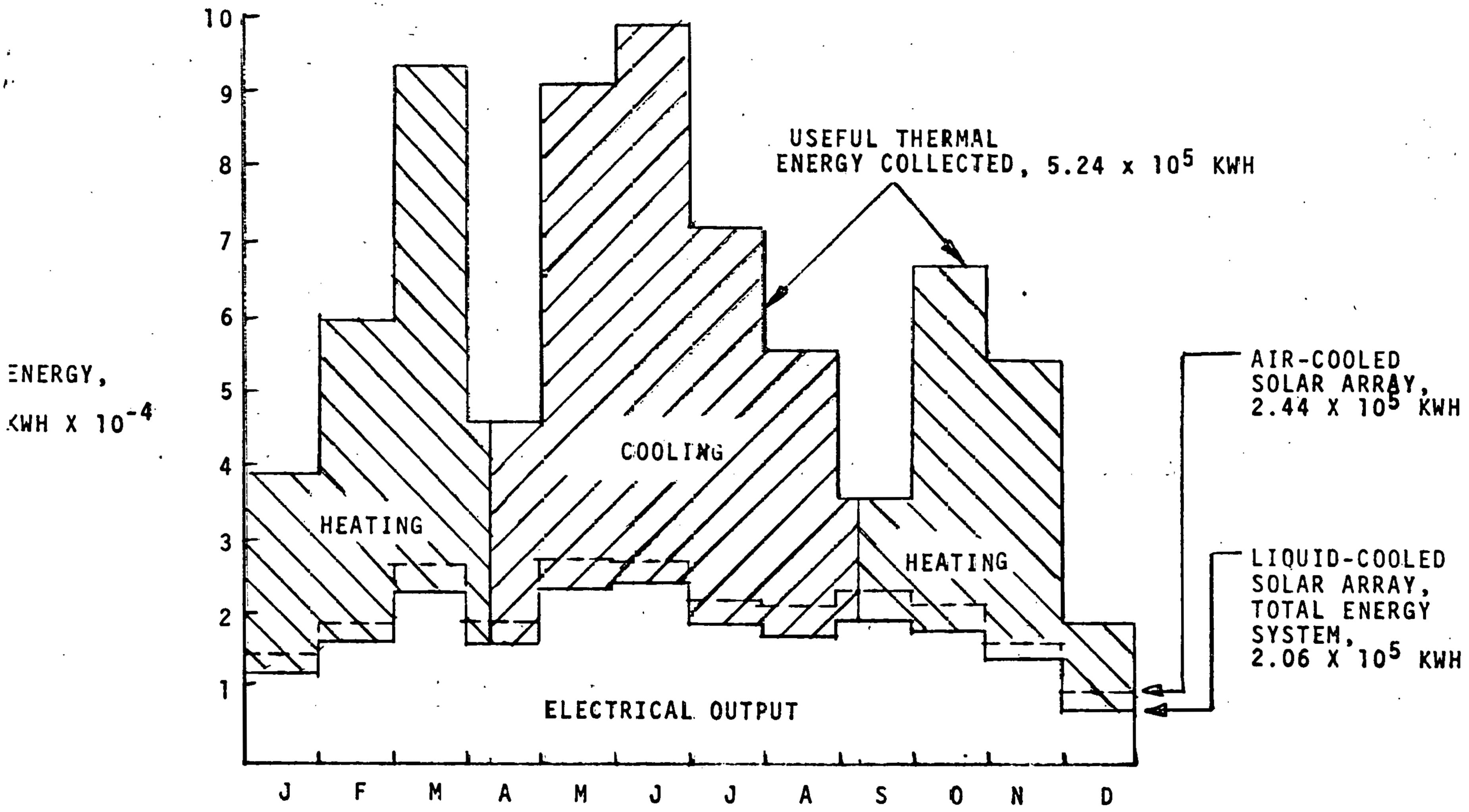
SOLAR ARRAY DESCRIPTION:

- 3.5:1 CONCENTRATOR ADJUSTED SEVERAL TIMES YEARLY
- BAY APERTURE: 25.4 X 81.3 CM
- BAY CELL AREA: 507.6 CM^2 (PARALLELED CELLS)
- STRING: 1344 SERIES BAYS
- OVERALL ARRAY
  12 STRINGS
  540 VOLTS NOMINAL
  400 AMPS PEAK
  3330 M^2 APERTURE
  818 M^2 SOLAR CELLS

BLOCK DIAGRAM, SCHOOL TOTAL ENERGY SYSTEM



PERFORMANCE - SCHOOL TOTAL ENERGY SYSTEM



CAPITAL COSTS

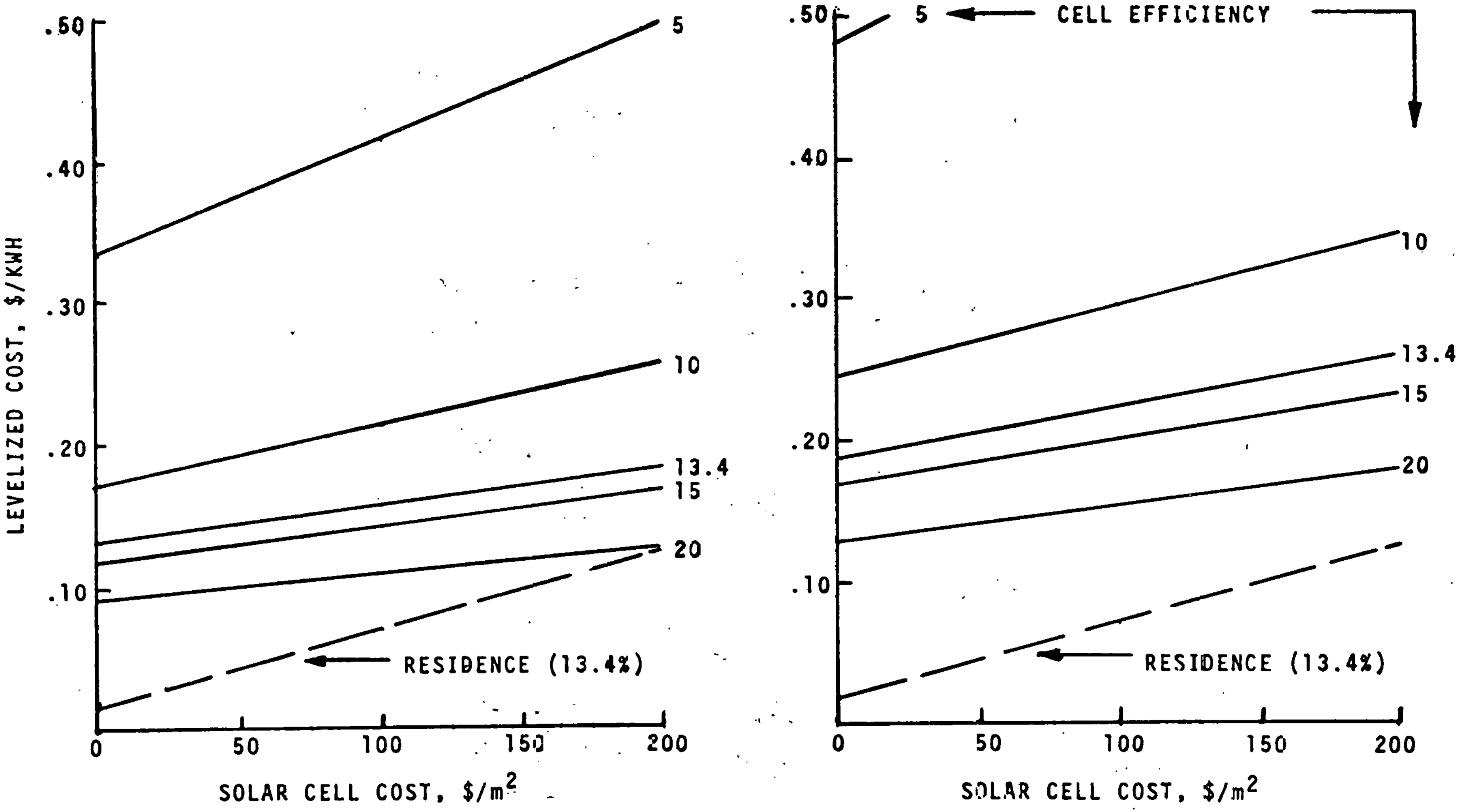
NOMINAL SYSTEM

- 818 M^2 SOLAR CELL AREA
- 3330 M^2 APERTURE

COST ELEMENT	PHOTOVOLTAIC-ONLY	PHOTOVOLTAIC/THERMAL
CAPITAL		
SOLAR CELLS (@ \$50/M^2)	\$ 40.9K	\$ 40.9K
COLLECTORS	88.6	122.0
SUPPORT, CABLING, ETC	115.7	210.1
DC/AC CONVERSION	24.0	24.0
PRIMARY THERMAL LOOP	-	8.7
SECONDARY THERMAL LOOP	-	30.3
TOTAL	\$269.2	\$436.0
O&M	\$ 10.3	\$ 12.7

LEVELIZED COST, INTERMEDIATE SCHOOL SYSTEM

- WASHINGTON, D.C. LOCATION
- NO ENERGY STORAGE
- 30 YEAR LIFE
- 15% DISCOUNT RATE



PHOTOVOLTAIC - ONLY

PHOTOVOLTAIC/THERMAL

MAJOR CONCLUSIONS
INTERMEDIATE SCHOOL SYSTEM

- NEW INTEGRATED DESIGNS PREFERRED
  - RETROFIT TOO COSTLY
- COMBINED PV/THERMAL NOT COST-EFFECTIVE FOR NORTHEAST; FURTHER STUDY REQUIRED
- SEASONALLY ADJUSTED LOW-RATIO CONCENTRATORS APPEAR MARGINAL; FURTHER STUDY REQUIRED

OVERALL CONCLUSIONS

- ORDER OF LIKELIHOOD IN MEETING ECONOMIC GOALS:
  - TRACKING CONCENTRATORS
  - FLAT-PLATE, INTEGRAL WITH ROOF
  - FLAT-PLATE, FREESTANDING PANELS
  - LOW-RATIO CONCENTRATORS
- INCLUDE ROOFING FUNCTION IN PV DESIGNS
  - DOUBLE DUTY NEEDED FOR COMPETITIVE DESIGN
- CRITICAL ISSUES
  - LONG LIFE
  - FEEDBACK TO UTILITY

CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS

ERDA
Albuquerque Operations Office

Contract No. E(11-1)2744

Period of Grant: June 15, 1975 to September 30, 1976

Value: $616,216

Dr. Paul F. Pittman

Manager, Power Electronics Applications, Principal Investigator

Westinghouse Research Laboratories

1310 Beulah Road

Pittsburgh, Pennsylvania 15235

Presented at the National Solar Photovoltaic Program

Review Meeting

August 3-6, 1976

University of Maine at Orono

Orono, Maine 04473

CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS

I. OVERALL OBJECTIVE - The overall objective of this program is to study the systems required to generate electricity utilizing photovoltaic solar cells, and to determine their cost and performance when installed during the 1985 to 2000 time period.

II. PREVIOUS ACTIVITIES - The original contract extended from June 15, 1975 to June 15, 1976 and included the conceptual design and systems analysis of three types of photovoltaic electric power systems. The systems analyzed were:

1. On-site Residential Power Systems (1-10 kW)
2. Intermediate Power System (100 kW - 10 MW)
3. Central Power System (50 - 1000 MW)

The original contract called for the development of conceptual system designs, the determination of subsystem requirements and conceptual designs, the performance of subsystem cost/performance tradeoffs, and finally the execution of cost/performance tradeoffs for the entire system. In addition, related non-technical issues were addressed.

III. CURRENT EFFORT - At present, the data generated during the original contract is being reviewed and organized into a final report covering all three systems.

IV. SUMMARY OF KEY RESULTS - The results are summarized by system as follows:

RPS - The key results are presented in Table 1. Seven different locations through the country were considered. These represent goegraphic variations which are representative of the entire country, and correspond also to reasonable demographic subdivisions. A total energy system supplying a percentage of the electrical and thermal loads of the residence provides the best cost/performance tradeoff in virtually all areas of the country. Based on the solar cell costs and efficiencies shown, which are generally in correspondence with ERDA's goals, the figures-of-merit calculated show on-site residential systems will become economically attractive nearly everywhere in the nation by 2000 if the volume and electric rate assumptions shown are fulfilled.

IPS - The IPS studied is a 500 kW system associated with a substation supplying a rather peaked commercial load, such as a shopping center. Two cases of ownership were considered, one by the proprietor and the other by the utility. The results of the proprietory ownership analysis are shown in Table 2. Although the normal industrial goal of 15% DCF ROI can be exceeded, the risk of such an investment is high, making it appear less attractive than that of utility ownership, the results of which are shown in Table 3. The utility owned IPS is assumed to be an adjunct to a battery load-leveling plant, and as a result of the use of common facilities and equipment, it can generate power at a busbar cost below 40 mills/kWh.

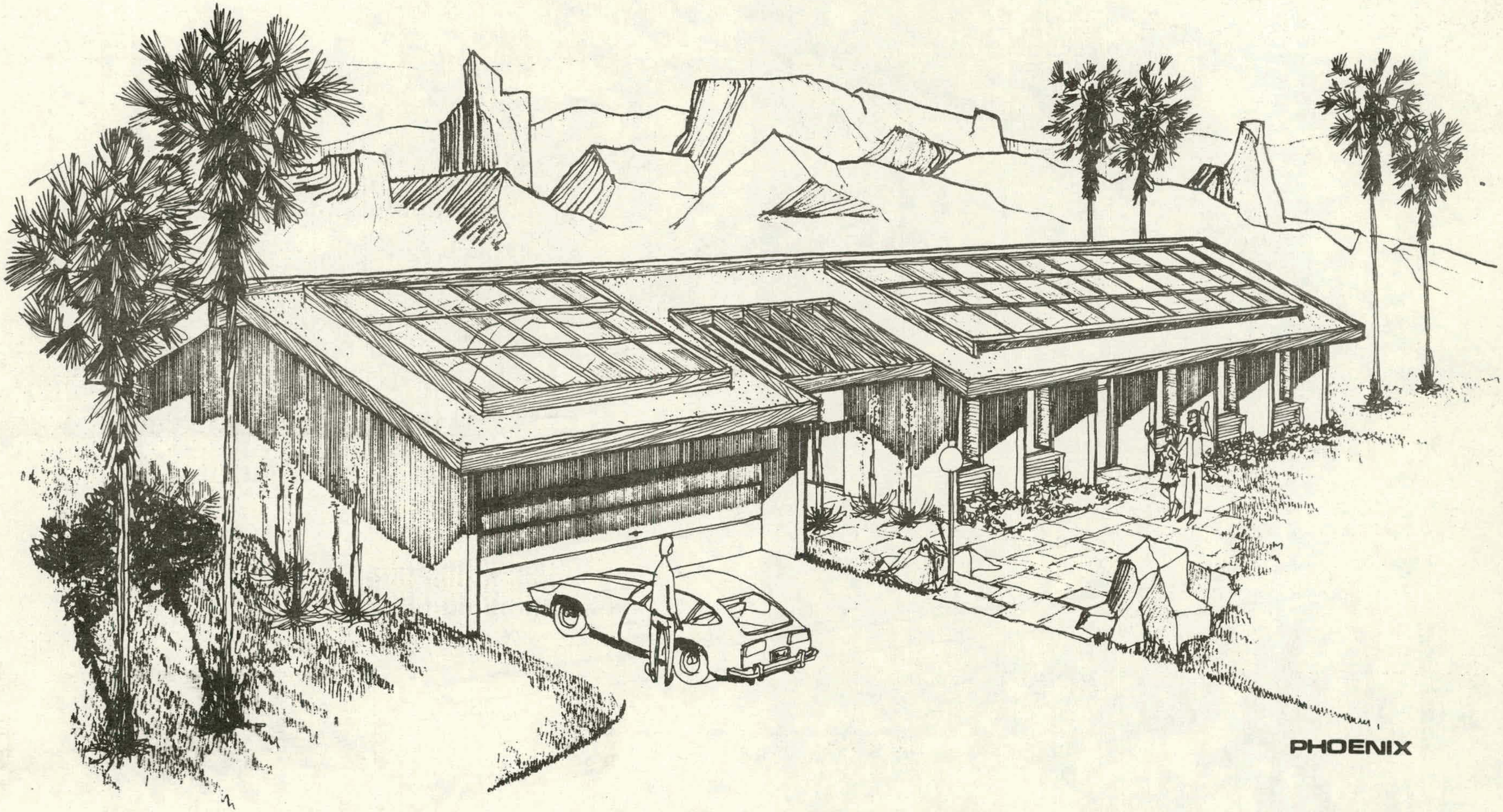
CPS - The CPS studied is a 100 MW central station power plant without storage. A number of tracked and fixed arrays were analyzed both with and without concentration, and with and without water or forced-air cooling. The overall result is that for solar cell costs below $400/kW, a fixed-tilt collector/reflector array yields an optimum cost/performance tradeoff. A solar cell cost of $100/kW at 10% efficiency will make possible a busbar electrical energy cost of 40 mills/kWh for a publicly owned utility, while an efficiency of 16% is needed for the same busbar energy cost if the utility is investor-owned. The results of a present-worth cost/benefit calculation including capacity displacement show a favorable cost/benefit ratio for a publicly owned-utility, but unfavorable for an investor owned utility using 10% cells, although only marginally so if 16% cells are used.

V. FUTURE PLANS - A follow-on addition has been received covering the period from June 15, 1976 to September 30, 1976. Included are the following four study tasks:

1. Autonomous residence.
2. Utility-residence interface.
3. Fresnel lens optimization.
4. Utility system reliability calculation methodology.

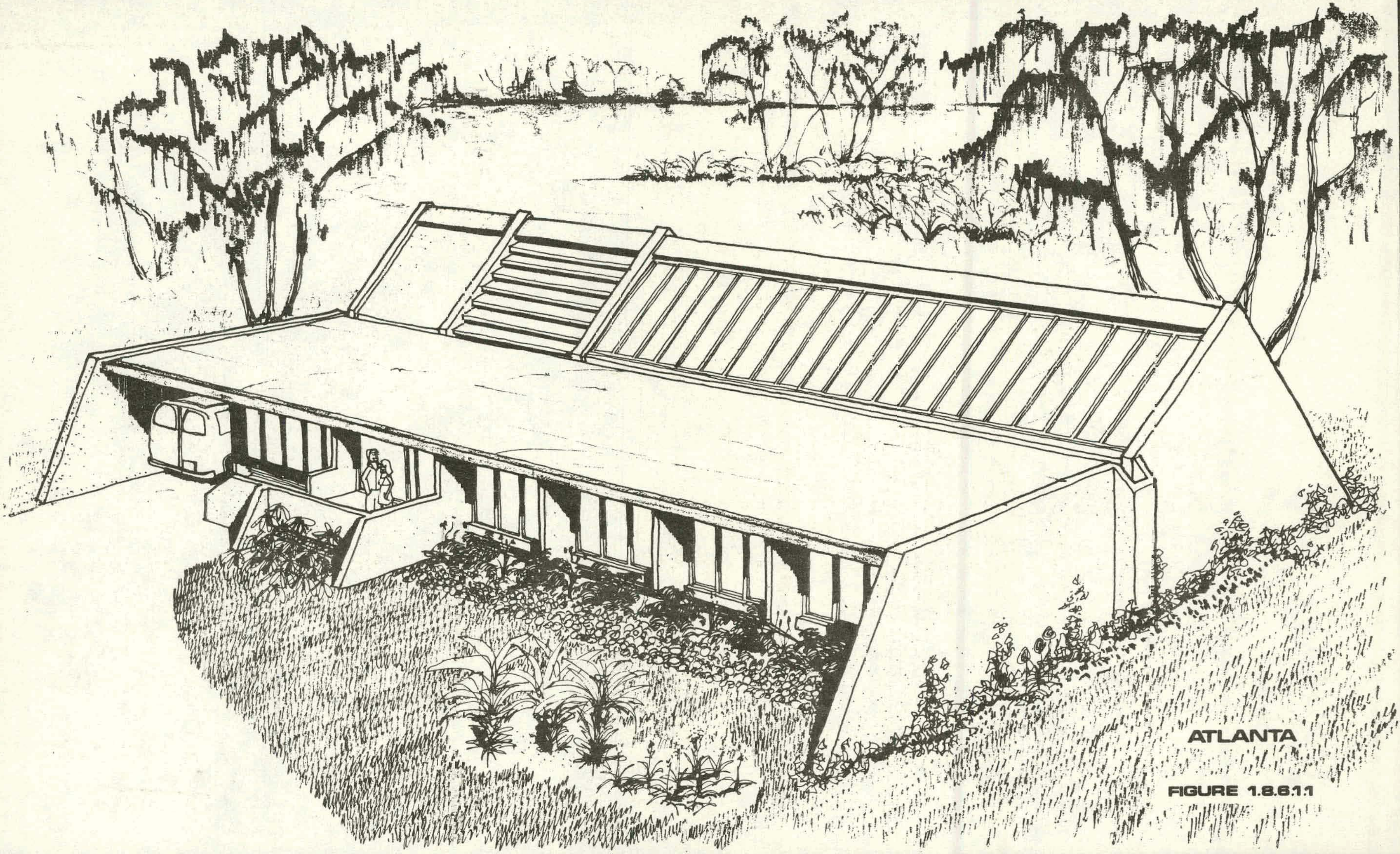
SYSTEMS STUDIED

1. RESIDENTIAL ON-SITE POWER SYSTEM (1 - 10 kW)
2. INTERMEDIATE POWER SYSTEM (0.1 - 10 MW)
3. CENTRAL POWER SYSTEM (50 - 1000 MW)



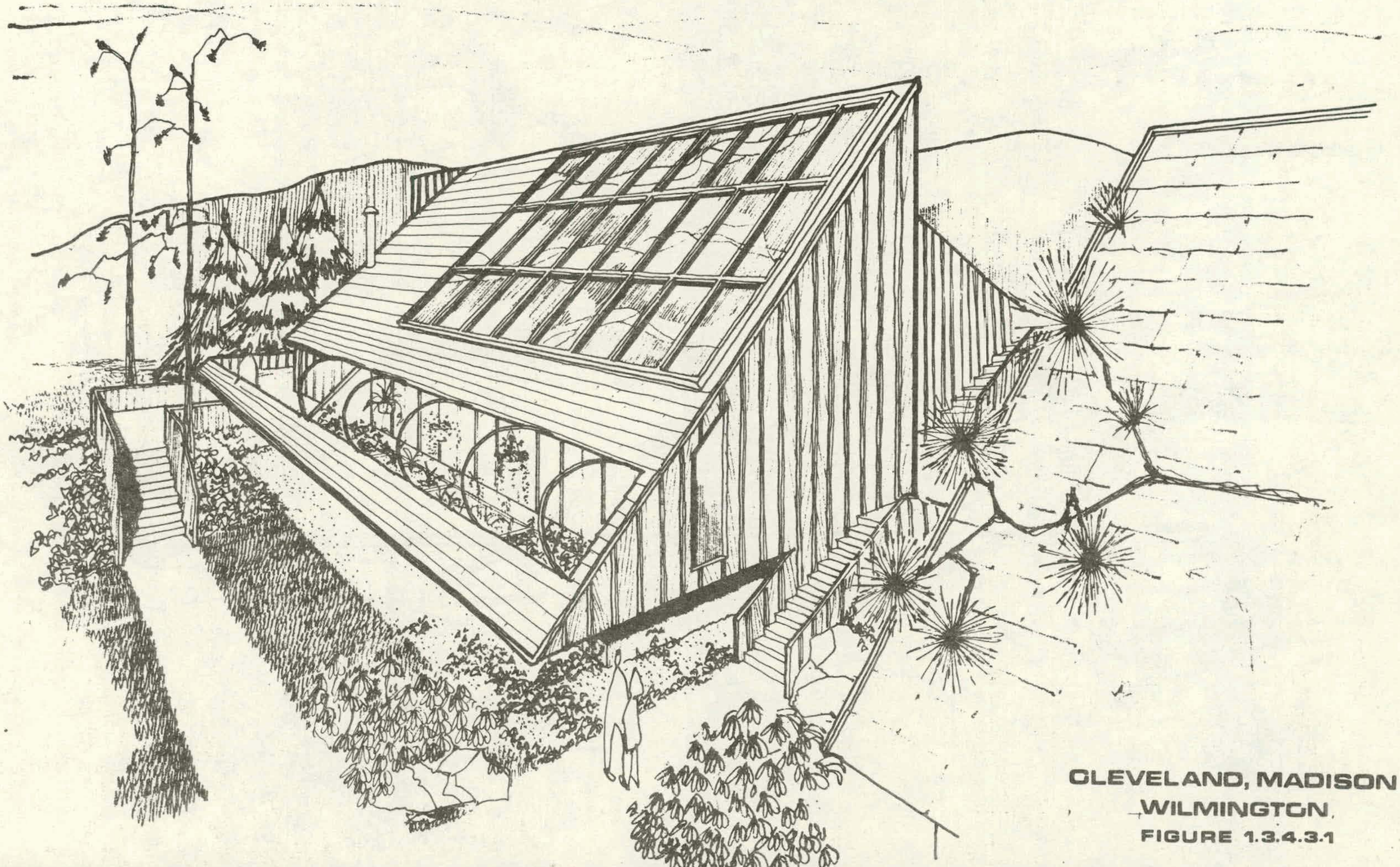
PHOENIX

FIGURE 1.8.4.1.1

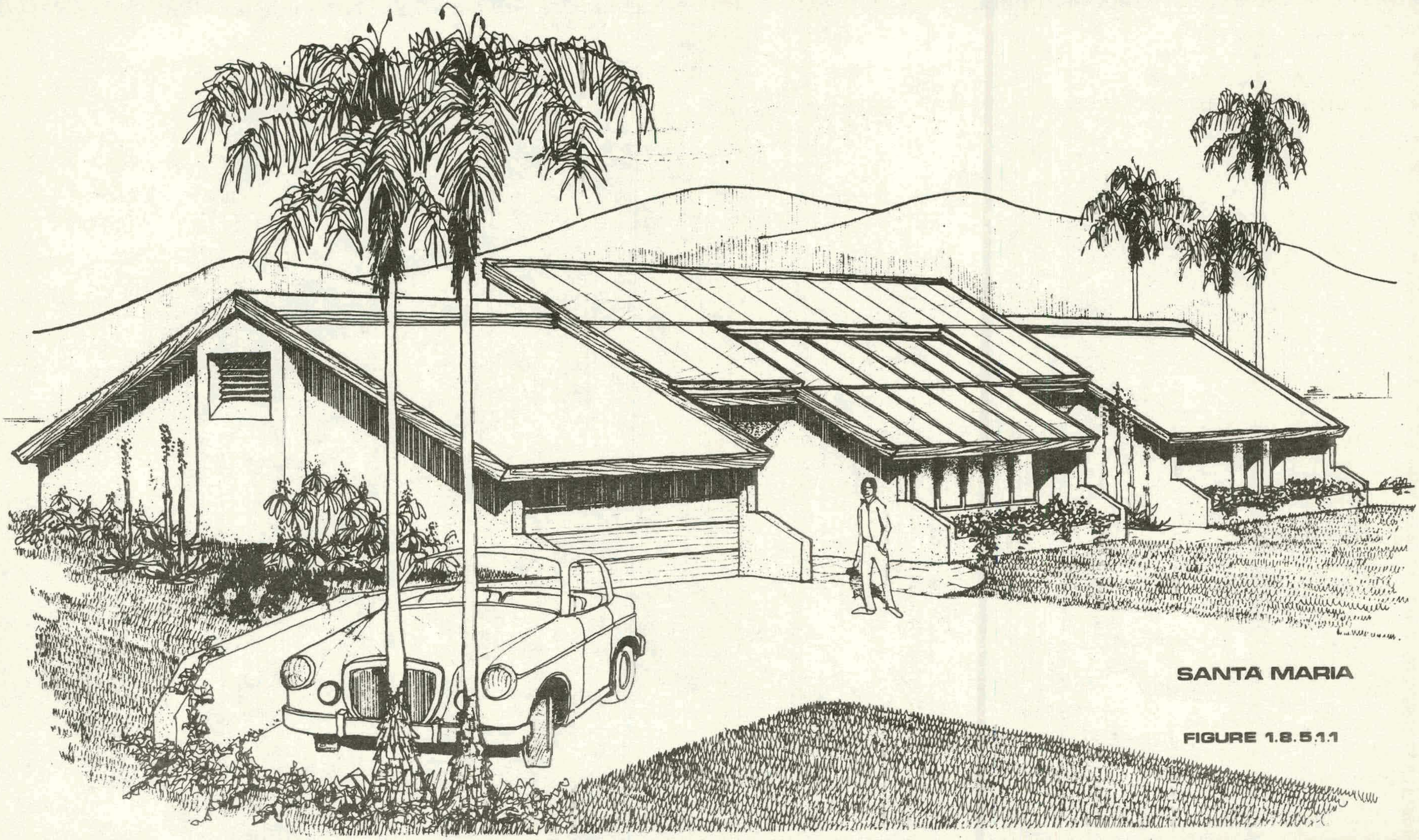


ATLANTA

FIGURE 1.8.6.1.1

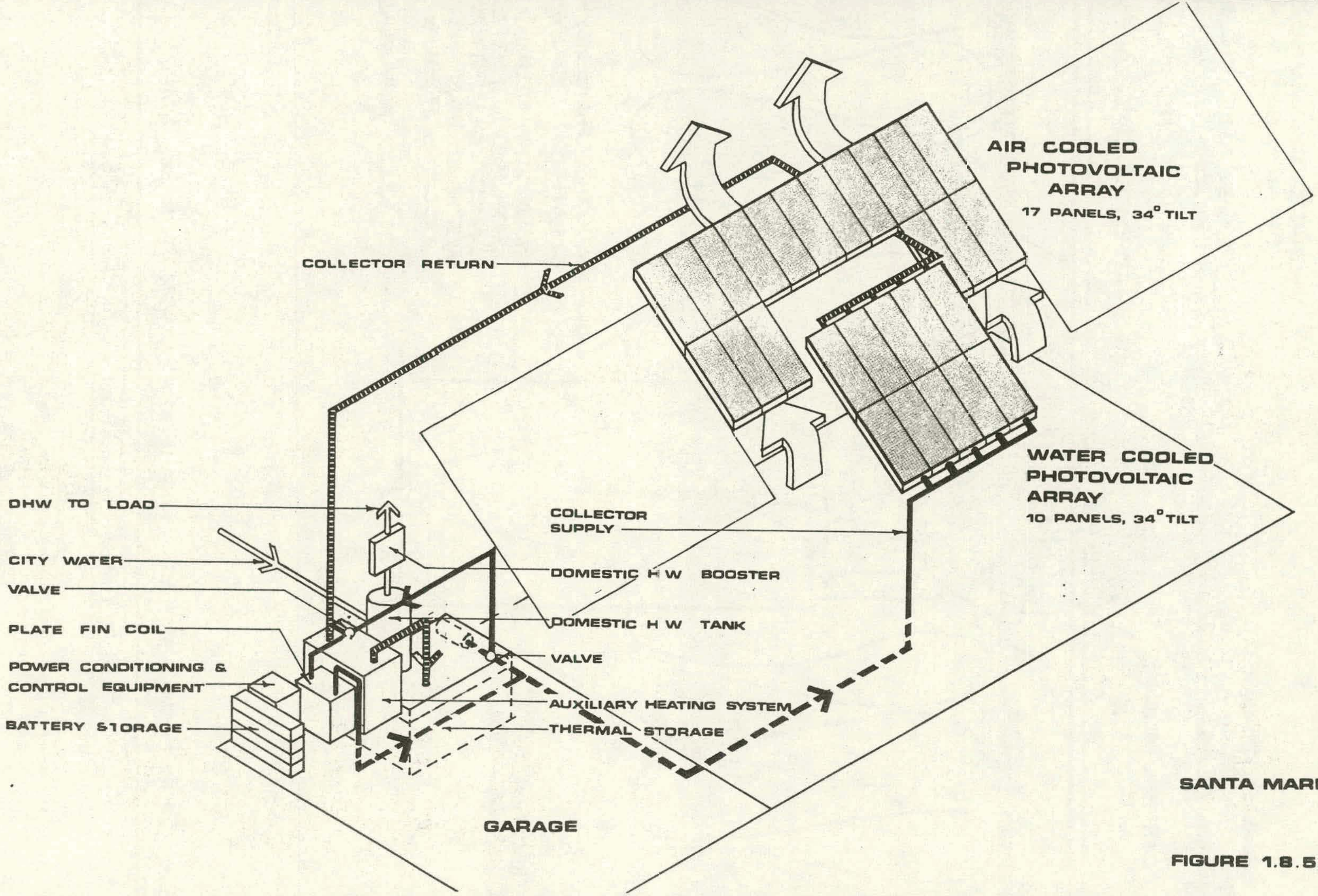


CLEVELAND, MADISON
WILMINGTON
FIGURE 1.3.4.3.1



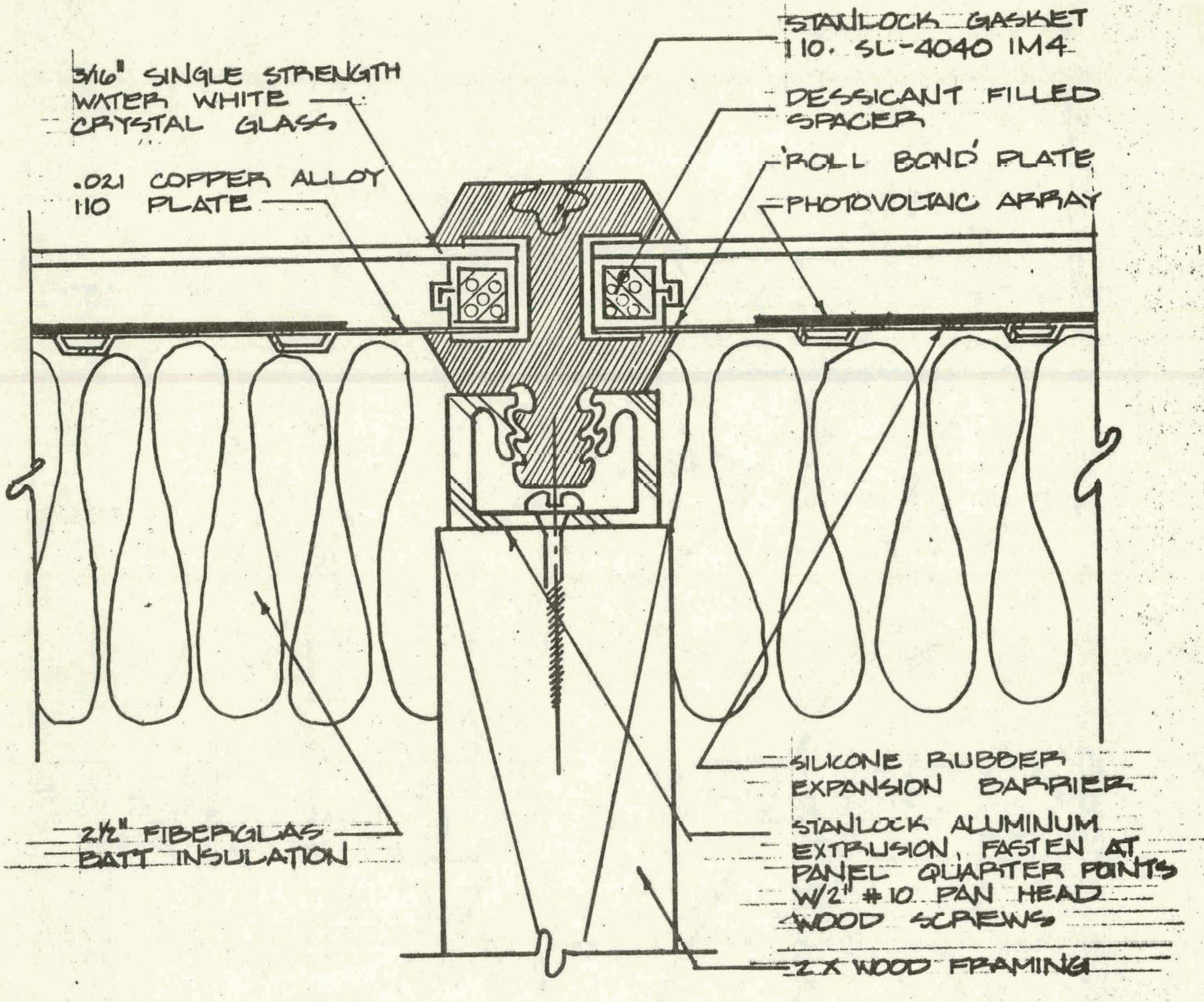
SANTA MARIA

FIGURE 1.8.5.1.1



SANTA MARIA

FIGURE 1.8.5.1.4



RPS PROPOSED COLLECTOR FRAMING

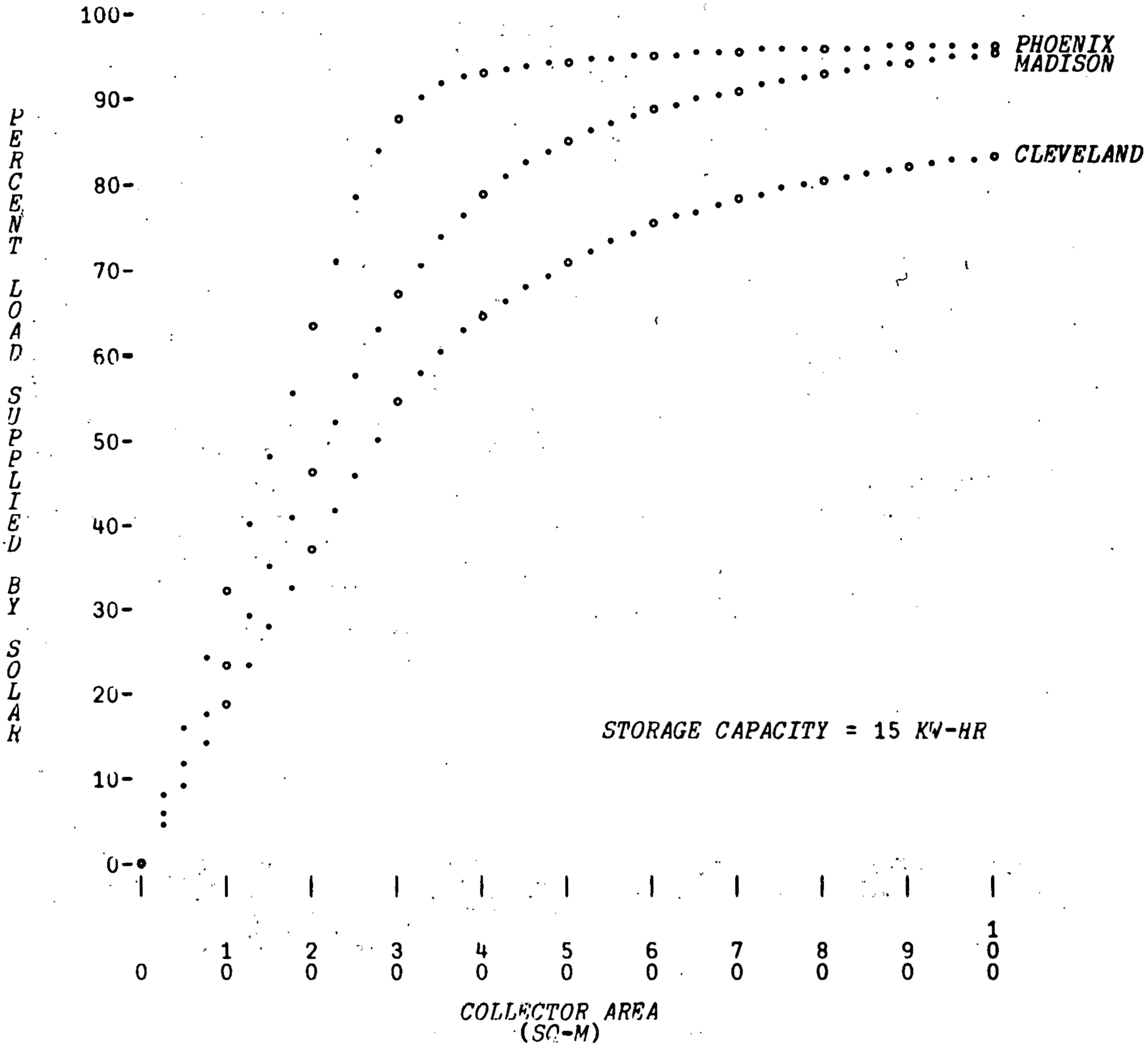
SLOPED JOINT DETAIL

SCALE = FULL SIZE

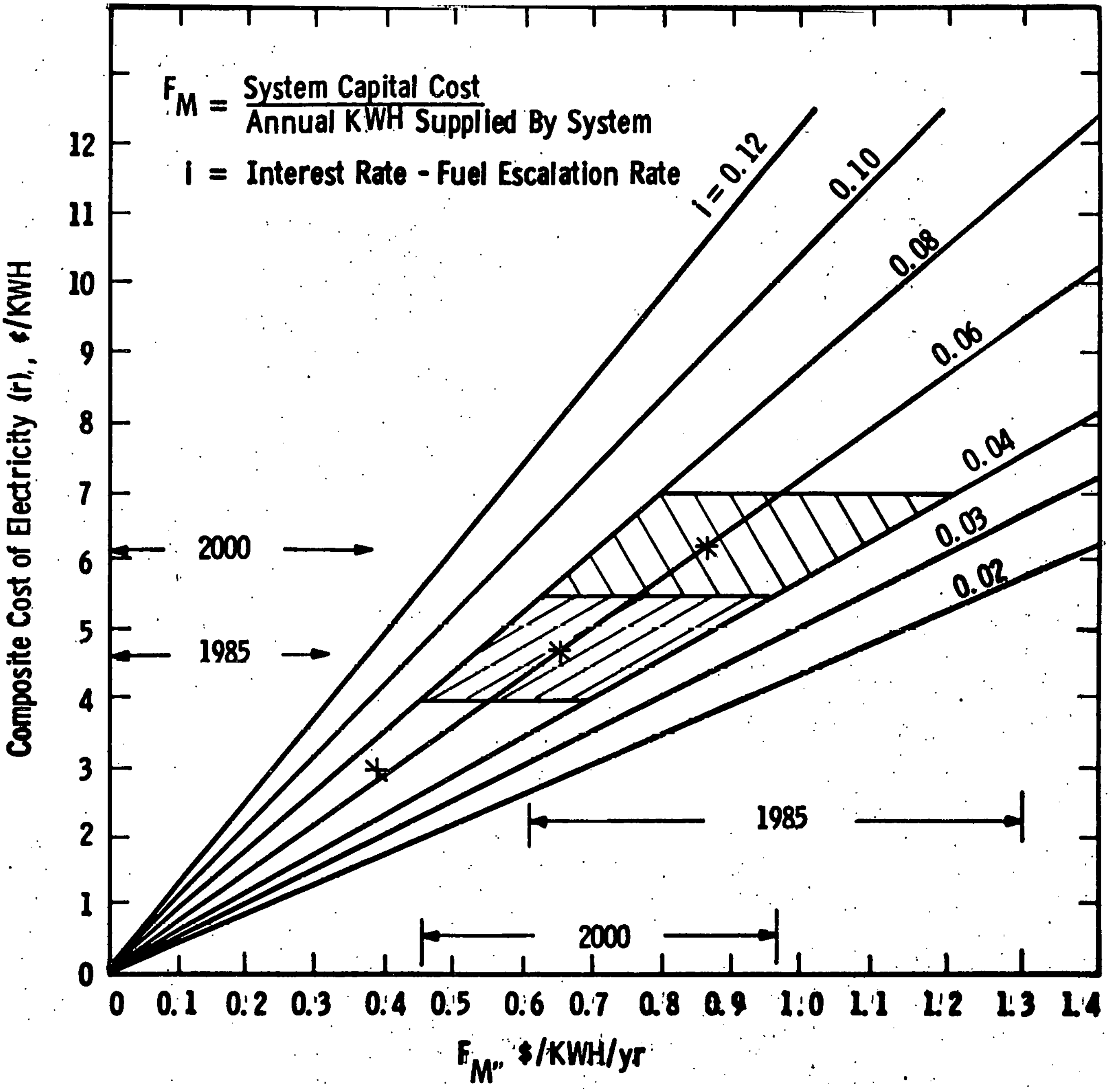
FIGURE 1.5.1.1.1

```
22 JUN 76 - 01:51:52 PM
PVEPS - ENERGY FLOW SIMULATIONS - V3.1  (TIME STEP = 1 DAY)
CASE 1  -  A INSOLATION DATA  -  NOMINAL LOAD 2
```

LOAD PROVIDED BY STORAGE



Curve 685764-A



Dwg. 6386A69

TABLE 1 – RPS CONCLUSIONS

Locations		7 Throughout the USA
Type of System		Electrical and Thermal
Electrical and Thermal Loads		Depend on Location
Return Power Flow to Utility		Not Included
Percentage of Loads Supplied		Depends on Location
Electrical Storage		Yes
Thermal Storage		Yes
Arrays:	Combinations Used at Different Sites	SC Silicon - Water Cooled SC Silicon - Air Cooled TF CdS - Air Cooled
Solar Cell Efficiency		SC Silicon - 16% TF CdS - 10%
Solar Cell Costs		1985 Silicon - $\$50/M^2$ 2000 Silicon - $\$20/M^2$ 2000 CdS - $\$10/M^2$

For Homeowner Ownership:	1985	2000
Average F_M Needed	.65	.87
Average F_M Achievable	.95	.70

Assumptions:

1. Precommercialization Program
2. Proportional Utility Energy Charges

Curve 685798-A

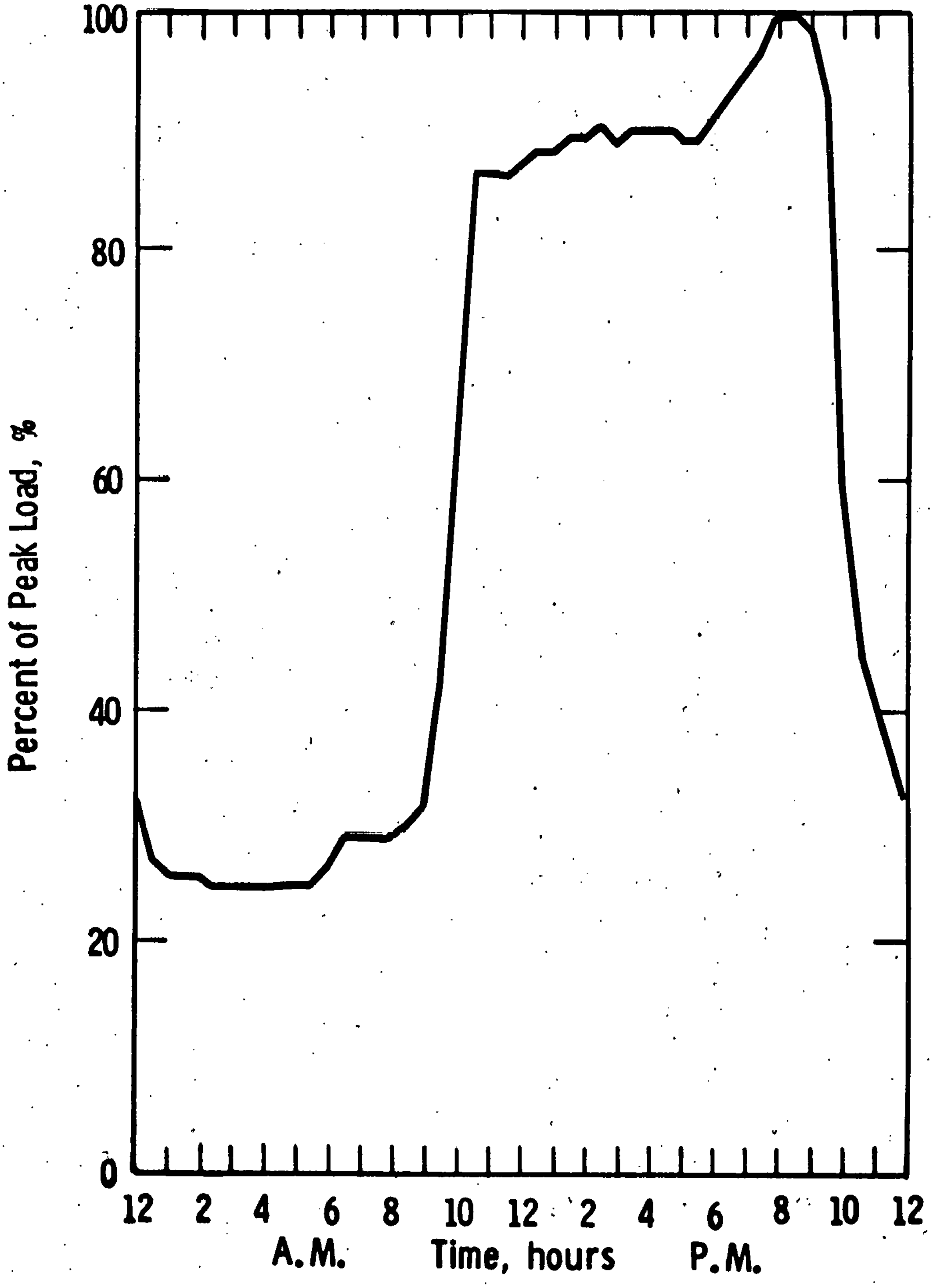
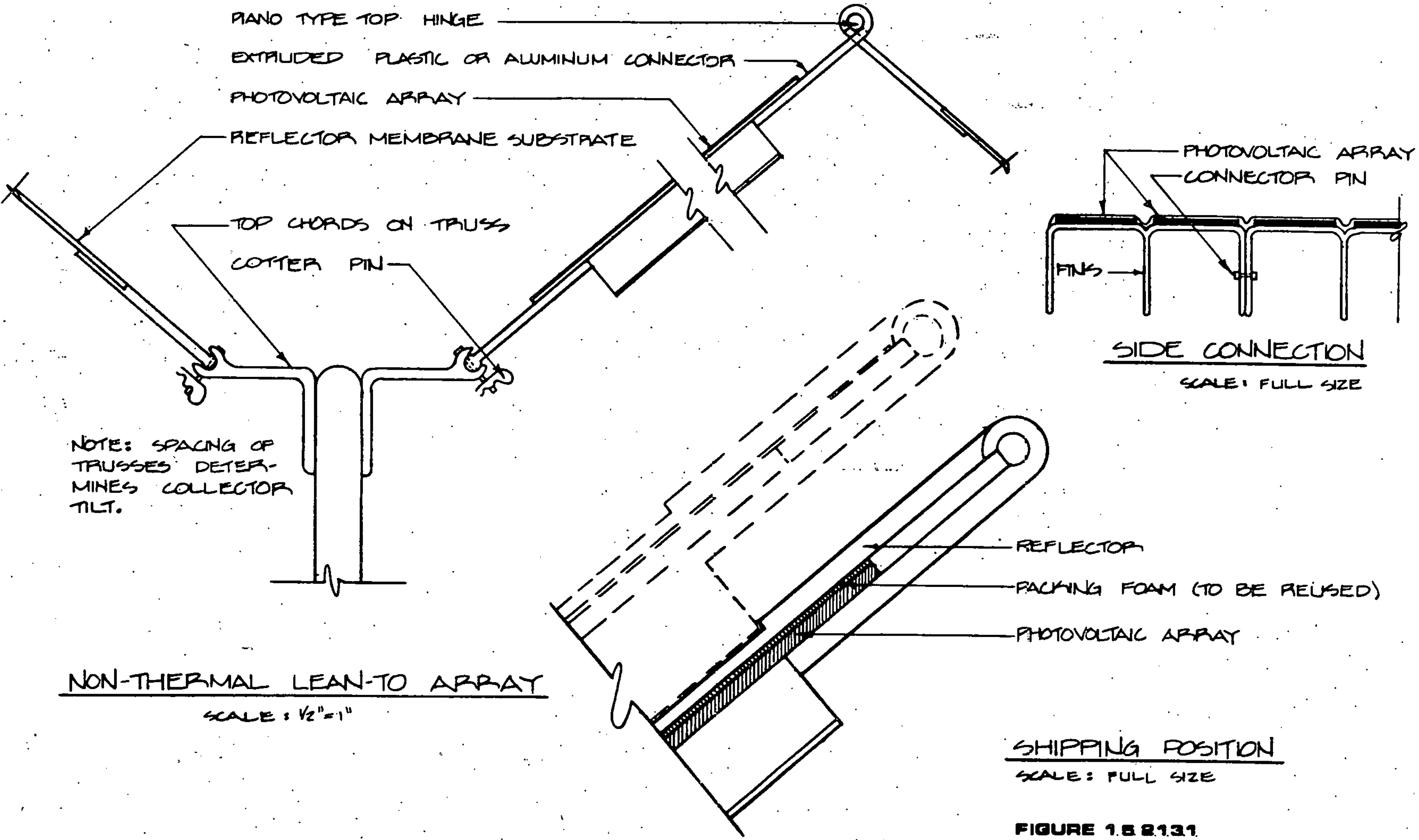


Fig. 2.1.2 — Commercial load curve



NOTE: SPACING OF TRUSSES DETERMINES COLLECTOR TILT.

NON-THERMAL LEAN-TO ARRAY

SCALE: 1/2"=1"

SIDE CONNECTION

SCALE: FULL SIZE

SHIPPING POSITION

SCALE: FULL SIZE

FIGURE 1.5.2.13.1

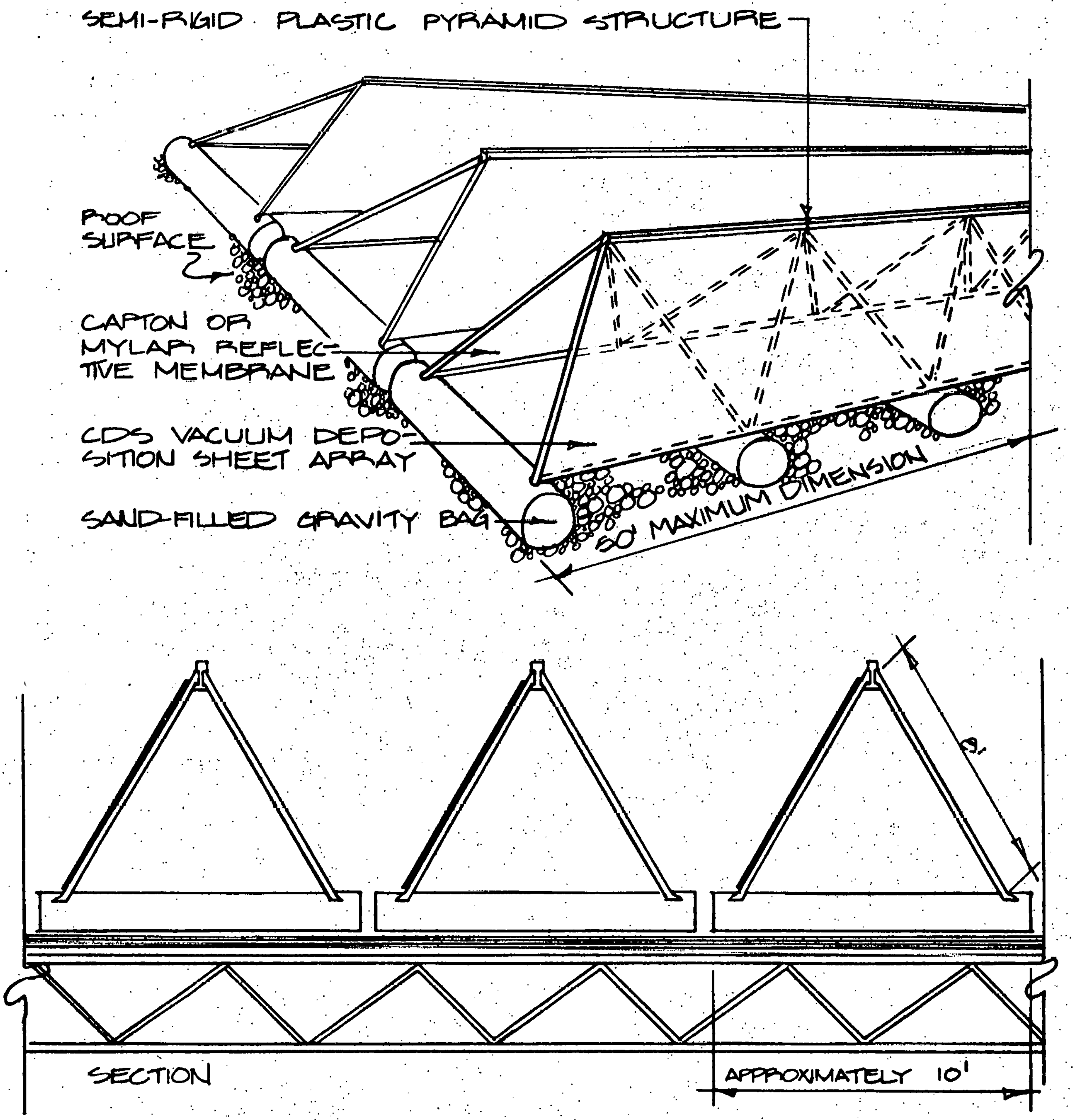


FIGURE 1.5.2.2.1.1

FLEXIBLE NON-THERMAL IPS PHOTOVOLTAIC ARRAY

Curve 686253-A

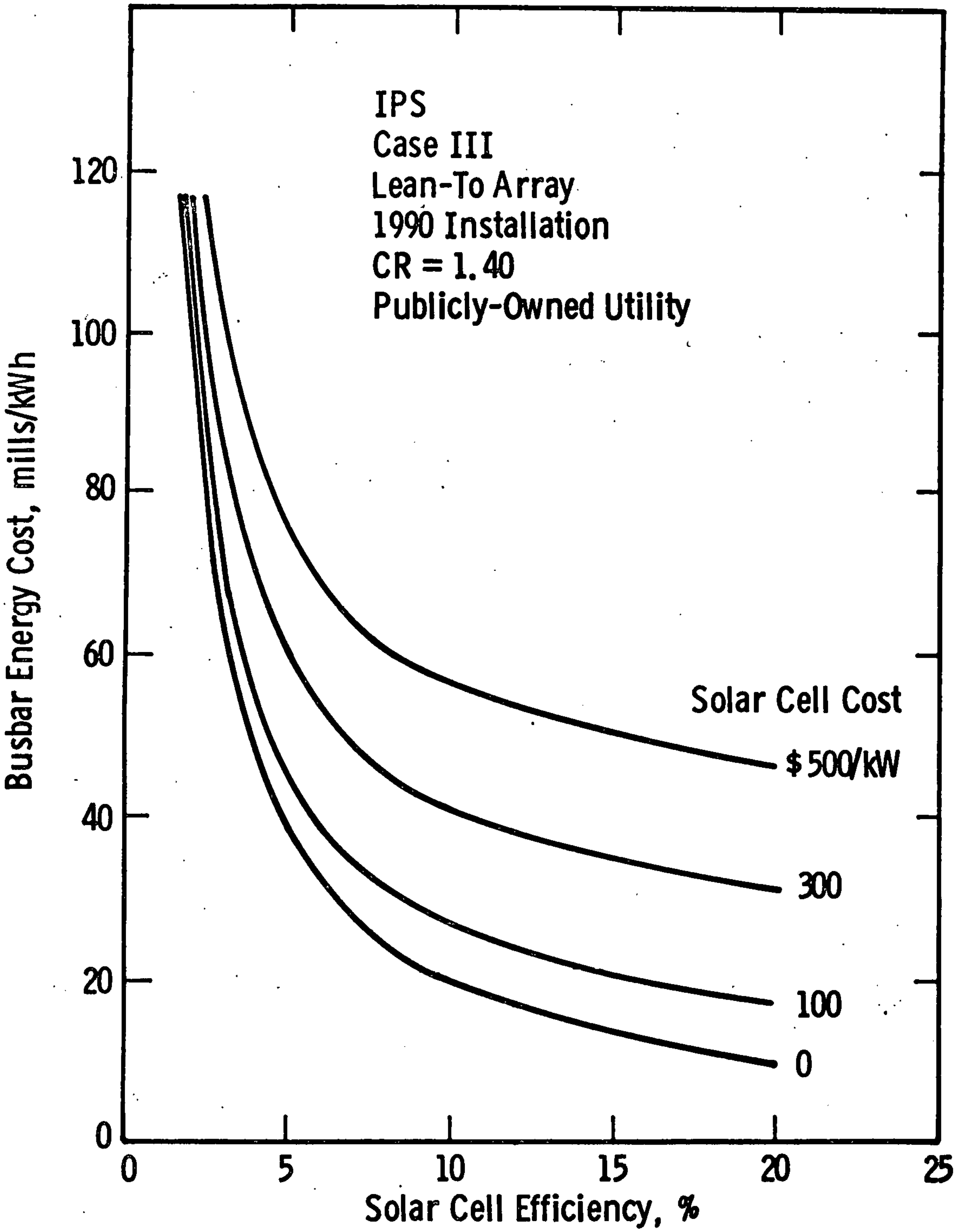


Fig. — Busbar cost of energy vs. solar cell efficiency

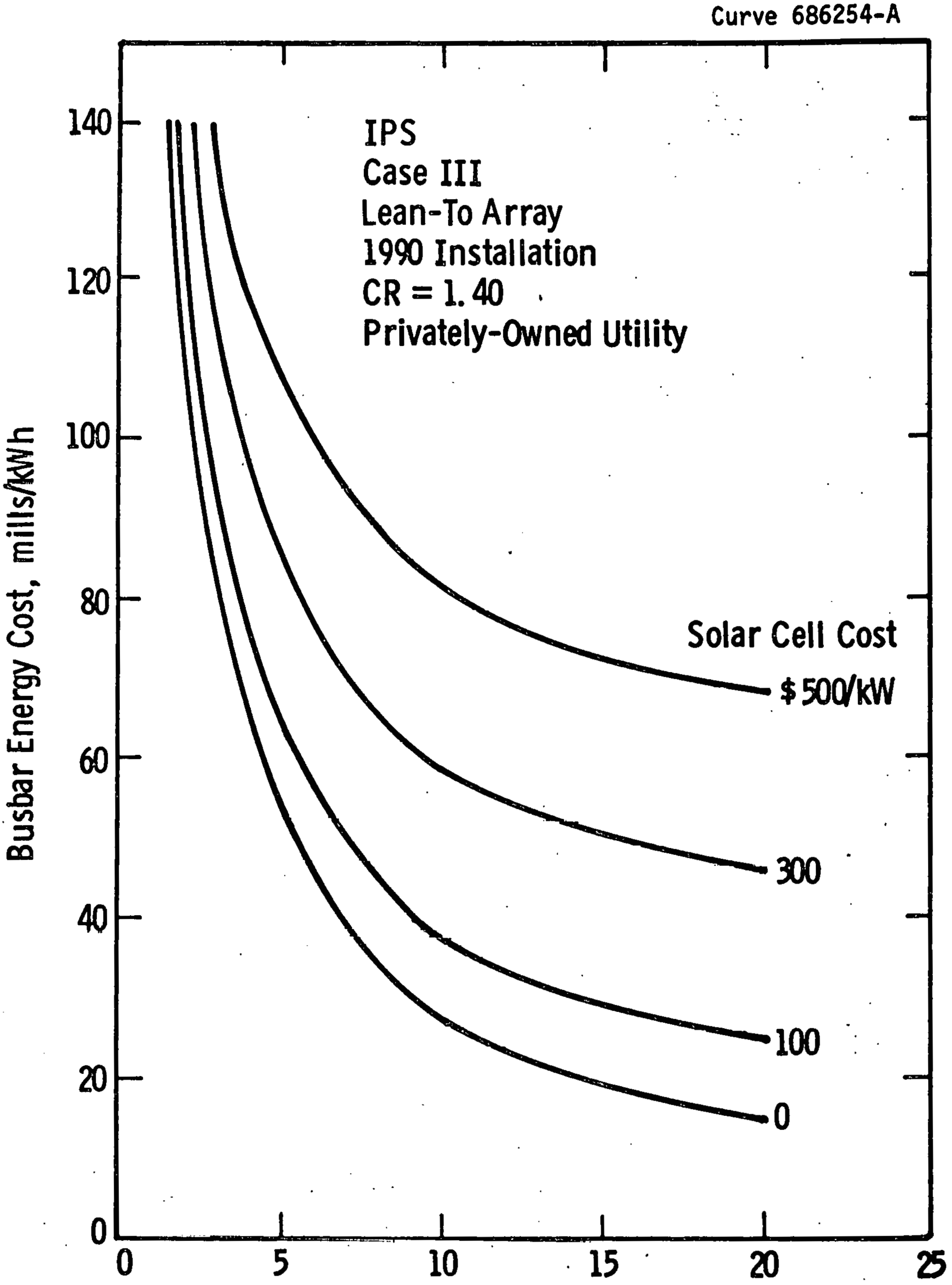


Fig. — Busbar cost of energy vs. solar cell efficiency

Dwg. 6386A71

TABLE 2 – IPS CONCLUSIONS

PROPRIETOR OWNED

Parameter	Units	Without Storage	With Storage
Location		Phoenix	Phoenix
Year of Installation		2000	2000
Night-Time Cost of Electricity	mills/kWh	20	20
Day-To-Night Ratio		2.5:1	2.5:1
Cell Efficiency	%	10	10
Cell Cost	$/kW	100	100
Type of Array		LT/TM*	LT/TM*
DCF ROI in 10 Years	%	15	20

* Lean-To or Tensioned Membrane

Dwg. 6386A72

TABLE 3 – IPS CONCLUSIONS

UTILITY OWNED

(Co-Located with Battery Load-Leveling Facility)

Parameter	Units	Privately Owned Utility	Publicly Owned Utility
Location		Phoenix	Phoenix
Year of Installation		1990	1990
Cell Efficiency	%	10	10
Cell Cost	$/kW	100	100
Type of Array		LT/TM*	LT/TM*
Busbar Energy Cost of IPS Plant	mills/kWh	<40	<40

* Lean-To or Tensioned Membrane

Dwg. 6382A77

Array Module	Fixed At Latitude	Horizontal EW Axis NS Track	Horizontal NS Axis EW Track	Vertical Axis At Lat. Tilt	Vertical Axis At 50° Tilt	Continuous Two Axis Tracking	Lean-To	Windrow
Si Flat Plate	378 (0.195)	409 (0.195)	477 (0.178)	480 (0.196)	500 (0.194)	524 (0.197)	487 (0.274)	433 (0.245)
Si V Trough	489 (0.296)	621 (0.296)	724 (0.270)	729 (0.298)	759 (0.294)	795 (0.299)		
Si CPC (3X)	474 (0.433)	916 (0.433)	1069 (0.395)	1076 (0.435)	1121 (0.431)	1174 (0.437)		
Si CPC (10X)		2302 (1.047)	2667 (0.950)	2701 (1.052)	2832 (1.048)	2949 (1.058)		
Si Fresnel (10X)				1914 (1.028)	2332 (1.052)	2841 (1.068)		
CdS Flat Plate	217 (0.110)	236 (0.116)	276 (0.116)	276 (0.111)	290 (0.112)	305 (0.118)	283 (0.164)	228 (0.138)

TABLE 3.2.4

KWH/M^2 OF CELL/YR. AND (KW_{PEAK}/M^2 OF CELL) FOR VARIOUS ARRAY/MODULE COMBINATIONS

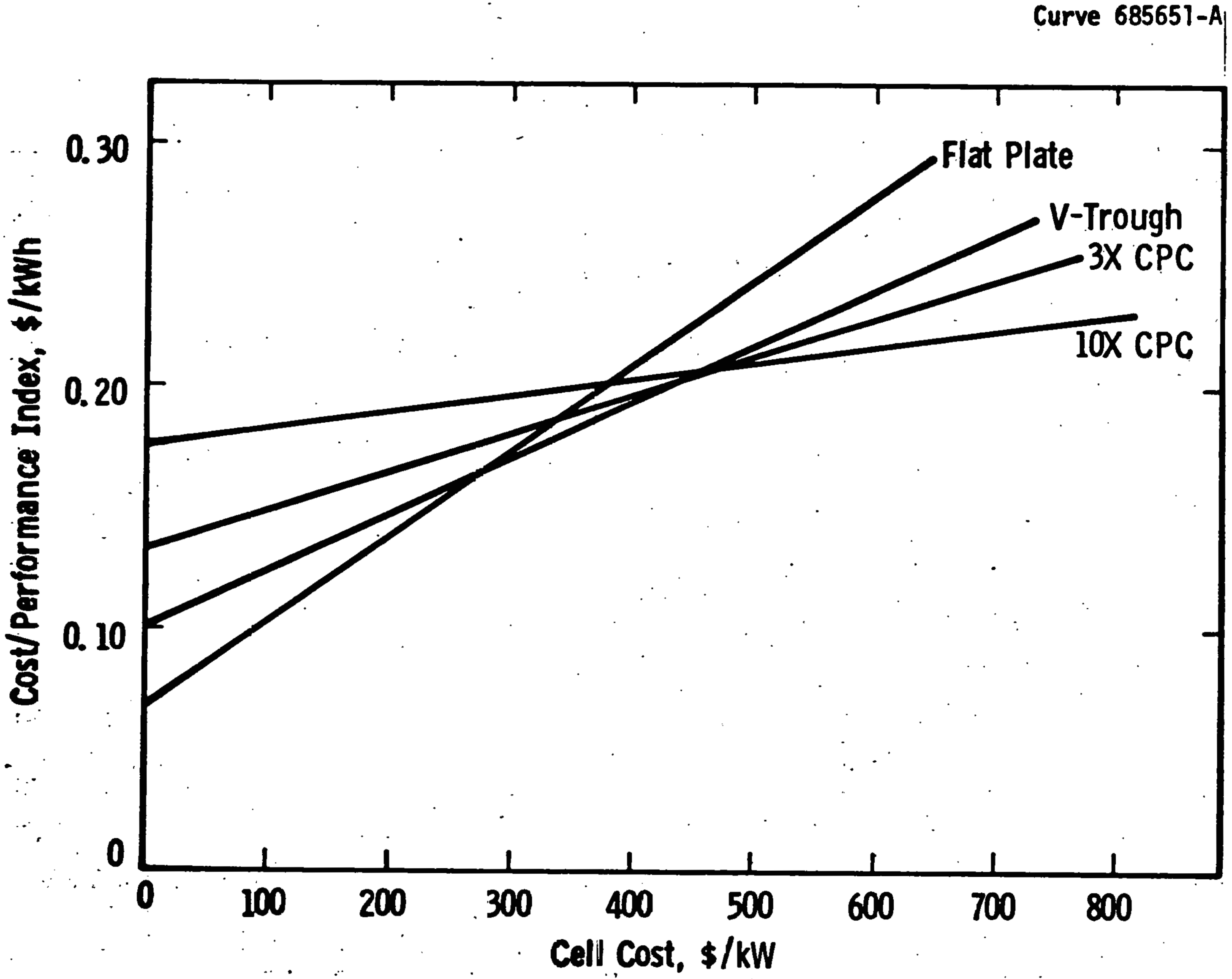


Fig. 3.3.2 – Effect of cell cost on cost-performance index for vertical axis tracking array

Curve 685799-A

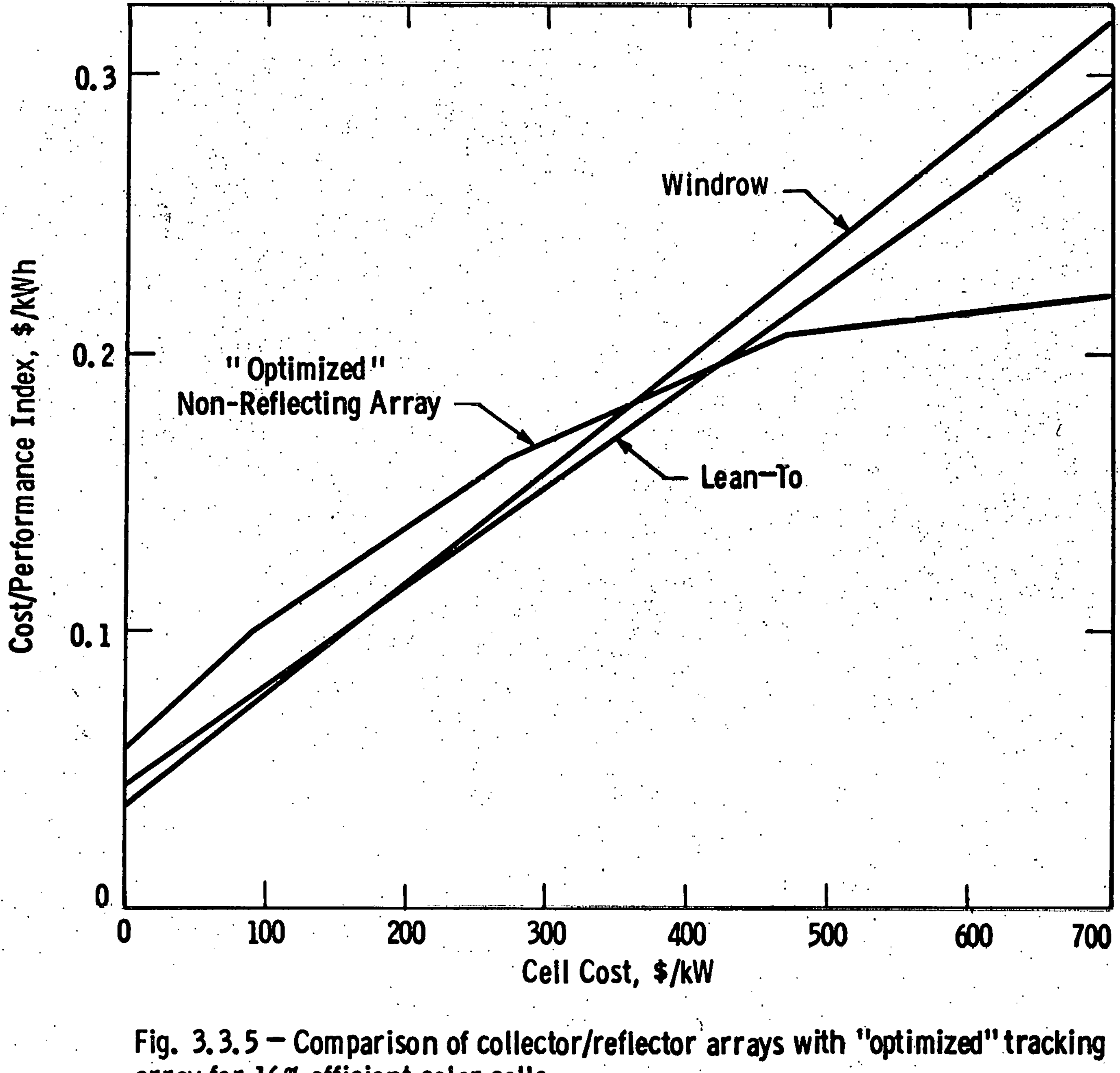


Fig. 3.3.5 – Comparison of collector/reflector arrays with "optimized" tracking array for 16% efficient solar cells

TABLE 3.3.8

TOTAL CAPITAL COST OF 100 MW_e SYSTEMS USING $500/KW SINGLE-CRYSTAL SOLAR CELLS

(ALL VALUES IN 1975 THOUSANDS OF DOLLARS)

(Privately Owned Utility)

	10X CPC VERTICAL AXIS TRACKING	LEAN-TO	WINDROW
Array	61,833	43,355	45,861
Power Conditioner	10,860	10,860	10,860
Facility	1,670	875	904
SUBTOTAL	74,363	55,090	57,625
Contingency & Spares	14,873	11,018	11,525
Indirect Costs	7,436	5,509	5,763
Interest During Construction	7,977	5,910	6,181
TOTAL CAPITAL COST	104,649	77,526	81,094
$/KWp	$1046/KW	$775/KW	$811/KW

TABLE 3.3.10

TOTAL CAPITAL COST OF 100 MW_e SYSTEMS USING $100/KW THIN-FILM SOLAR CELLS

(ALL VALUES IN 1975 THOUSANDS OF DOLLARS)

(Privately Owned Utility)

	VERTICAL AXIS TRACKING	LEAN-TO	WINDROW
Array	44,109	21,401	20,635
Power Conditioner	10,860	10,860	10,860
Facility	1,535	1,038	1,116
SUBTOTAL	56,504	33,299	32,611
Contingency & Spares	11,301	6,660	6,522
Indirect Costs	5,650	3,330	3,261
Interest During Construction	6,061	3,572	3,498
TOTAL CAPITAL COST	79,156	46,861	45,892
$/KWp	$792/KW	$469/KW	$459/KW

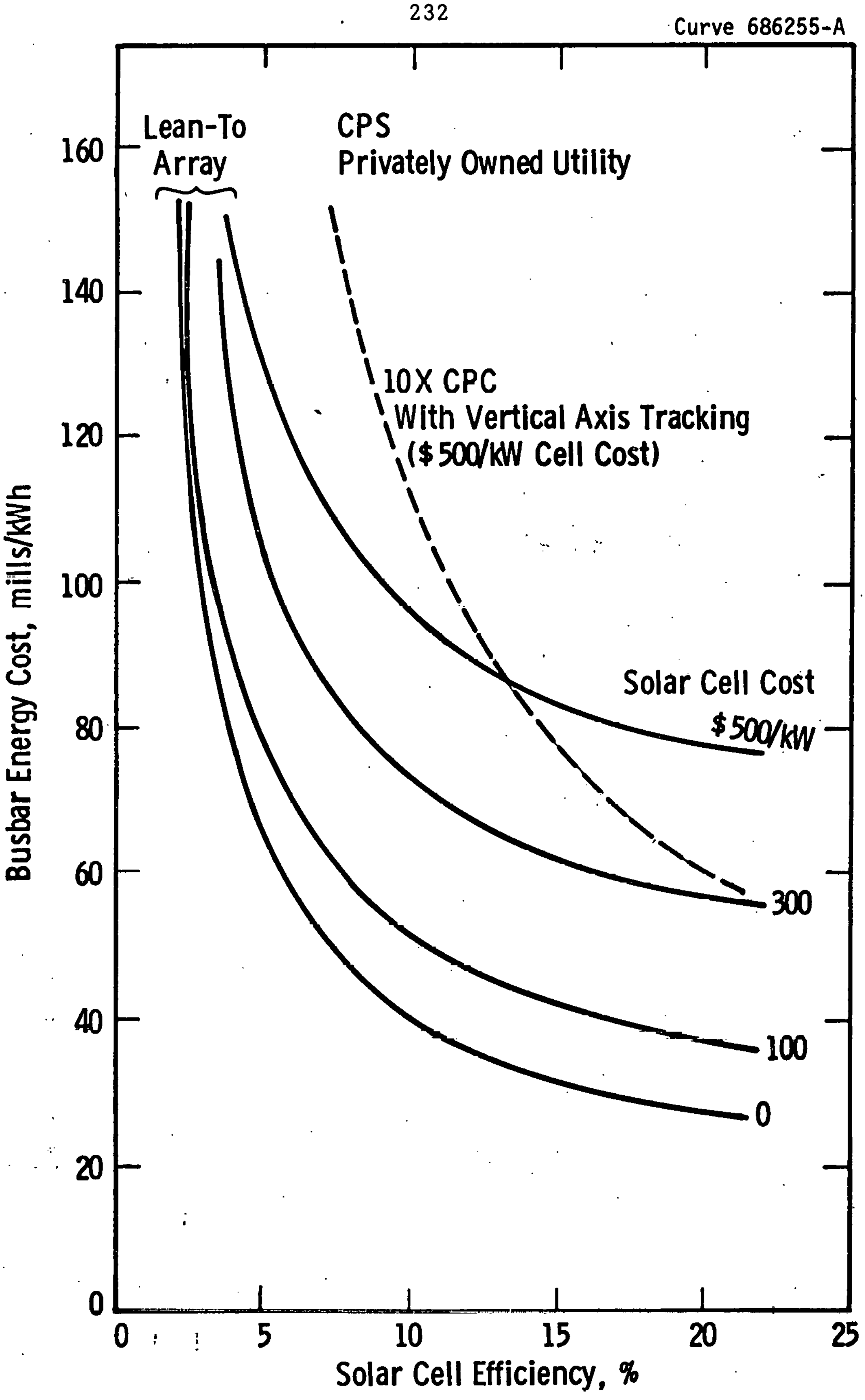


Fig. 3.3.9— Energy cost vs. cell efficiency for lean-to system and 10 X CPC with vertical axis tracking

Dwg. 6386A70

TABLE 4 – CPS CONCLUSIONS

Parameter	Units	Privately Owned Utility	Publicly Owned Utility
Location		Phoenix	Phoenix
Year of Installation		1990	1990
Cell Efficiency	%	16 (10)	10
Cell Cost	$/kW	100	100
Type of Array		LT/W*	LT/W*
Busbar Energy Cost of CPS Plant	mills/kWh	<40 (50)	<40
Cost/Benefit Ratio		1.1 – 1.5 (1.4 – 1.9)	0.9 – 1.2

* Lean-To or Windrow

PLANNED FUTURE EFFORTS

1. AUTONOMOUS RESIDENCE
2. UTILITY/RESIDENCE INTERFACE
3. LINEAR FRESNEL LENS OPTIMIZATION
4. UTILITY MARGIN CALCULATION METHODOLOGY

CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC POWER SYSTEMS

ERDA CONTRACT E(11-1) - 2748
JUNE 15, 1975 - SEPTEMBER 30, 1976
VALUE: $509,165

SPECTROLAB, INC.
  BECHTEL CORPORATION
  FACILITIES SYSTEMS ENGINEERING CORPORATION
  INGENASU ASSOCIATES
  MIDWEST RESEARCH INSTITUTE

FREDERICK T. C. BARTELS
  PROGRAM MANAGER AND PRINCIPAL INVESTIGATOR
SPECTROLAB, INC., 12500 GLADSTONE AVENUE
SYLMAR, CALIFORNIA 91342

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC
  PROGRAM REVIEW MEETING
  AUGUST 3-6, 1976

UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

OBJECTIVES

The objectives of the original contract (6/75 - 6/76) were:

- To develop conceptual designs for three terrestrial photovoltaic systems categories: a single-family residence, a central power station, and a shopping center.
- To analyze these designs to define the system/user interface, determine system requirements, optimize cost/performance trade-offs in system design and operation, and identify technical, economic and institutional factors of importance in projecting future use of photovoltaic systems in these applications.

Work on the original contract objectives has been completed and a final report is in preparation. Subsequently, the original contract has been extended to cover additional work on intermediate systems, with the additional objectives of developing a simplified design procedure for on-site systems and comparing other intermediate system applications to the shopping center system previously analyzed. Work on the additional objectives will be completed by 30 September.

This presentation will cover primarily the work done and results obtained under the original contract objectives.

CONTRACT ACTIVITIES

The approach taken by the Spectrolab team can be outlined as follows:

I. Define system requirements and component technology:

- Define system load models for each application, and identify other requirements (integration with building, etc.).
- Develop detailed designs for concentrating and non-concentrating array modules and optimize cost and performance.
- Survey technology for energy storage and power conditioning.

II. Prepare and analyze system conceptual designs:

- Define system configuration and choose components.
- Determine preferred operational modes.
- Size components and determine optimum fraction of load carried by solar system.
- Integrate with utility system (central power) or with other elements of building (on-site systems).

III. Analyze PEPS attractiveness to potential users and identify barriers to commercialization:

- Compare PEPS cost to conventional power cost on a parametric basis.
- Interview utilities and building owner/developers to obtain critiques of system designs.
- Identify most effective technical and economic measures to assist commercialization.

SUMMARY OF RESULTS

Central power station is most attractive.

- Concentrating array design approaches competitive cost even with expensive cells.
- A variety of approaches are available for meeting storage and back-up requirements.
- Implementation presents fewest problems to utility.

Shopping center application is also attractive.

- Provided design is developed as a total package (not attractive as retrofit).
- If non-concentrating module cost is less than $1/watt installed (not an easy application for concentrating arrays).
- Can be designed without storage or inversion.
- Side benefits very attractive to center owner/developers.

Residential application is least attractive.

- Poorest load match to photovoltaic system
- Poorly defined load and small system syze make design optimization difficult.
- Not attractive to utilities because of operational and maintenance problems.
- Questionable appeal to homeowners.

FUTURE PLANS

Complete work on additional contract objectives:

- Develop simplified (no computer simulation) PEPS design producers for use by others in evaluating specific PEPS applications.
- Survey other applications for intermediate systems and recommend preferred applications for experimental/ demonstration projects.

OBJECTIVES OF ERDA SYSTEM DESIGN AND ANALYSIS STUDY

- Develop Conceptual Designs for Three Applications Categories:
  - Single-Family Residence (four locations)
  - Intermediate System - Shopping Center
  - Central Power Station (50 to 1000 mW)
- Analyze Designs To:
  - Determine System/User Interface Requirements
  - Optimize Cost/Performance Trade-Offs
  - Assess Cost - Competitive Status
  - Identify Key Factors Related to Commercialization
- Spectrolab Team Goal:
  - Achieve Sufficiently Detailed and Comprehensive Designs so that Useful Design Critiques Can Be Obtained From Potential Users

INTERMEDIATE SYSTEM DESIGN STUDIES

STUDY	RESULT
Study Trends in Center Design	Medium-Size (250,000 ft^2) one-story Design Most Desirable
Analyze Energy Consumption	Presently 110 W/m^2 and 1.6 kWh/m^2-day; Reduced to 42 W/m^2 and 0.6 kWh/m^2-day
Design Energy-Conserving Building Systems for	
● Lighting	Natural Lighting in Mall Areas, 20 kHz Operation of Fluorescent Lamps Reduces Energy 15%
● Air Cooling	Four-Effect Absorption Chiller Designed, COP = 2.5 at 350°-400°F Inlet, 2000 m^2 Thermal Collectors Supply 65% of Input Energy

INTERMEDIATE SYSTEM DESIGN STUDIES

(CONTINUED)

STUDY	RESULT
Air Handling	Variable-Volume System Chosen; Uses Variable-Speed DC Drives
Choose Optimum Electrical System	DC System is Preferred, No 60-Hz Inverter Required
Choose Optimum Array Design	Fixed Panels (45° tilt) With Reflectors (35° tilt) Provide 19.2% Enhancement 7500 m^2 Array Generates 2.09 Million kWh/yr, 45% of Requirement
Evaluate Storage	Storage Optional; Peak Array Output ≈100% of Load
Integrate Systems Into Total Package	First Cost Increases 15.6%, Annual Operating Cost Decreases 42.2%, Payback Period ~6 years at Present Electrical Rates (1.82¢/kWh)
Obtain Evaluation From Prospective Users	Design Considered Attractive

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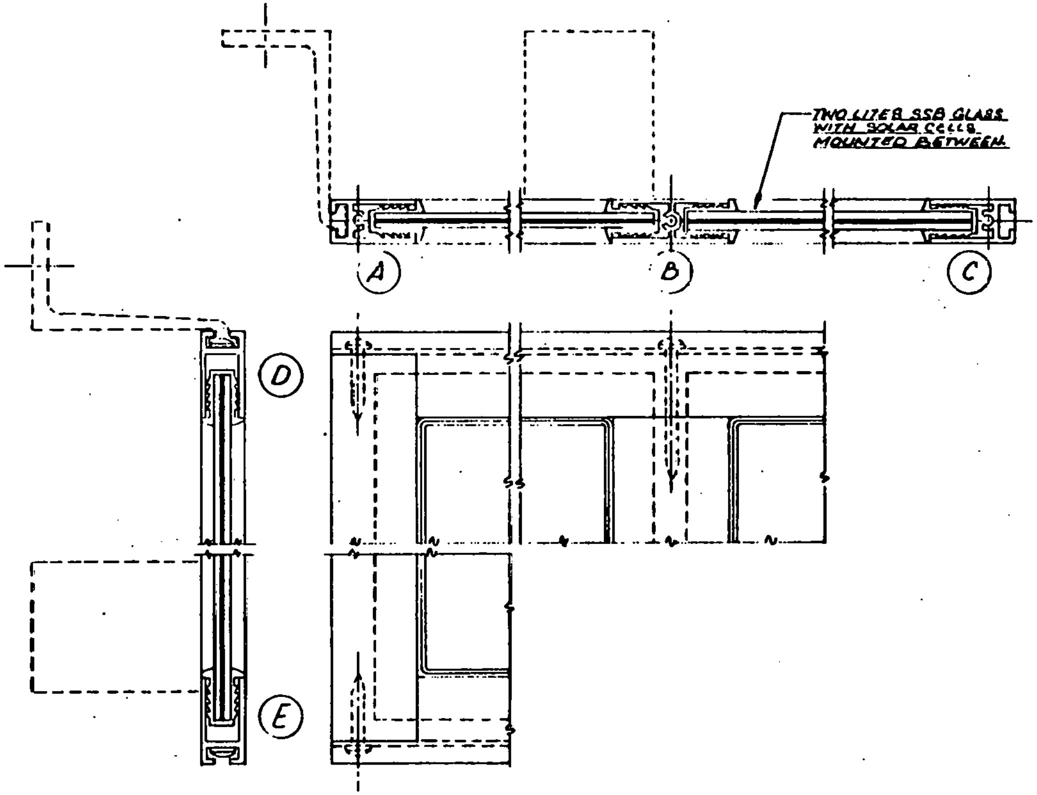
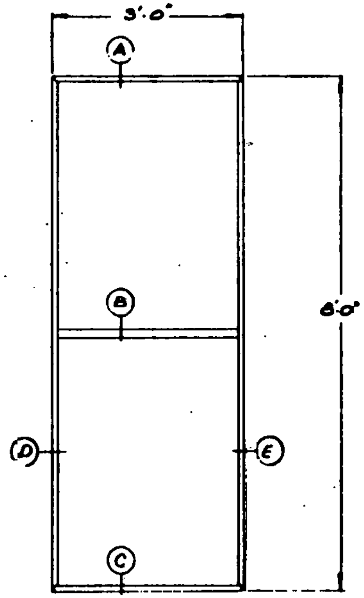
REVISIONS

SYM	ZONE	DESCRIPTION	BY	DATE	APPROVED





PLAN VIEW
SCALE: 3/8"=1'-0"

QTY REQD	IDENTIFYING NO.	DESCRIPTION	MATERIAL	MAT'L SPEC		ITEM NO.

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES.
BREAK ALL SHARP EDGES .010 — .030
REMOVE ALL BURRS
DIMENSIONS PER USASI Y 14.5
SURFACE FINISH √ PER MIL-STD-10

TOLERANCES
DECIMALS FRACT.
.X = ± 1/16 = ±
.XX = ± ANGLES
.XXX = ± X°X' = ± 1°

FINISH:

DO NOT SCALE PRINT

NEXT ASSY	USED ON
APPLICATION	

DRAFTSMAN DATE
CHECKER DATE
DESIGNER DATE
ENGINEER DATE
DATE
APPROVED DATE
APPROVED DATE

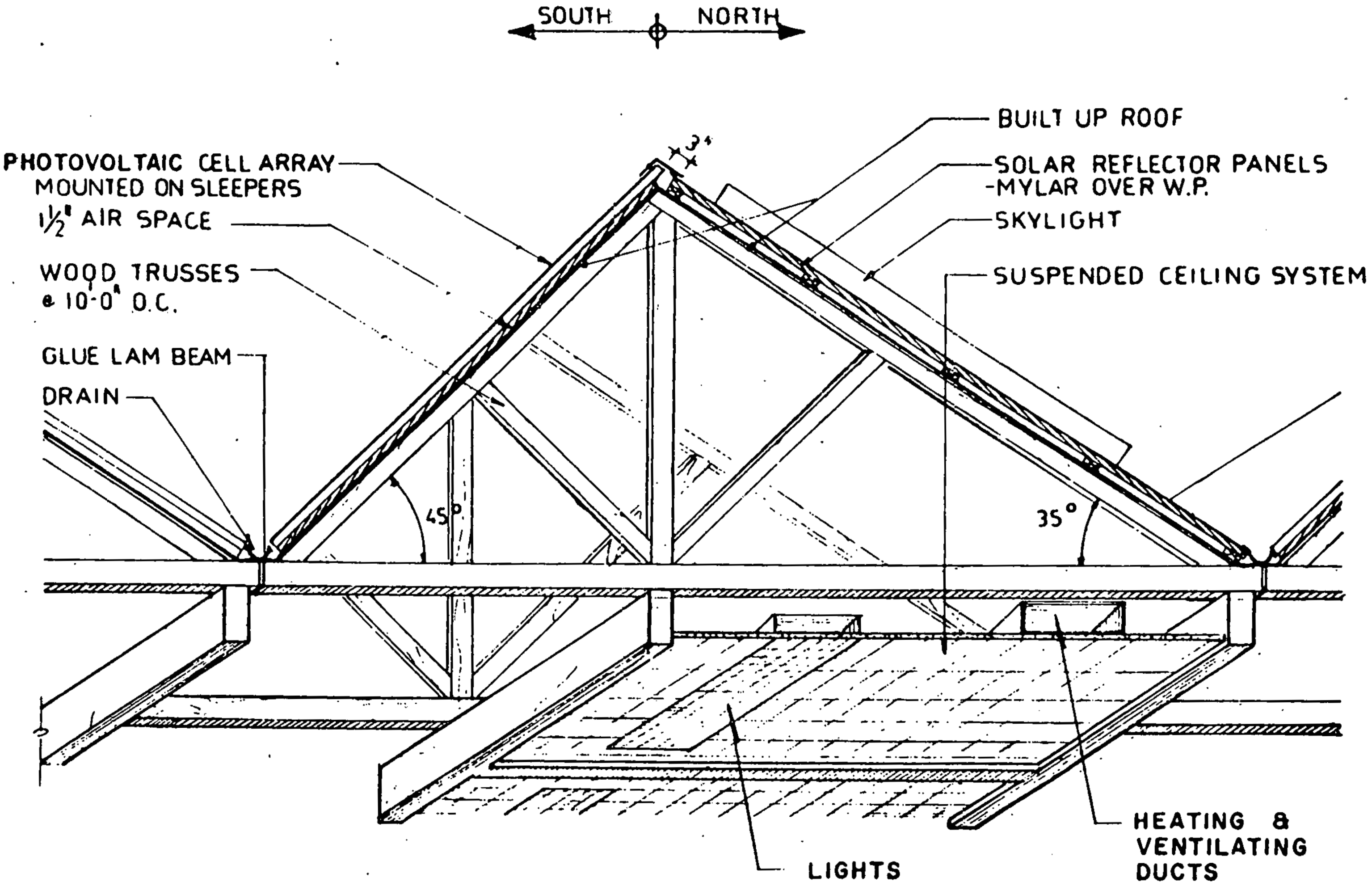
spectrolab
a DIVISION OF [illegible] INC.
12484 GLADSTONE AVE. SYLMAR, CALIF.

LAYOUT COLLECTOR
PANEL

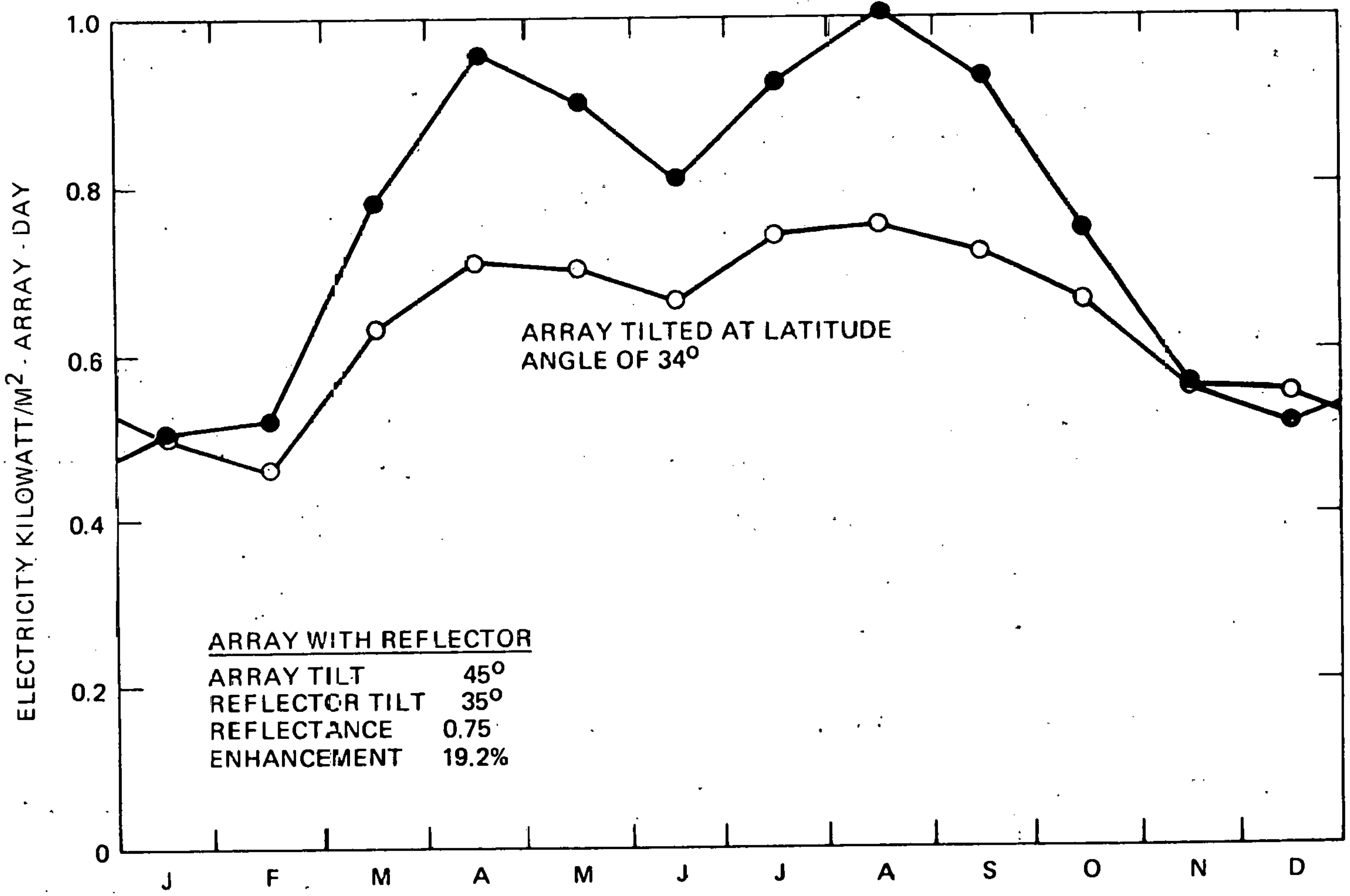
CODE IDENT NO. 15901
SIZE C
REV LTR
SCALE FULL
WEIGHT
SH
OF 1

UNLESS OTHERWISE SPECIFIED.

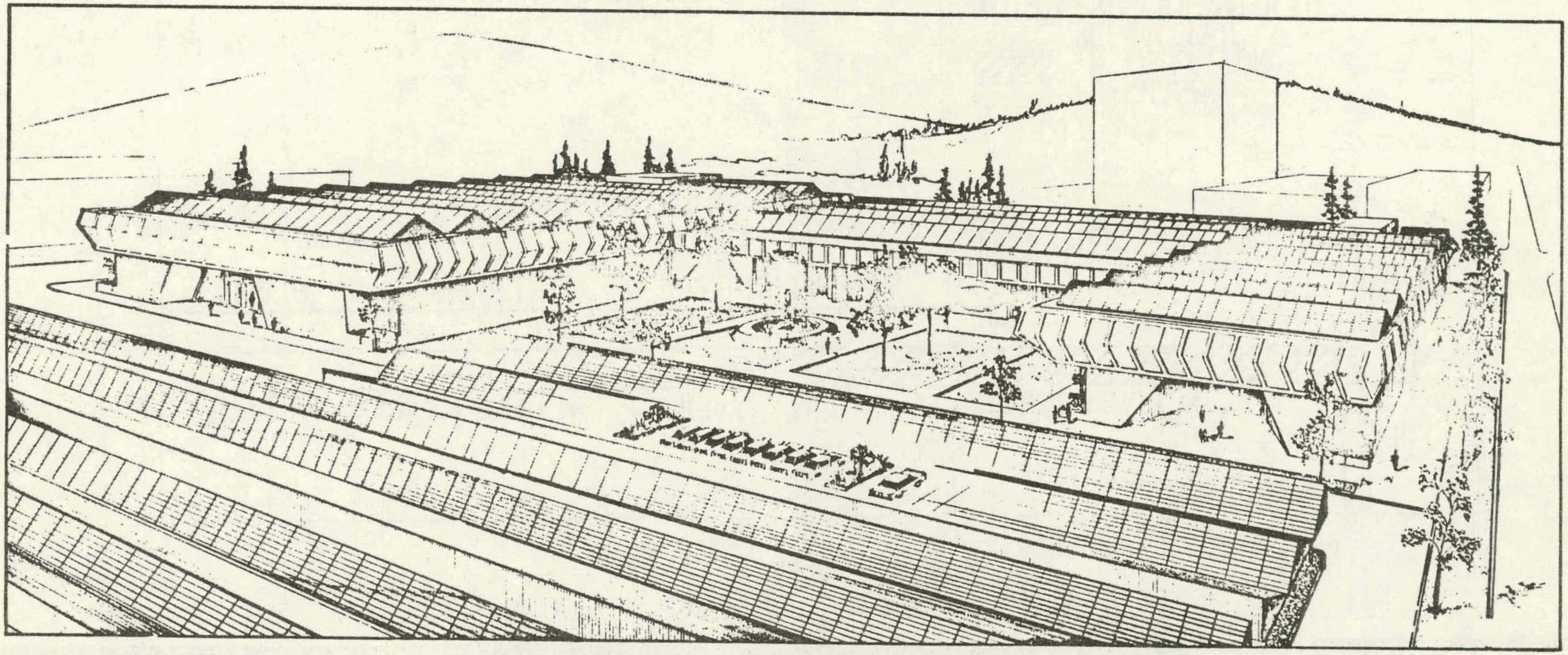
SECTION THROUGH CELL ARRAY AND REFLECTOR



AVERAGE MONTHLY ARRAY OUTPUT
RIVERSIDE 1962 DATA

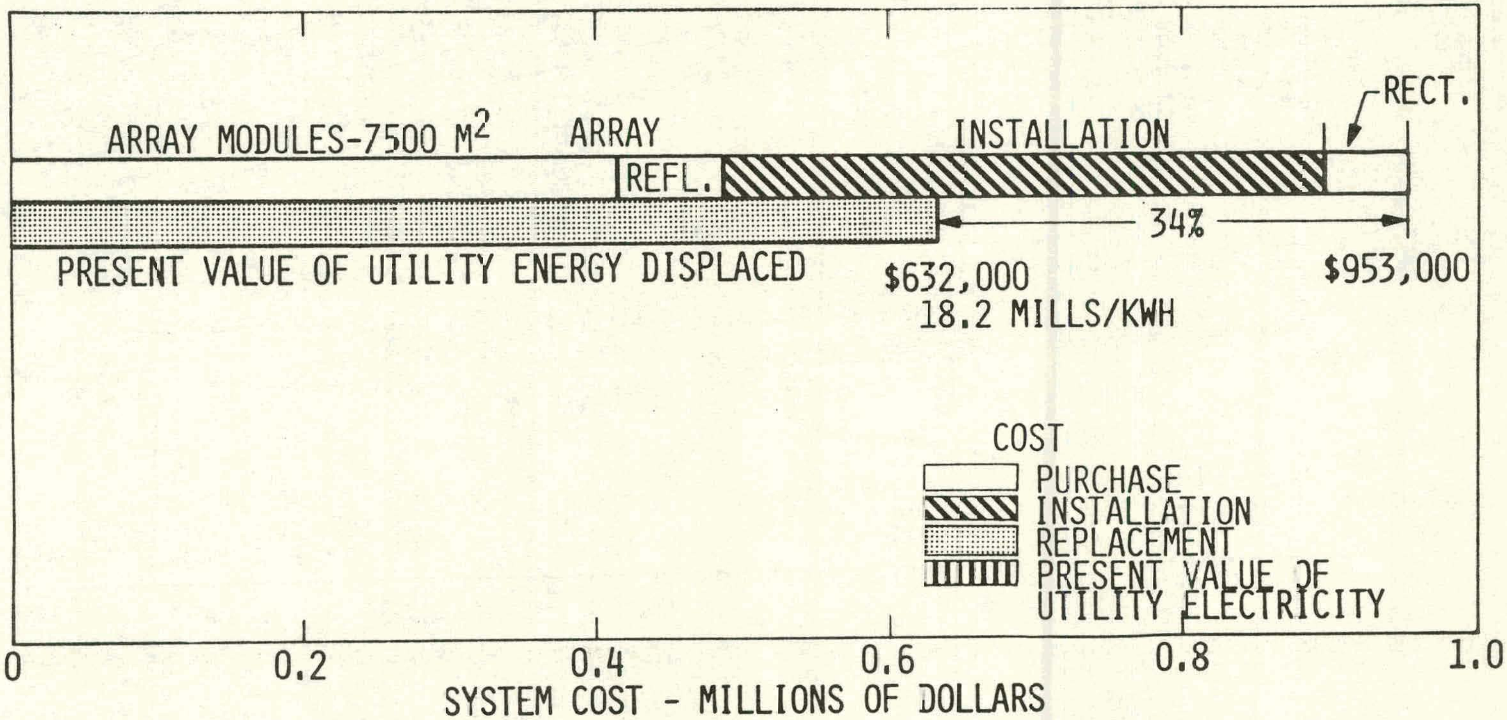


SHOPPING CENTER - ELEVATION VIEW



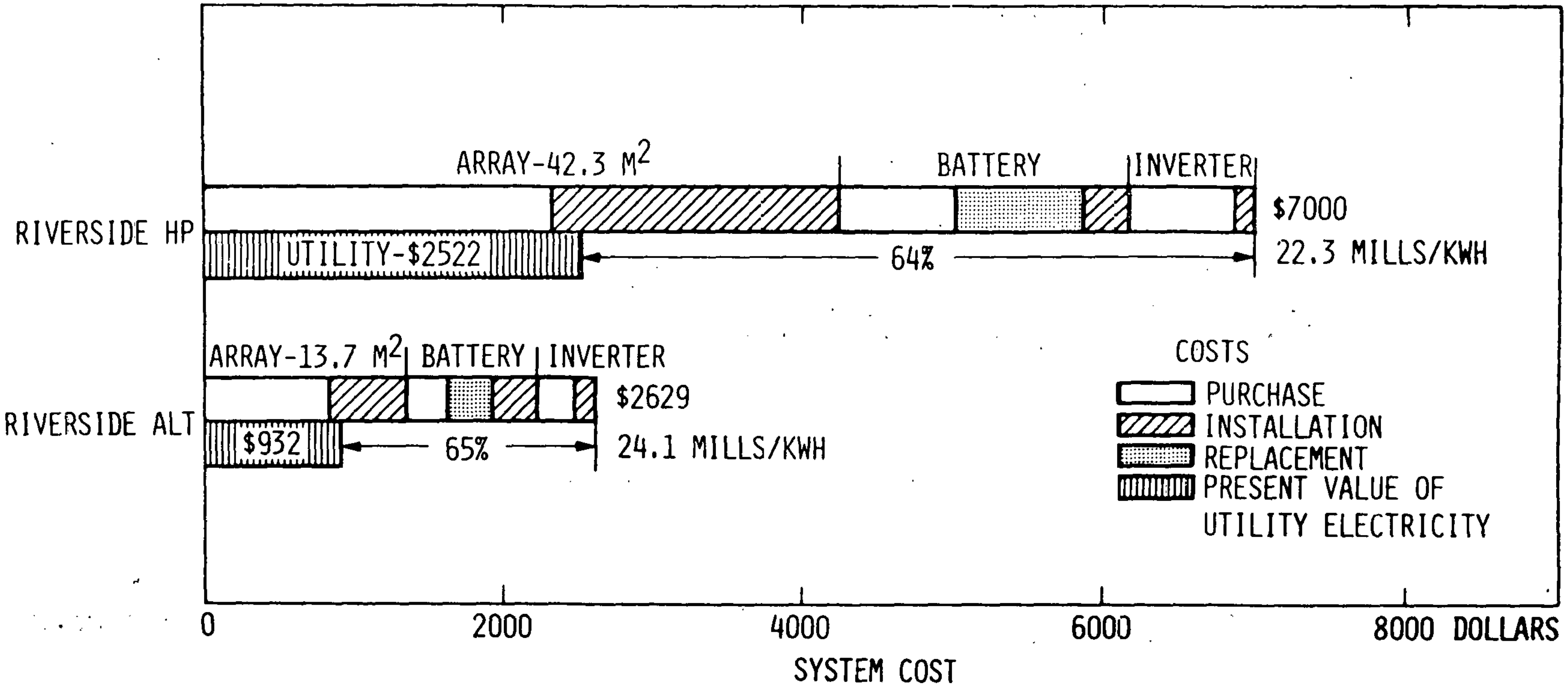
SHOPPING CENTER PEPS COST COMPARISON

RIVERSIDE DATA - SOLAR FRACTION = 0.45

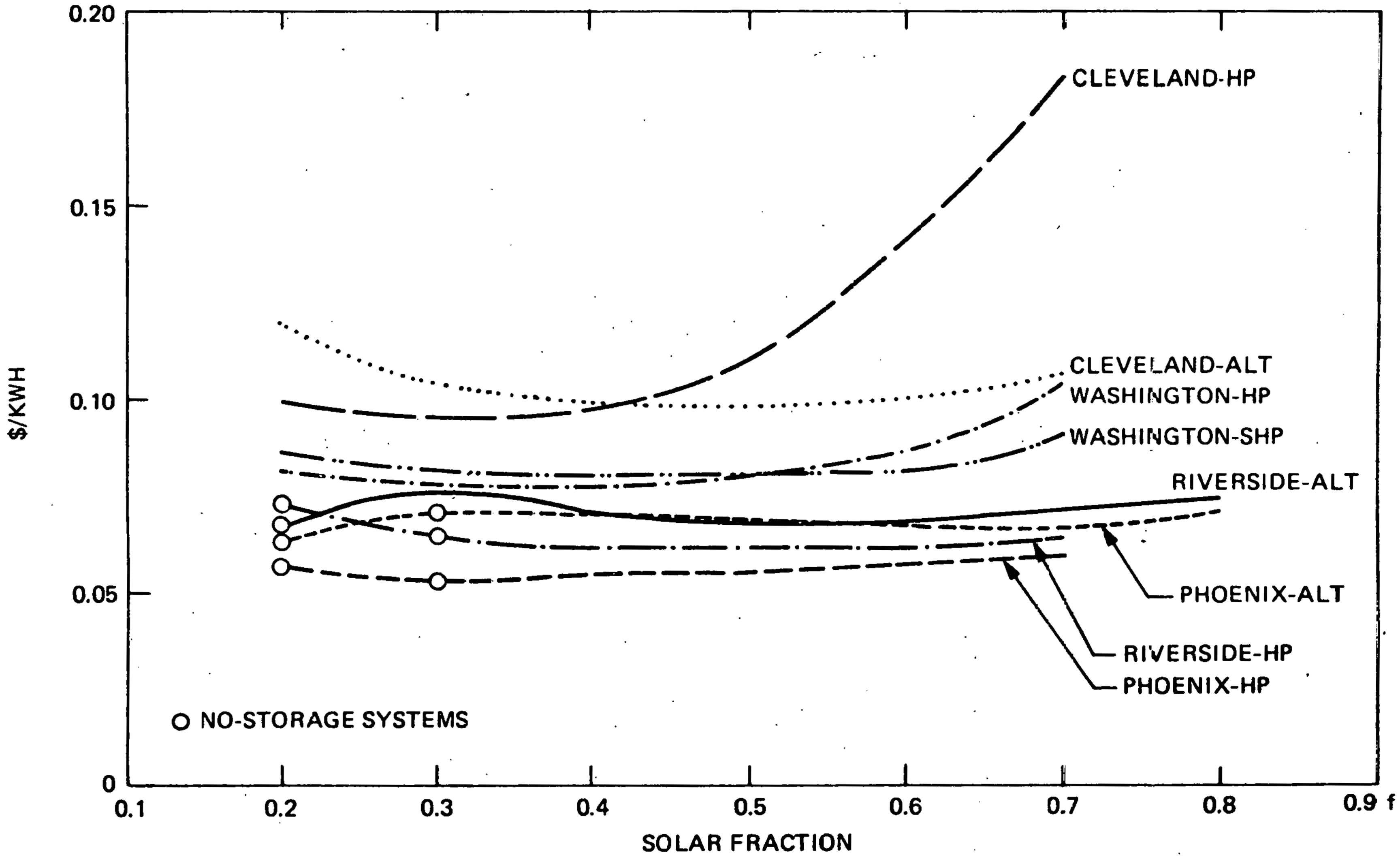


RIVERSIDE RESIDENTIAL SYSTEM COST COMPARISON

SOLAR FRACTION = 0.5



COST OF SOLAR ELECTRICITY



CENTRAL STATION - ARRAY DESIGN STUDIES

OPTICS: 2-Element (Parabolic Trough Plus CEC)
Conc. Ratio = 20 (geom)

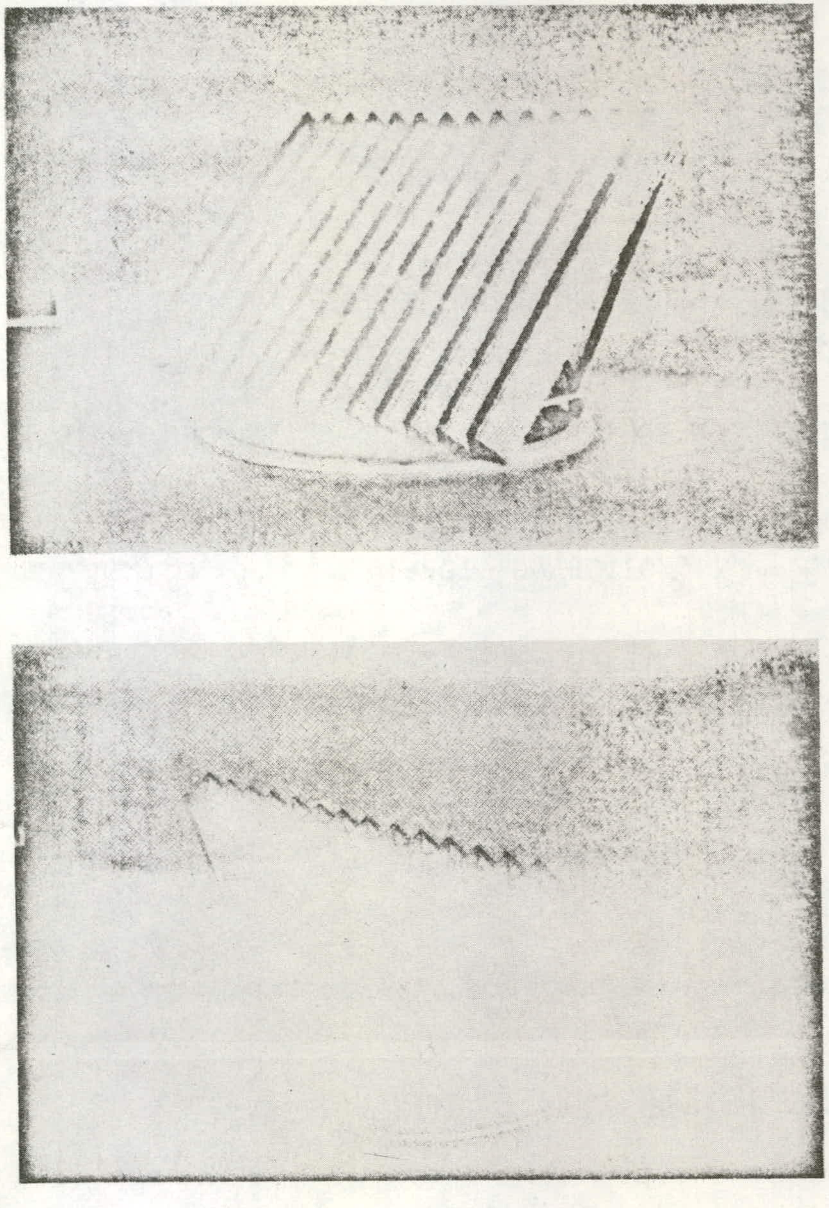
TRACKING: Azimuth only, Aperature/Land Area = 0.2,
Shadowing Losses ~3%

COOLING: Direct Convection, $K_E = 0.3$ kW/m^2 - °C
Obtainable With Interrupted Fins

STRUCTURE: 208.1 m^2 Aperture (40′ x 56′), Designed For
70 mph Wind

PERFORMANCE: 302 kWh/m^2 Aperture (15% Cells), 0.3 Capacity
Factor w/o Storage

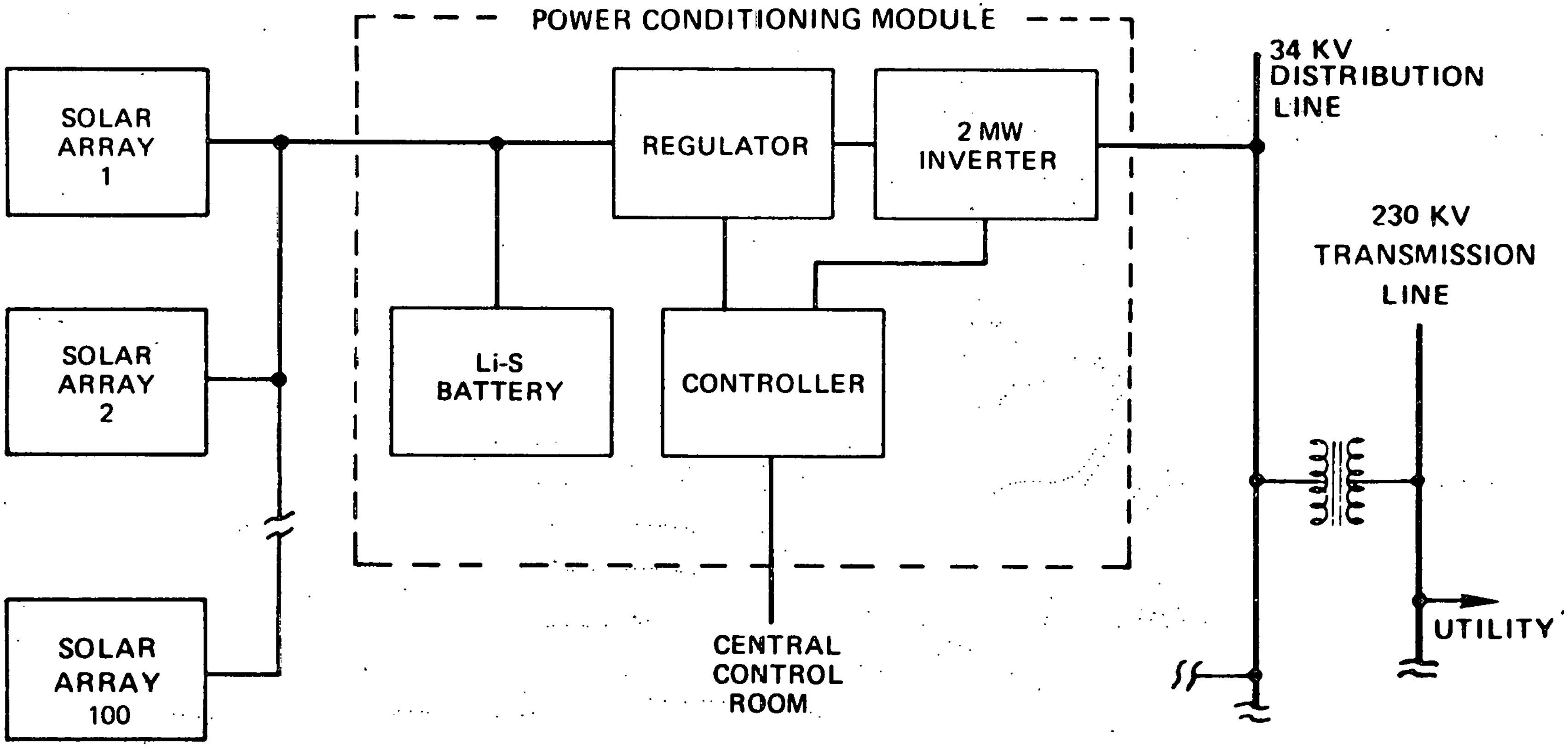
COST: \$102/m^2, \$815/kW pk, \$1065/kW Rated With \$132/m^2
Cells (\$1.20/watt) incl. Site Prep., DC Wiring



CONCENTRATING ARRAY MODULE

208.1 M^2 APERTURE

POWER CONDITIONING MODULE FUNCTIONAL BLOCK DIAGRAM



SOLAR ARRAY 1

SOLAR ARRAY 2

SOLAR ARRAY 100

POWER CONDITIONING MODULE

REGULATOR

2 MW INVERTER

Li-S BATTERY

CONTROLLER

CENTRAL CONTROL ROOM

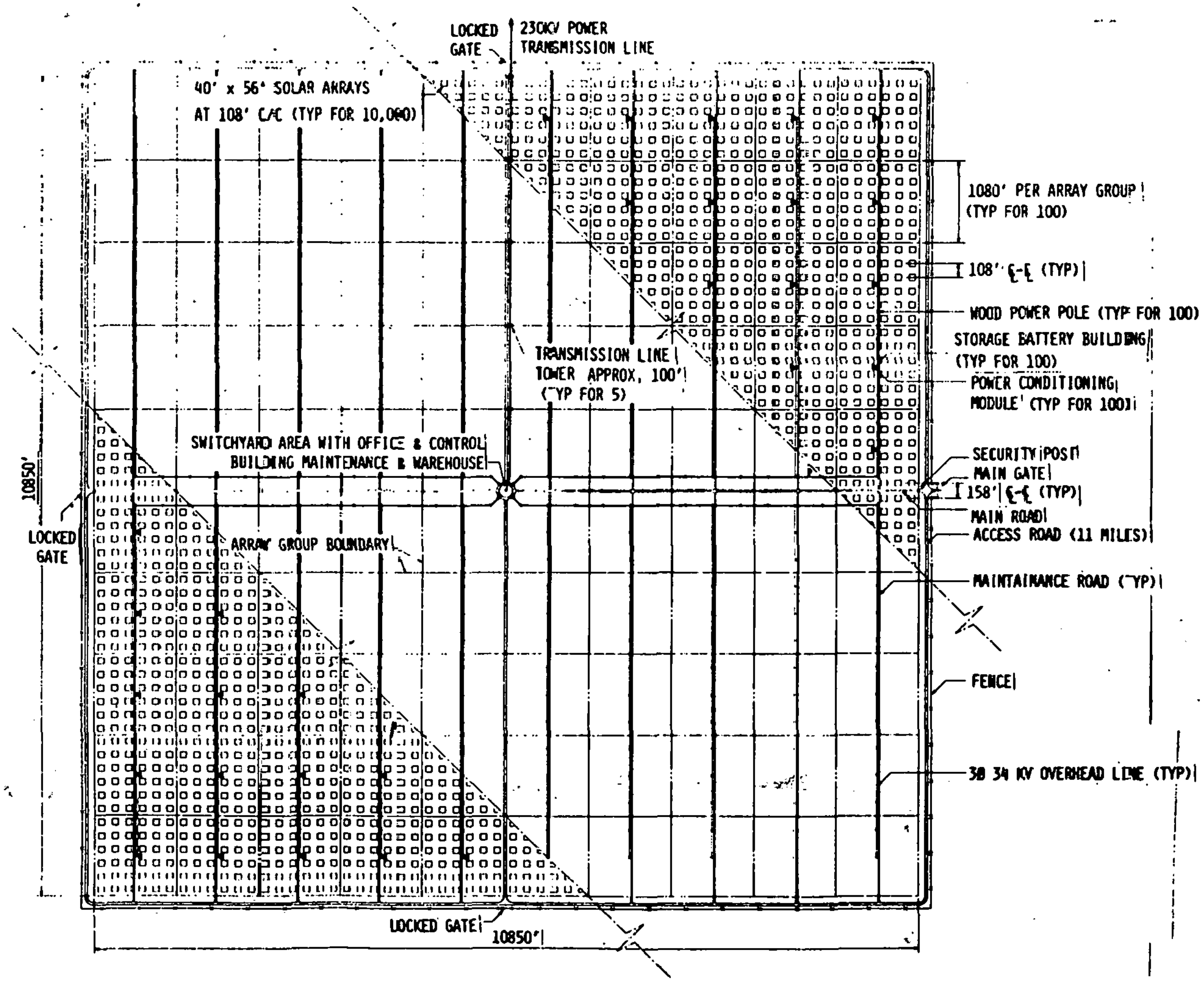
34 KV DISTRIBUTION LINE

230 KV TRANSMISSION LINE

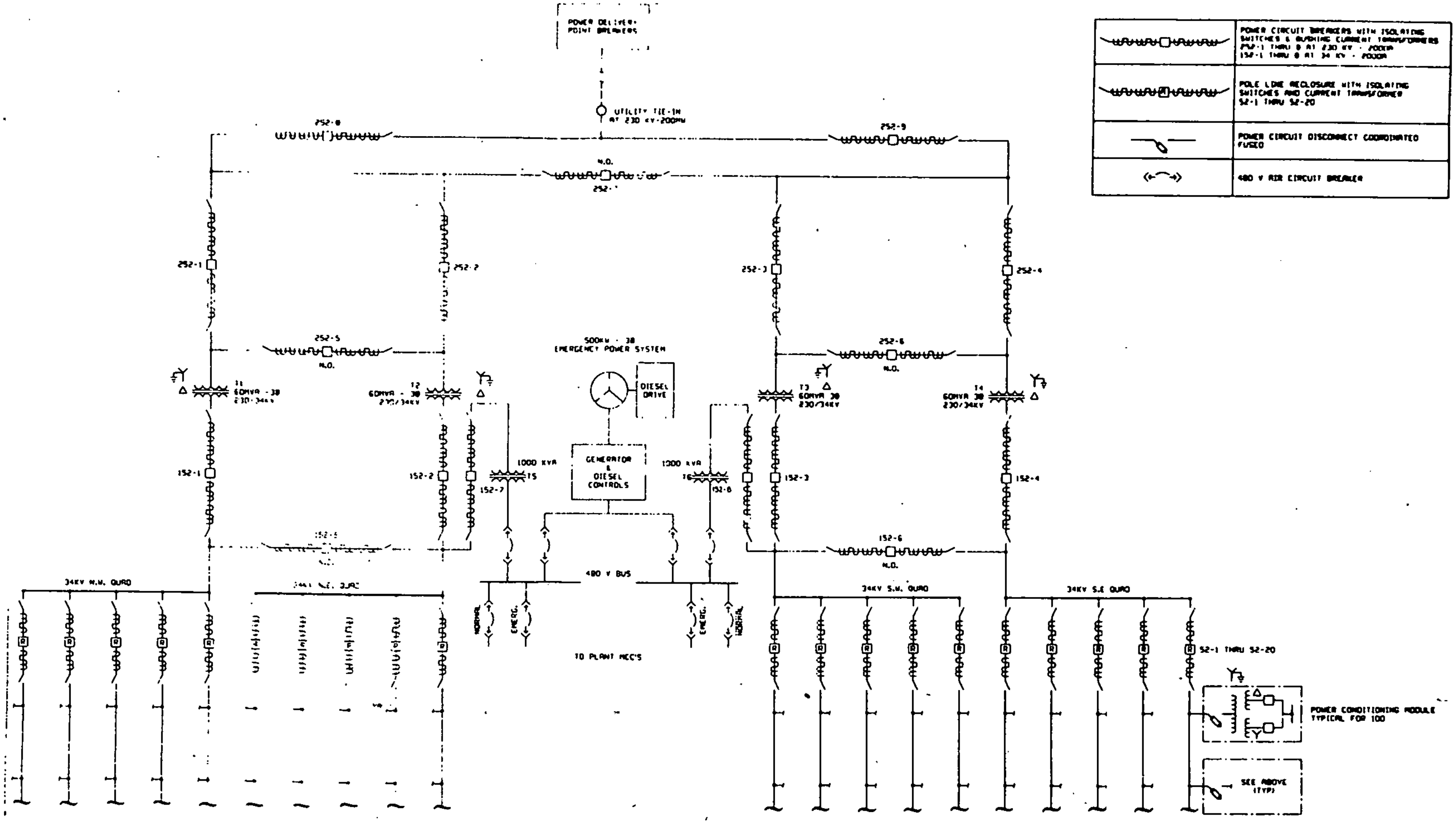
UTILITY

200 MW PLANT LAYOUT

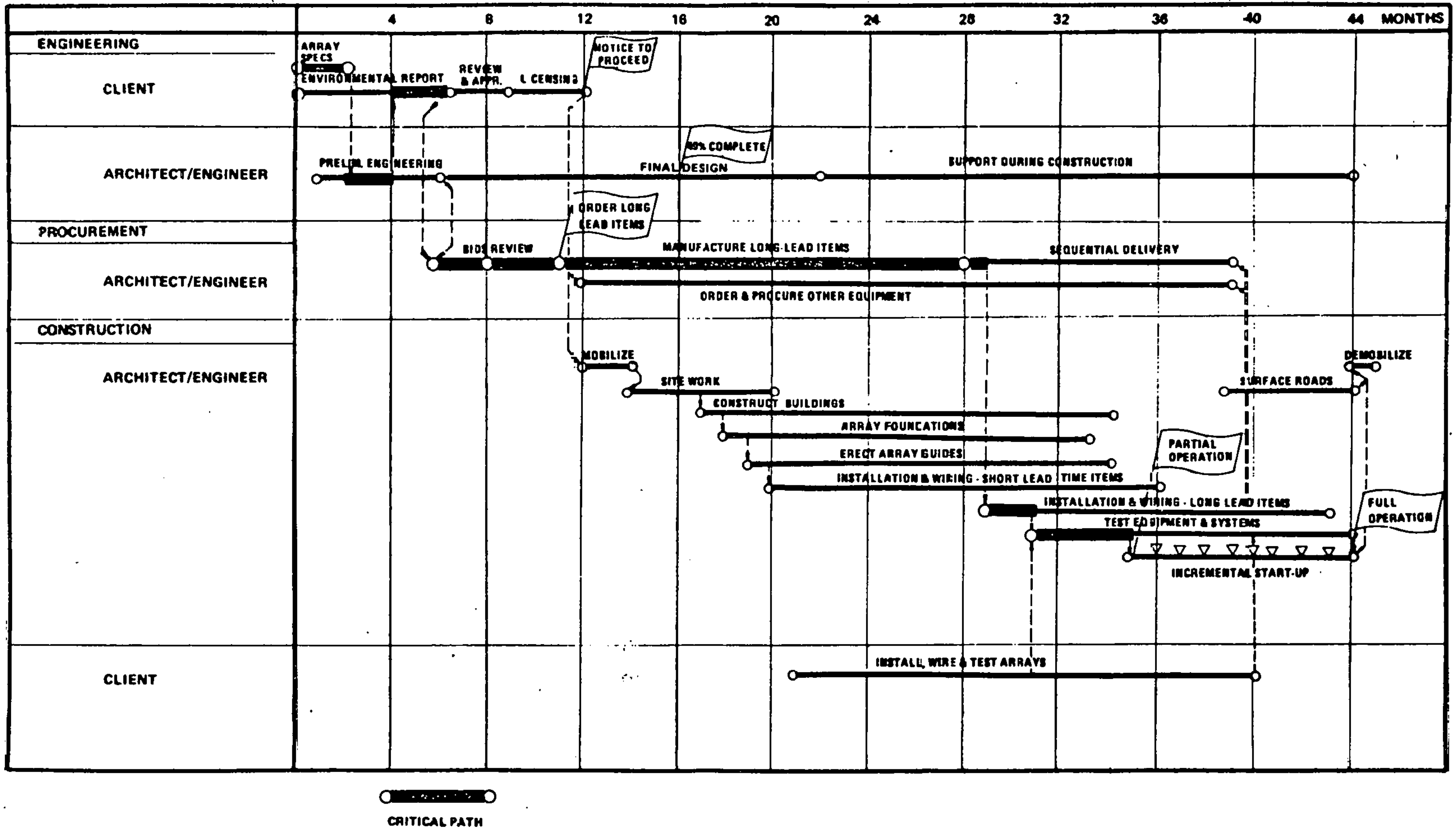
PLANT AREA
4.22 SQ. MILES
10.94 SQ. KM



POWER WIRING SINGLE-LINE DIAGRAM

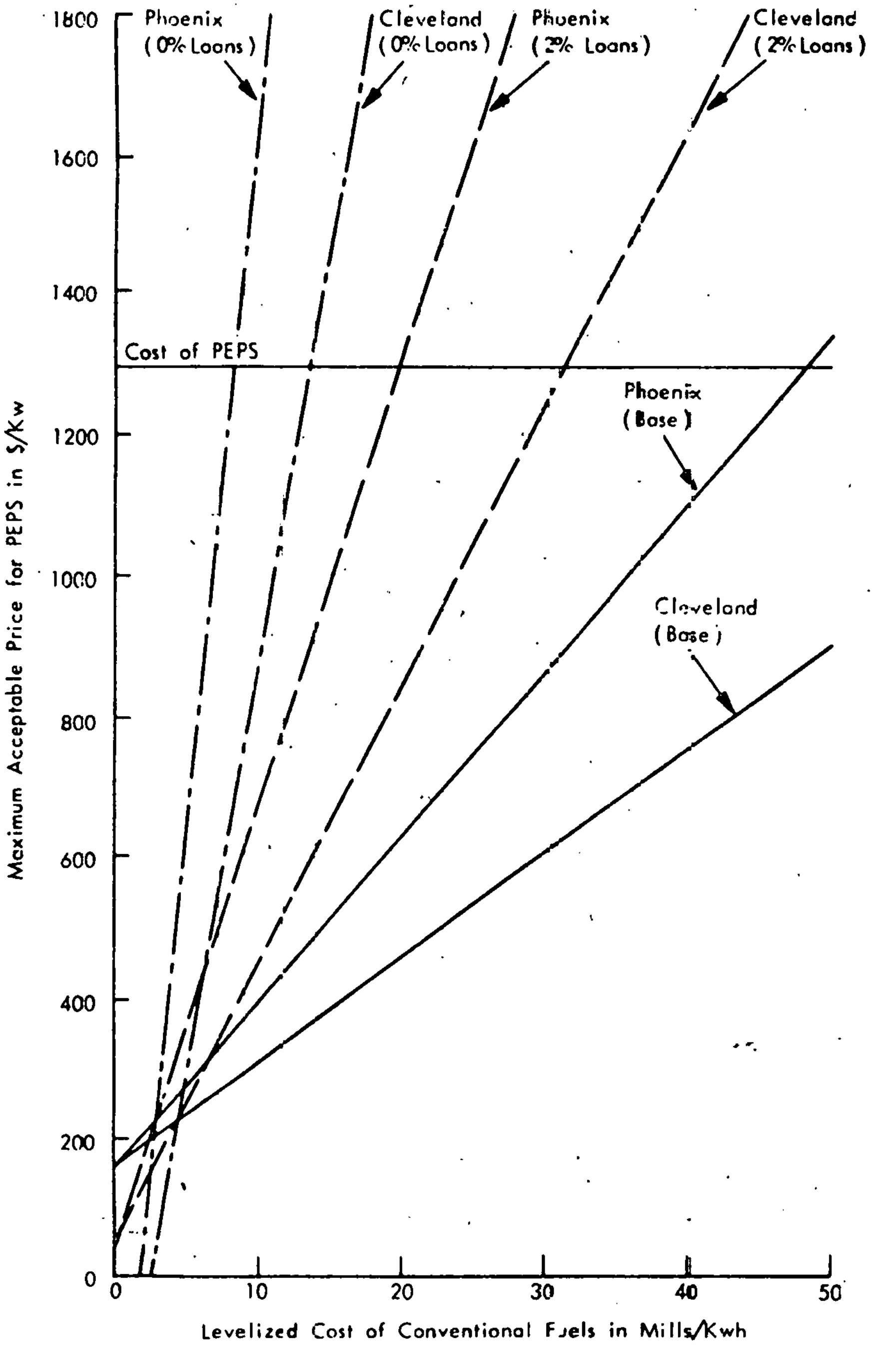


ENGINEERING AND CONSTRUCTION SCHEDULE



CENTRAL POWER STATION COST COMPARISON
1990 Installation - 1975 Dollars
200 MW Rated Capacity

	Millions of 1975 Dollars	
PHOTOVOLTAIC PLANT	No Stor.	3 Hr. Stor.
Arrays & Foundations	$212.94	$212.94
Site Prep., DC Wiring	18.89	18.89
Inverter	28.29	34.58
Battery Storage (Incl. Replacement)	-	91.10
Engr. & Contingency	28.59	47.34
Subtotal	$288.71	$404.85
Gas Turbine Back-Up	26.44	26.44
Total	$315.15	$431.29
Plant Capacity Factor	0.308	0.393
CONVENTIONAL PLANT		
Plant Cost (Coal-Fired Int-Duty)	$110.03	$110.03
Present Value - 30 yr Fuel Supply	94.78	121.03
Total	$204.81	$231.06



EFFECT OF LOW-INTEREST LOANS ON COMPETITIVE POSITION OF PEPS

CENTRAL POWER STATION SYSTEM
SUMMARY OF CONCLUSIONS

- Concentrating Arrays are Nearly Cost-Competitive Even With High-cost Cells

- Storage is Optional; Back-up Generation Requirement Depends on Level of Penetration

- Further Engineering Development of Concentrating Array Designs is Recommended

- Government Assistance to Reduce High Capital Carrying Charges is Most Effective Way of Stimulating Commercialization

COMPARISON OF APPLICATIONS

CENTRAL POWER STATION IS MOST ATTRACTIVE

- Concentrating Array Design Approaches Competitive Cost Even With Expensive Cells
- A Variety of Approaches are Available for Meeting Storage and Back-up Requirements
- Implementation Presents Fewest Problems to Utility

SHOPPING CENTER APPLICATION IS ALSO ATTRACTIVE

- Provided Design is Developed as a Total Package (Not Attractive as Retrofit)
- If Non-Concentrating Module Cost is Less Than $1/watt Installed (not an easy Application for Concentrating Arrays)
- Can be Designed Without Storage or Inversion
- Side Benefits Very Attractive to Center Owner/Developers

COMPARISON OF APPLICATIONS

(CONTINUED)

RESIDENTIAL APPLICATION IS LEAST ATTRACTIVE

- Poorest Load Match to Photovoltaic System
- Poorly Defined Load & Small System Size Make Design Optimization Difficult
- Not Attractive to Utilities Because of Operational & Maintenance Problems
- Questionable Appeal to Homeowners

LOW COST THIN FILM $CdS-Cu_2S$ SOLAR CELL DEVELOPMENT USING CHEMICAL SPRAYING

D. H. Baldwin Co., El Paso, Texas
Sandia Laboratories, Albuquerque, New Mexico

ERDA Contract No. E(29-2)-3579
June 1, 1976 - Nov. 30, 1976

$110,000	(D. H. Baldwin)
$80,000	(Sandia)

Principal Investigators: J. F. Jordan - Baldwin
G. A. Samara - Sandia

Presented at the
National Solar Photovoltaic Program Review Meeting
August 3-6, 1976
University of Maine at Orono
Orono, Maine 04473

ABSTRACT

I. Objectives

The overall objectives of this program are to (i) further develop the process for producing low cost thin film CdS-Cu_2S solar cells using chemical spraying, (ii) increase the average cell efficiency and (iii) ensure long-term cell stability. Important to the achievement of these objectives is the development of an understanding of the cell's characteristics and morphology, and of the spray process.

II. Previous Activities

Earlier work dealt mainly with the development of the spray process with emphasis on determining those process parameters which affect the stoichiometry and properties of the constituent thin films as well as the cell efficiency. The economics of the process for large scale terrestrial applications were also investigated.

Cells with average sunlight efficiency of 4.5% have been produced with some cells exceeding 5% efficiency. Some preliminary electrical and optical characterization of the cells were made.

A variety of analytical tools were used to determine the chemical composition, structure, impurity content and impurity depth profiles in the various thin films. Considerable concentration of impurities were found and their sources identified. The $A\ell$ in the $A\ell$-CdS layer was identified as an oxide. The equivalent thickness of the Cu_xS is ~ 300 nm (assuming stoichiometry and bulk density), but the depth distribution of this material into the CdS layer is much greater than this thickness, so that the junction is quite complex. The stoichiometry of the Cu_xS is $x > 1.98$.

III. Current Activities

The emphasis of the work during this period has been on (i) device characterization, (ii) process control and (iii) life testing.

Device Characterization: SEM results have given detailed information on the grain size and structure of the various layers constituting the cell. The SnO_x layer is relatively uniform with surface grains ~ 100 nm in size. The $A\ell$-CdS layer appears to have smaller grain size than the SnO_x, and it is highly laminated. The CdS layer also tends to be laminated, but it exhibits grain growth in which the surface grain size can be up to several 100 nm. The Cu_xS forms around these grains and extends deep into the CdS layer. These features strongly affect the device characteristics.

With present films, < 50% of the incident photons reach the junction. The sources of these optical losses have been determined. The glass results in ~ 7.5% absorption loss mainly due to Fe_2O_3 absorption. This can be eliminated by using a "no iron" glass. Low resistivity SnO_x causes another ~ 7.5% loss in transmission due to absorption and scattering. This loss can probably be significantly reduced by using a thinner SnO_x layer and by enhancing the grain size. he absorption constant of the CdS layer in the spectral range of interest is very igh (~ 10^3) possibly due to combined impurity absorption and scattering. This constant can potentially be reduced by a factor > 10^2 resulting in greatly improved transmission.

More detailed studies of the electrical and spectral response of the cells have been initiated. I_{sc} and I-V as a function of λ and C-V characteristics are being investigated. The peak collection efficiency of the cells is ~ 70%. The short wavelength side is dominated by the CdS absorption whereas the long wavelength side is determined by the Cu_xS layer. The C-V response has yielded a carrier concentration in the CdS of $1.5 \times 10^{16} cm^{-3}$ for cells with $\eta = 4.5\%$. This is in agreement with resistivity data. The C-V data also indicated regions where Cu compensation or deep levels in the CdS begin to dominate the capacitance.

Refinements in the Rutherford backscattering measurements have provided a more quantitative evaluation of the Cu_xS distribution and clearly show that the Cu_xS extends deep into the CdS layer. This is corroborated by the SEM data.

Impurities affect the optical and electrical properties of the various layers. A complete impurity analysis has been made and sources of impurities determined. Several processing steps have been taken to control the levels of some of these impurities (see below).

Process Control: The spraying process used thus far has involved the use of air driven nozzles which break up the stream of solvent containing the active chemicals into droplets varying in diameter by 100:1. A new ultrasonically driven nozzle which produces more uniform droplets has been developed. With this nozzle two means of dispersal are employed: electrostatic and air dispersal. In the electrostatic mode no air is used while in the air dispersal mode this nozzle uses 10% of the air required for the earlier nozzle and this should significantly reduce the level of contamination of the films by air-borne impurities. Preliminary results on films produced by the new nozzle show smoother films with considerably higher transmission. The minimum droplet size thus far obtained in the new nozzle is 125 μm. Previous high speed photography of film formation has shown that droplet size should be < 50 μm.

A new controlled atmosphere spray booth has also been developed. This permits the use of nitrogen instead of air as both a propellant and as a carrier for removing the products of the chemical reaction during film formation. A scrubber is attached to the booth which removes these products and permits recirculating clean dry nitrogen. This booth is just being placed in service.

Life Testing: Both accelerated and roof-top tests are in progress. The accelerated test is run continuously at 1 sun and 100°C for 100 hours. Both temperature and illumination are closely controlled, and the voltage is monitored during the test. The roof-top tests have been in progress for 4000 hours under El Paso sunlight. The tests have indicated two sources of some device degradation: high residual chlorine content in the CdS film and shunting by peripheral Cu_xS unprotected from the atmosphere by the back Cu/Pb electrode. This degradation is eliminated in cells with low chlorine content and where the peripheral Cu_xS layer is removed.

J. F. Jordan - Baldwin	R. S. Berg - Sandia
C. Lamkin - Baldwin	R. D. Nasby - Sandia
	G. A. Samara - Sandia

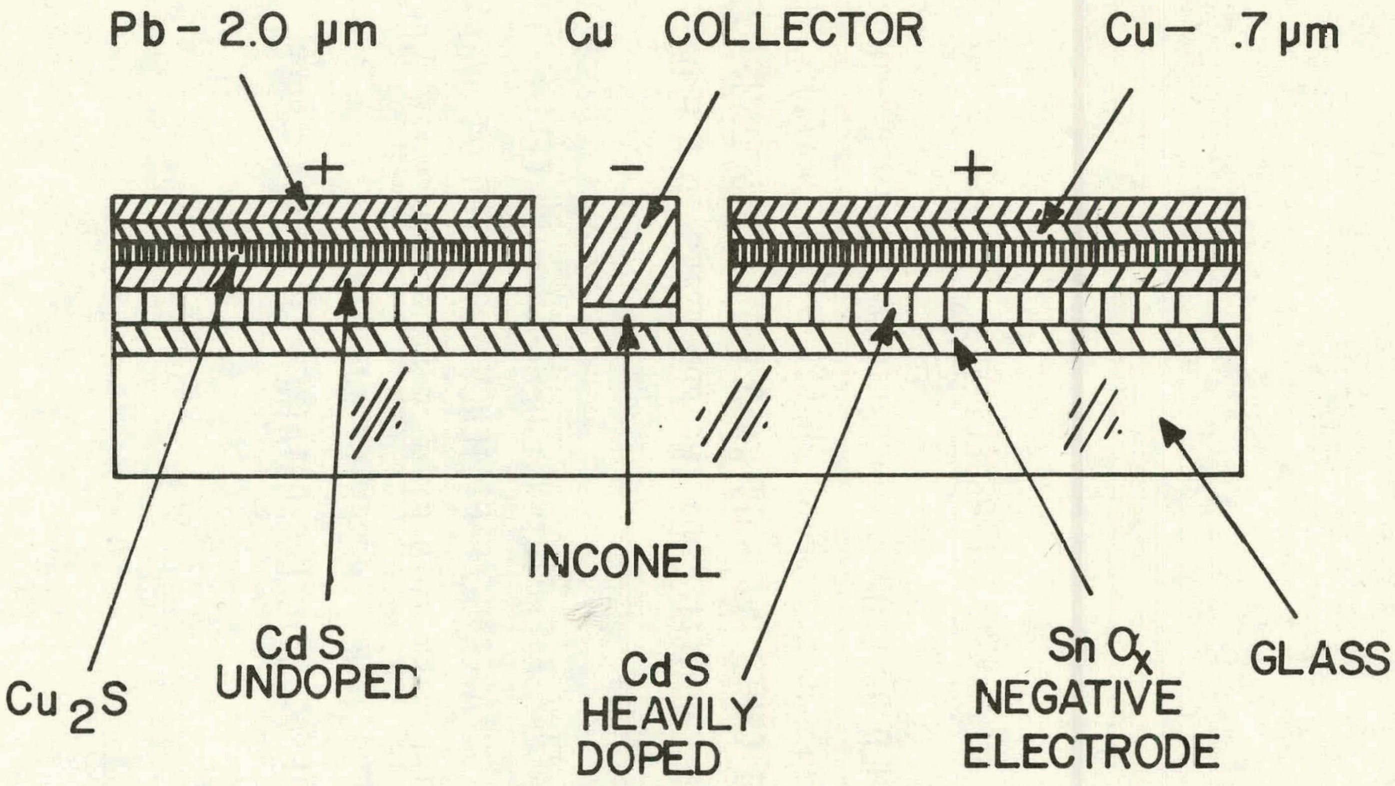
OVERALL OBJECTIVES

TO FURTHER DEVELOP A PROCESS FOR THE MANUFACTURE, ON A LARGE SCALE, OF SOLAR CELLS COSTING APPROXIMATELY 6 CENTS PER WATT ($60/KW). THIS ENVISAGES ADAPTING CHEMICAL SPRAYING PROCESSES TO A FLOAT GLASS PLANT.

I. INCREASE EFFICIENCY OF THIN FILM CELLS FROM 4.5% AVERAGE EFFICIENCY TO EXCEED 5% AVERAGE.

II. LIFE TEST THIN FILM CELLS OF THE 4.5% AVERAGE EFFICIENCY PRESENTLY AVAILABLE.

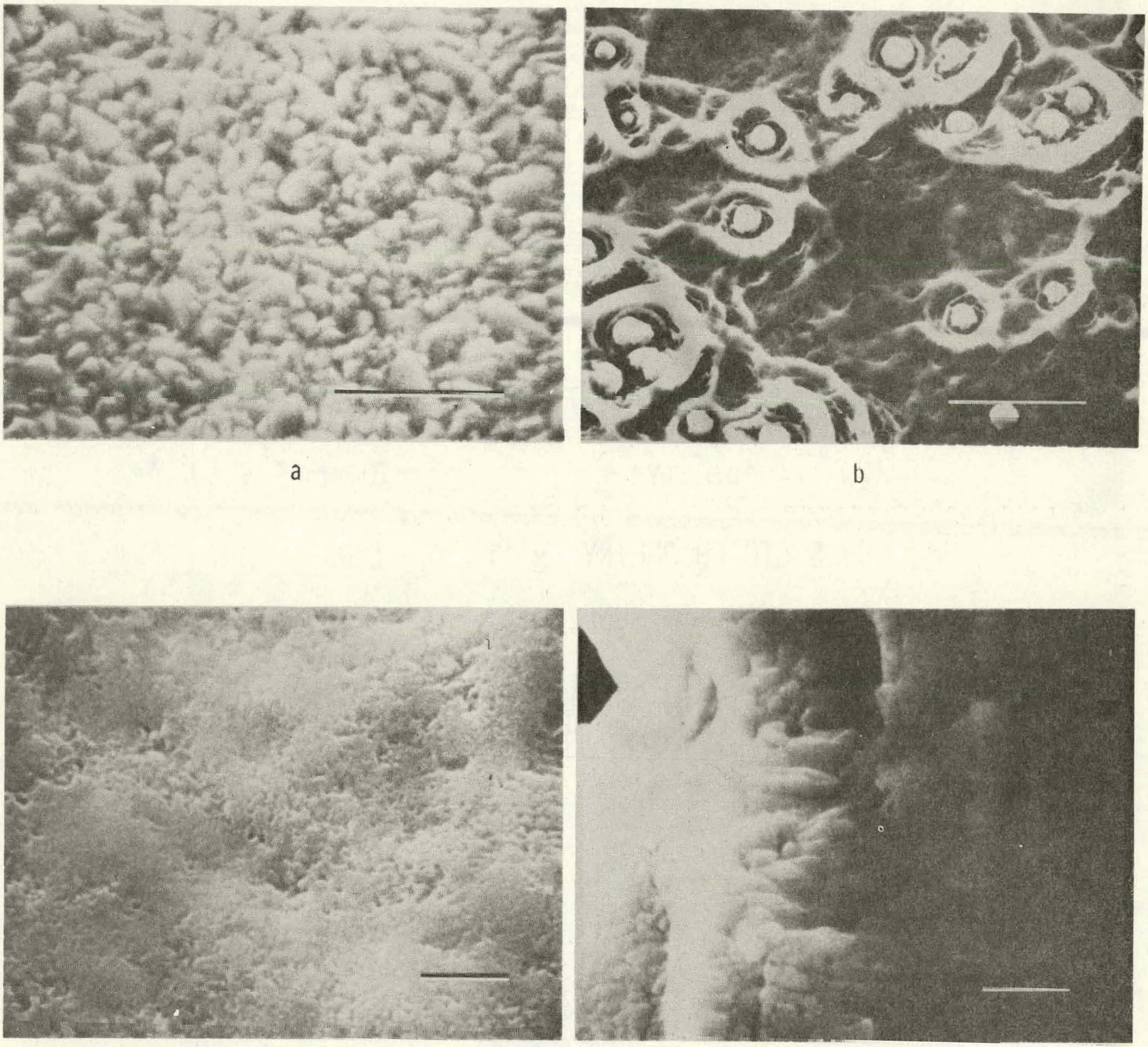
III. LIFE TEST CELLS OBTAINED IN ITEM I ABOVE.



CROSS SECTION OF BACKWALL SOLAR CELL

CURRENT STATUS

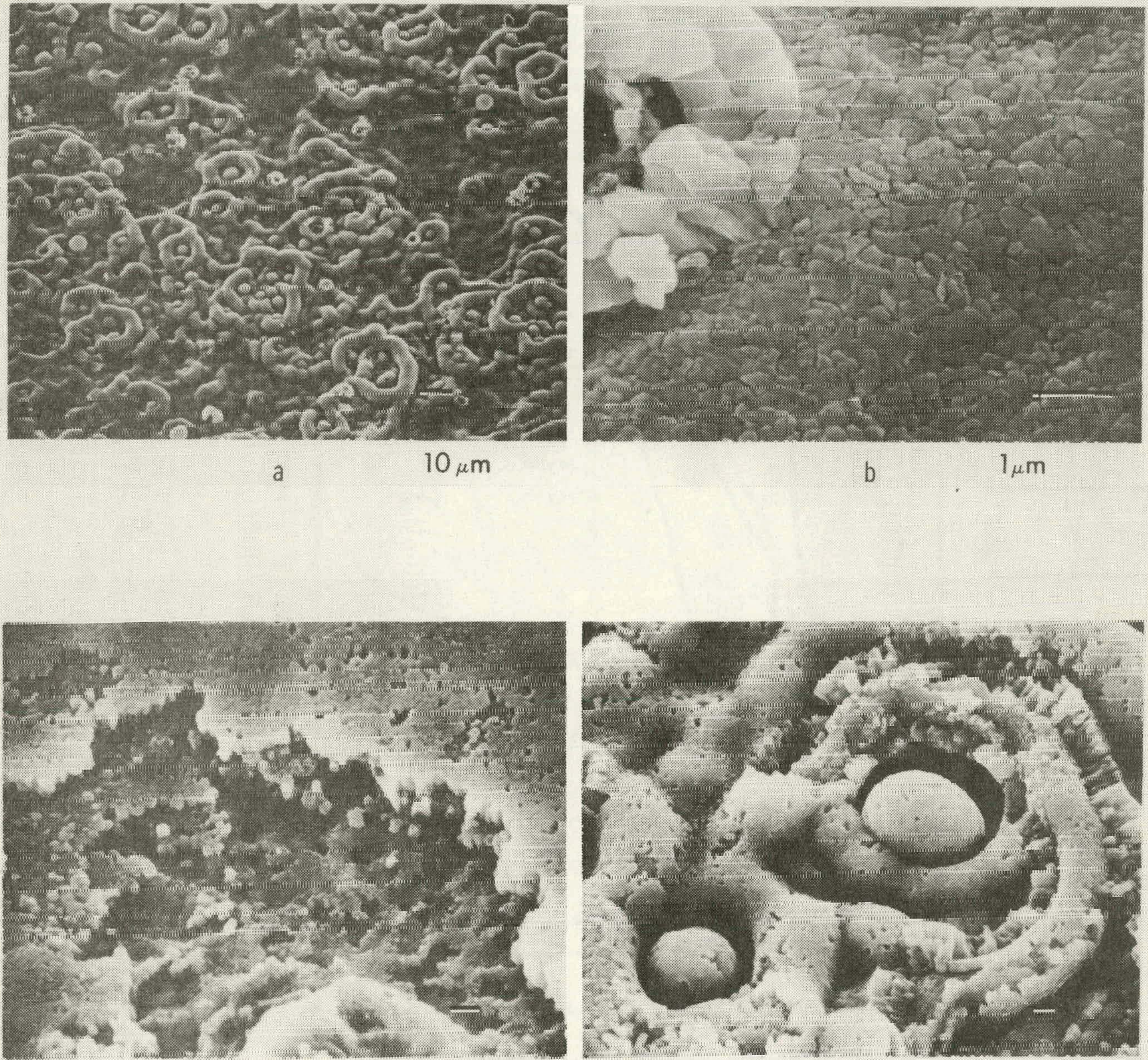
I_{SC}	18 - 20 MA/CM^2	
V_{OC}	360 - 410 M.V.	
ρ (RESISTIVITY)	~ 30 OHM-CM	(CDS)
U (MOBILITY)	~ 10 CM^{2}V^{-1}S^{-1}	"
Cu_xS STOICHIOMETRY x >	1.98	
η (MAX. IN SUNLIGHT)	5.2%	
η (AVG. IN SUNLIGHT)	4.5%	



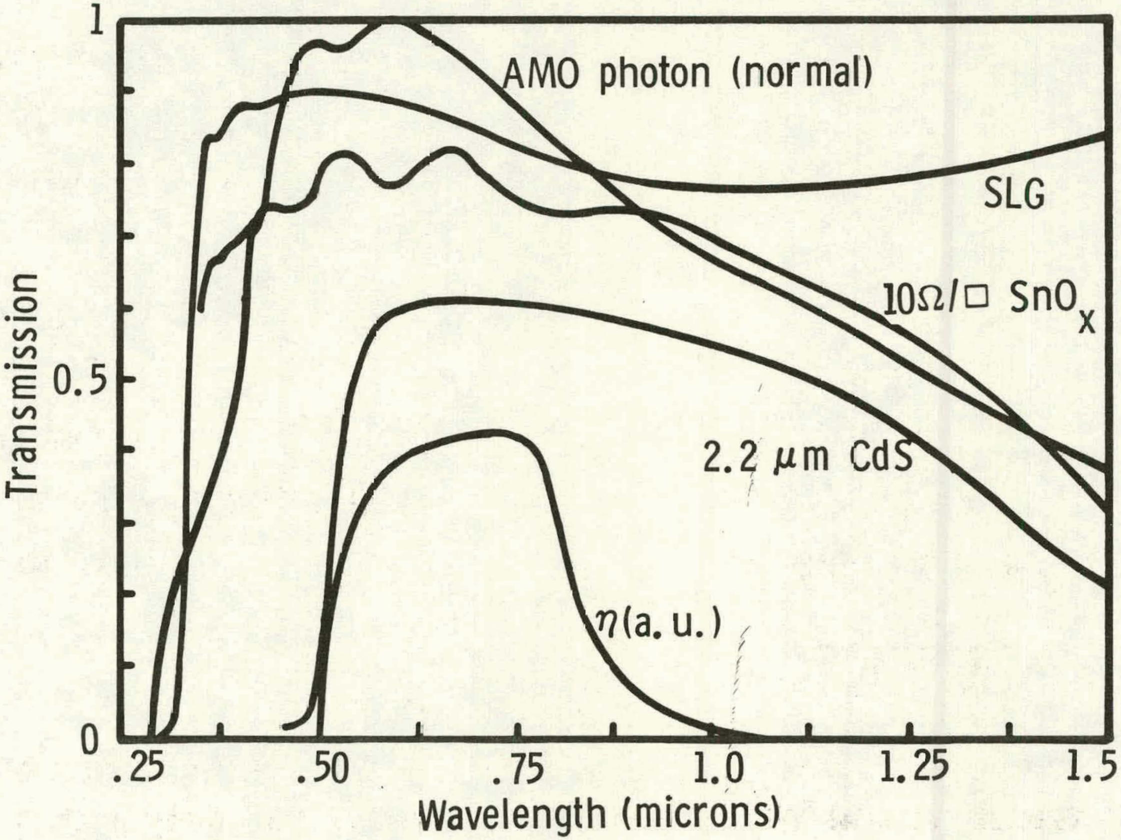
a b

c d

a) SnO$_X$ surface, b) Aℓ-CdS surface, treated to bring out the fine structure, c) same as b, but at higher magnification, and d) cross section showing the distinction between the two CdS layers. The marker in b is 10 μm, otherwide 1 μm.



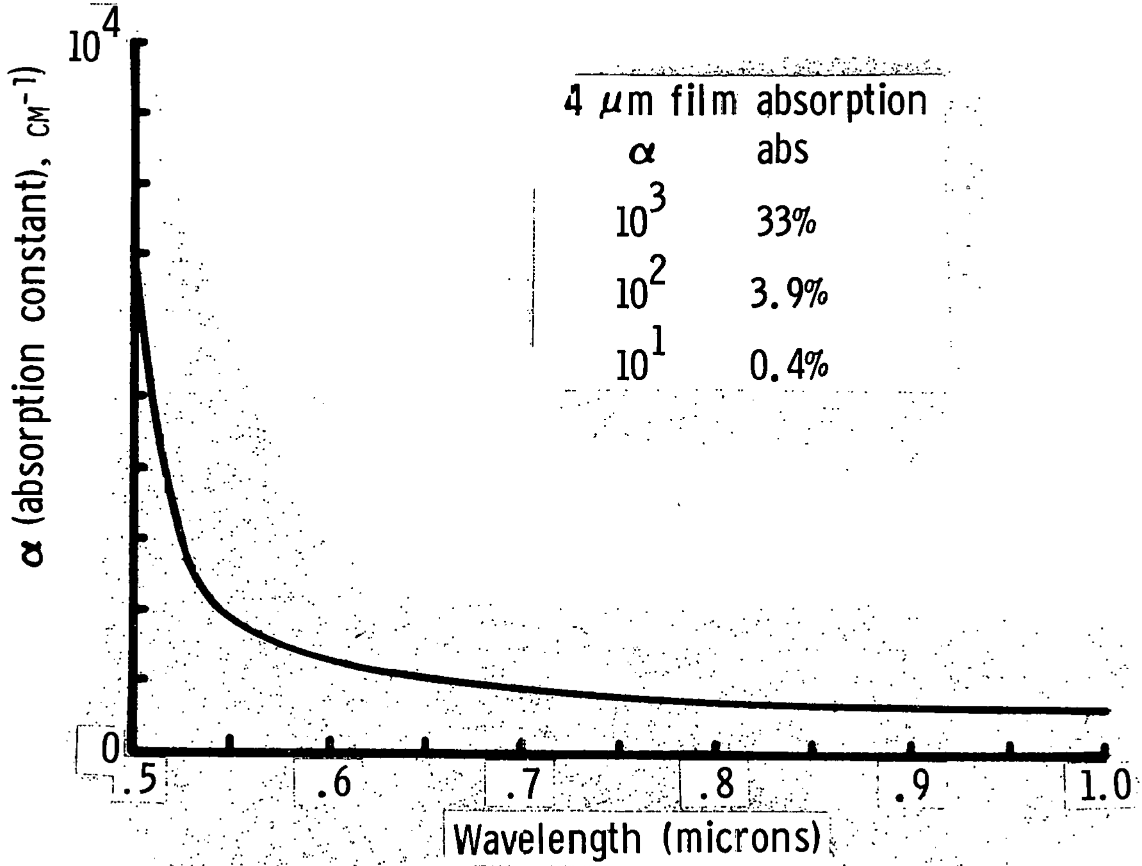
SEM photographs of a KCN etched Cu_xS layer. c) and d) have been ultrasonically etched for 20 sec. The marker in a is 10 μm, otherwise 1 μm.



Transmission curves for the various layers. The air mass zero photon spectrum is shown for reference. The slope of the collection efficiency curve reflects the CdS and Cu_xS properties.

PHOTON LOSSES IN THE GLASS AND SnO_x LAYER FOR THE TOTAL AM1 AND INTER-BANDGAP PART OF THE AM1 SPECTRUM, GIVEN IN PERCENT OF THE PHOTONS AVAILABLE. LINES 2-5 ARE INTEGRATED SPECTRAL TRANSMISSIONS, AND ARE NOT COMPENSATED FOR INTERFACE REFLECTIONS. LINES 6-8 ARE ABSORPTIONS CALCULATED FROM THE TRANSMISSION AND REFLECTION VALUES. LINES 4 AND 5 SHOW A TRADE-OFF IN THE PRESENT SnO_x MATERIAL BETWEEN ELECTRICAL RESISTIVITY AND OPTICAL TRANSMISSION.

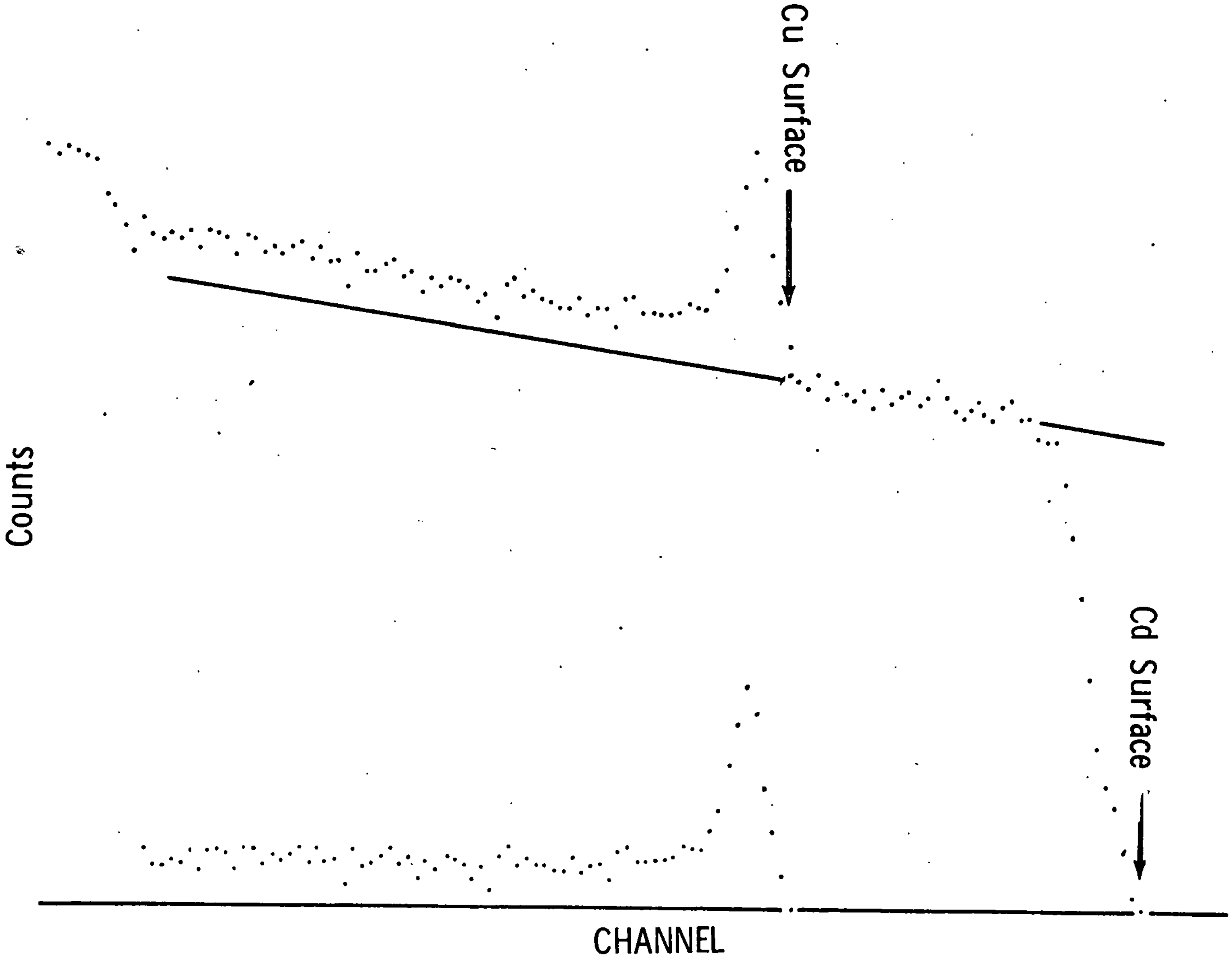
	TOTAL AM1	IBG ($.508 < \lambda < 1.06$)
1. AM1 (PHOTONS/CM^2/SEC).	4.07×10^{17}	1.89×10^{17}
2. STANDARD SODA-LIME GLASS (SLG) (AM1)	82.7 %	82.9 %
3. "NO IRON" SLG (AM1)	89.6 %	90.4 %
4. SnO_x($4\Omega/\square$) ON STD SLG	50.5 %	68.7 %
5. SnO_x($10\Omega/\square$) ON STD SLG	57.5 %	75.9%
6. ABS. OF ($4\Omega/\square$) ON STD SLG	32 %	14 %
7. ABS. OF ($10\Omega/\square$) ON STD SLG	25 %	7 %
8. ABS. OF ($10\Omega/\square$) ON "NO IRON" SLG	1 %	1 %



4 μm film absorption

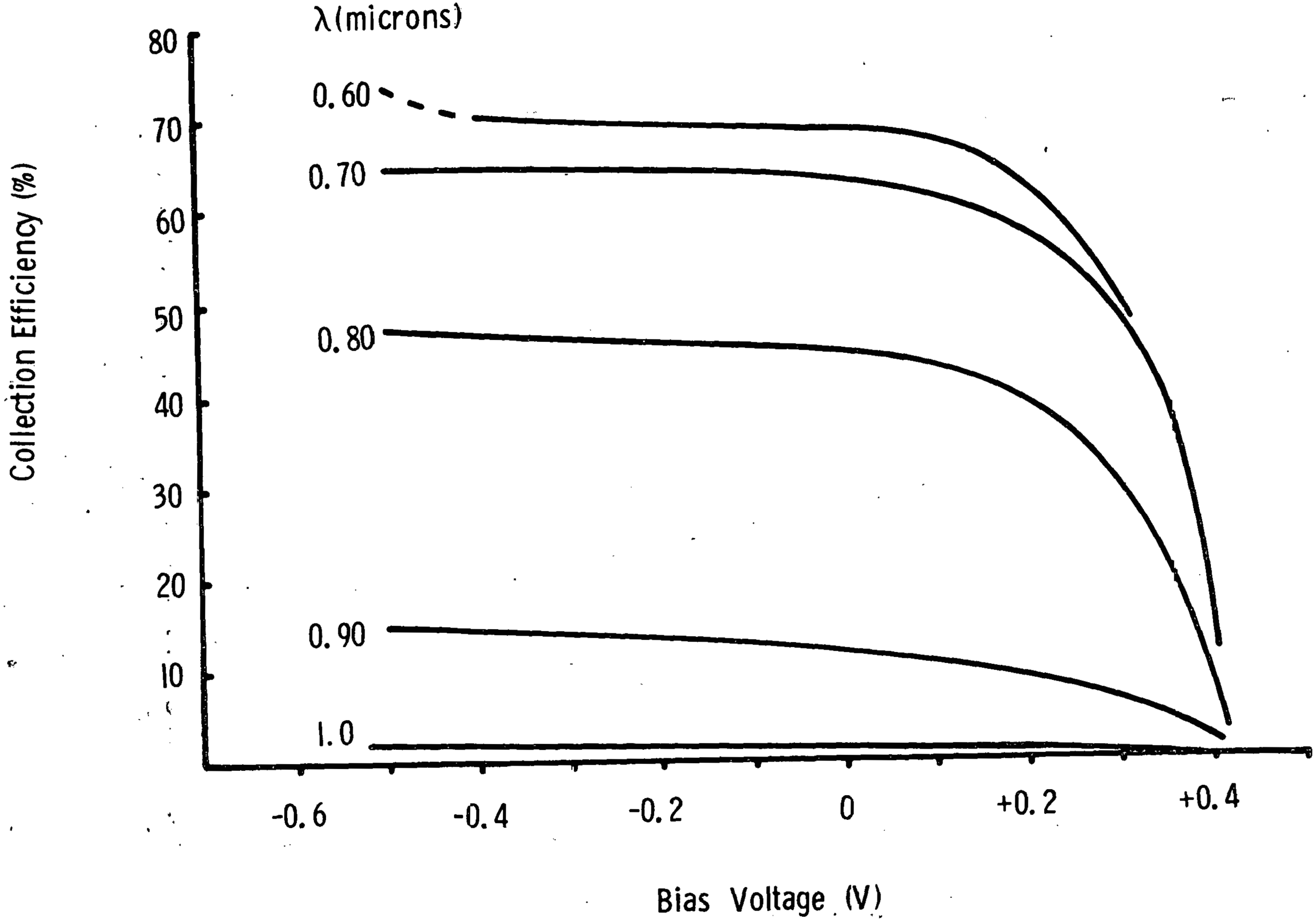
α	abs
10^3	33%
10^2	3.9%
10^1	0.4%

CdS absorption constant and net absorption

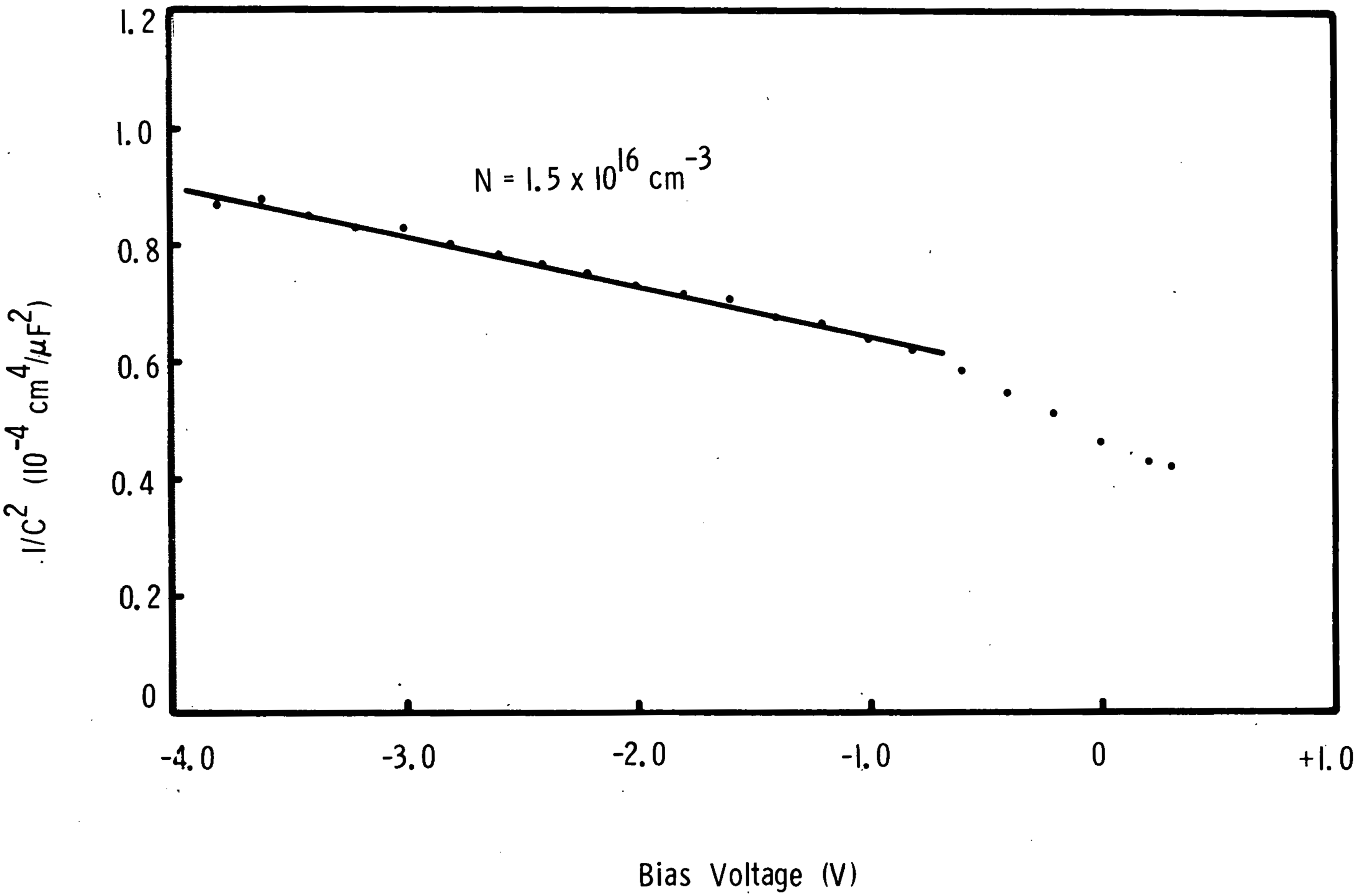


Rutherford Backscattering spectrum showing a determination of the copper profile in the near surface region by subtracting the extrapolated CdS background. The lower trace shows the resulting copper profile.

Cell Spectral Response



DARK CAPACITANCE DEPENDENCE ON VOLTAGE



FILM IMPURITIES AND THEIR SOURCES

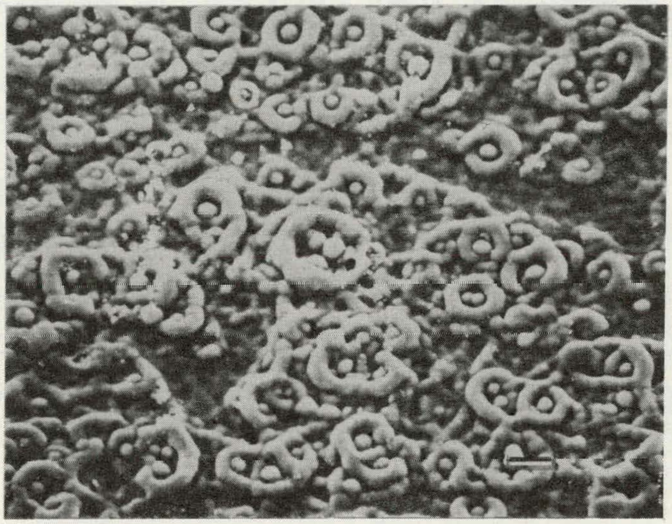
FILM IMPURITY	STARTING CHEMICALS	WATER AND SPRAY EQUIPMENT	AIR	SUBSTRATE
O			MAJOR	
NA	X			C
MG	I	X		
Aℓ	I			
SI	I	X		
Cℓ	MAJOR			
K	X			C
CA	X			
MN		I		
FE	I	C-M		
NI	I			
CU	I	X		
ZN	X			
SR	I			
PB			C	

I = PPM

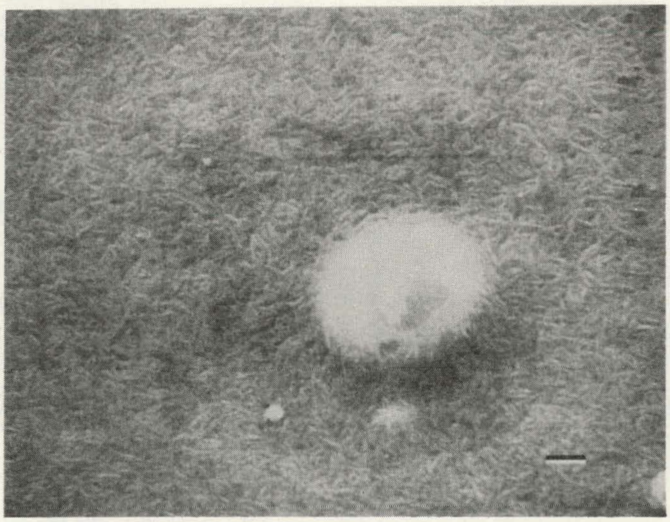
X = TENS OF PPM

C = HUNDRED OF PPM

M = THOUSANDS OF PPM

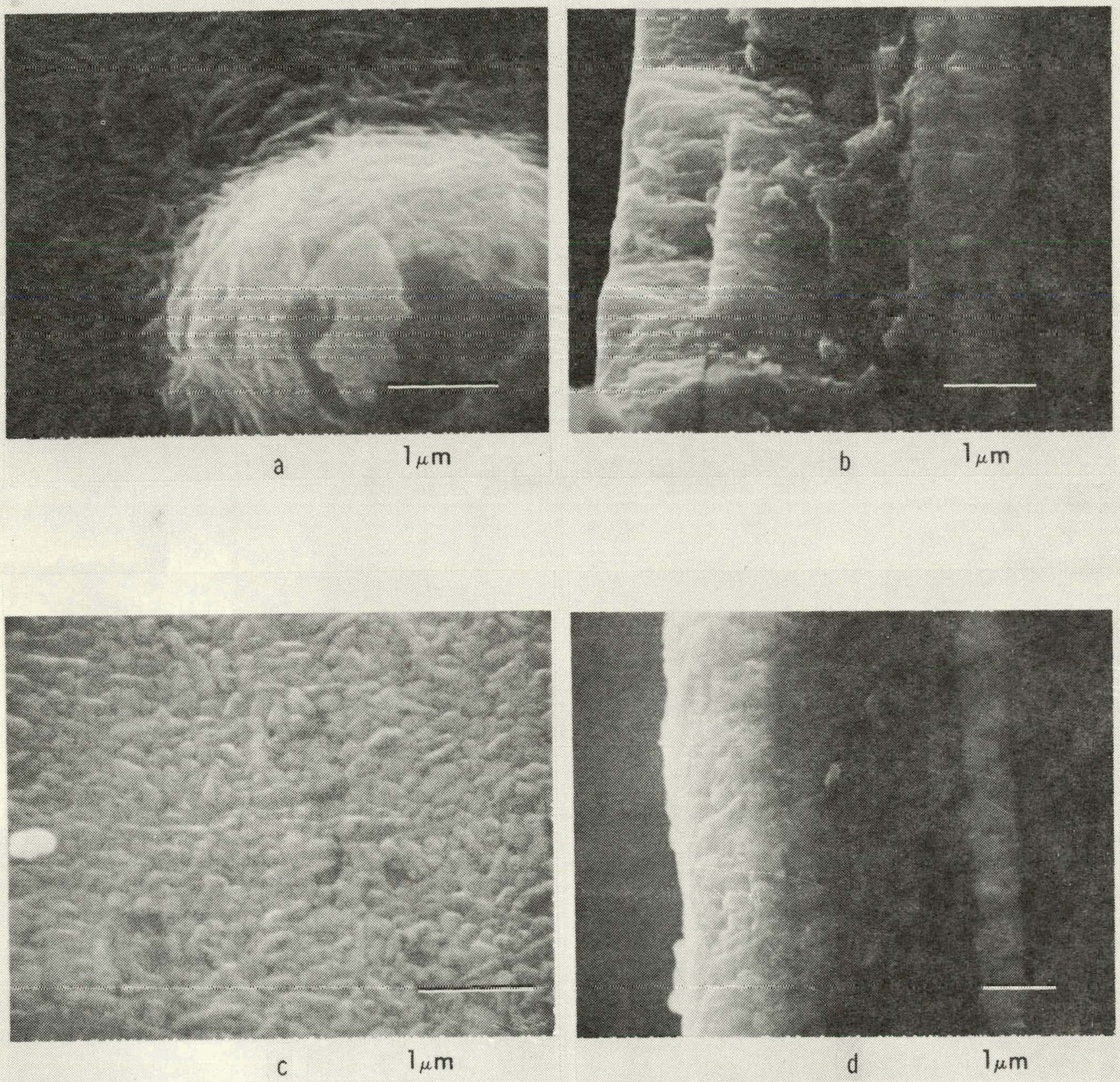


a

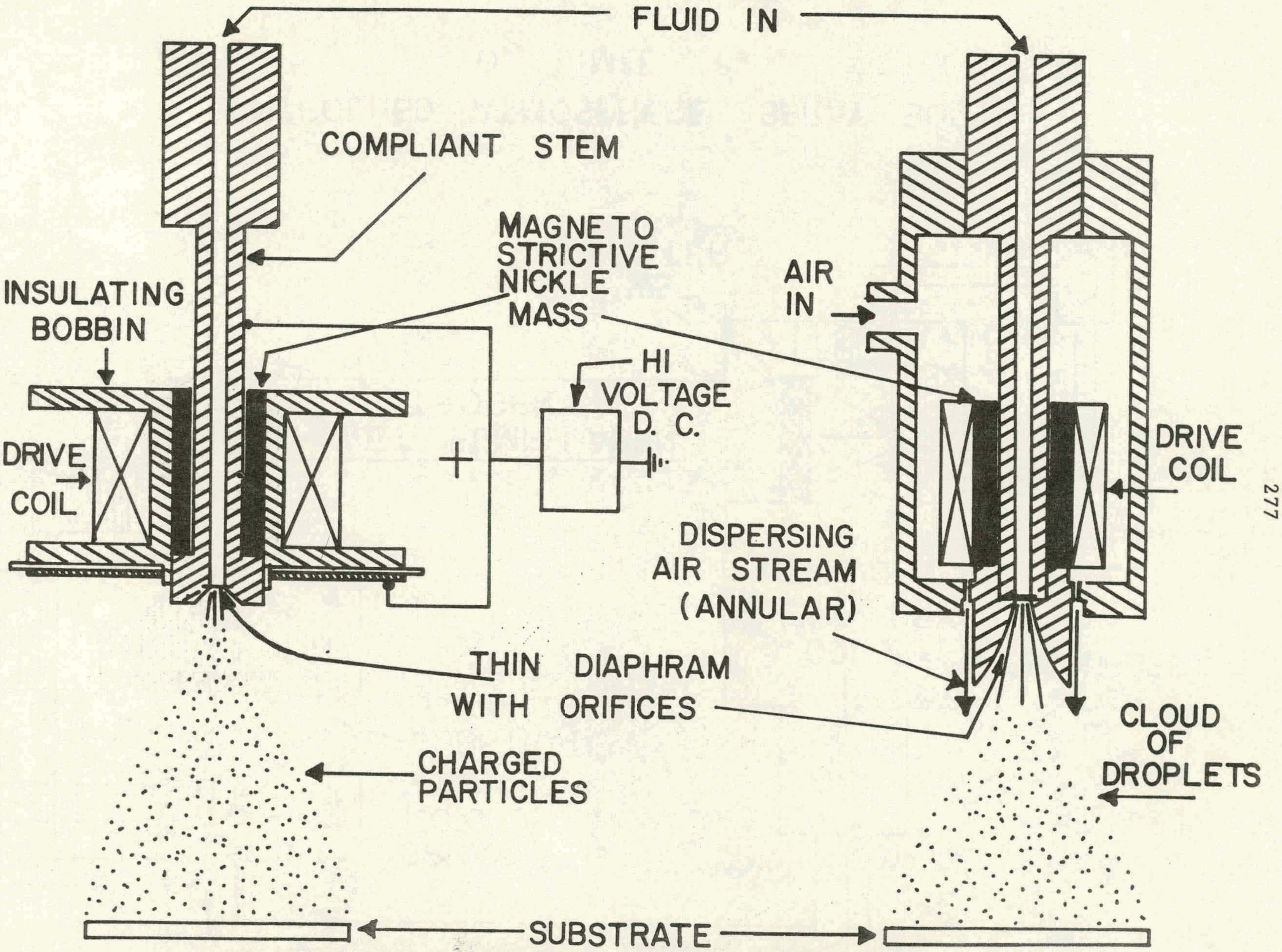


b

SEM photographs of the surface of the CdS film from a) the standard spray nozzle and b) the "uniform drop" nozzle. The marker is 1 μm.



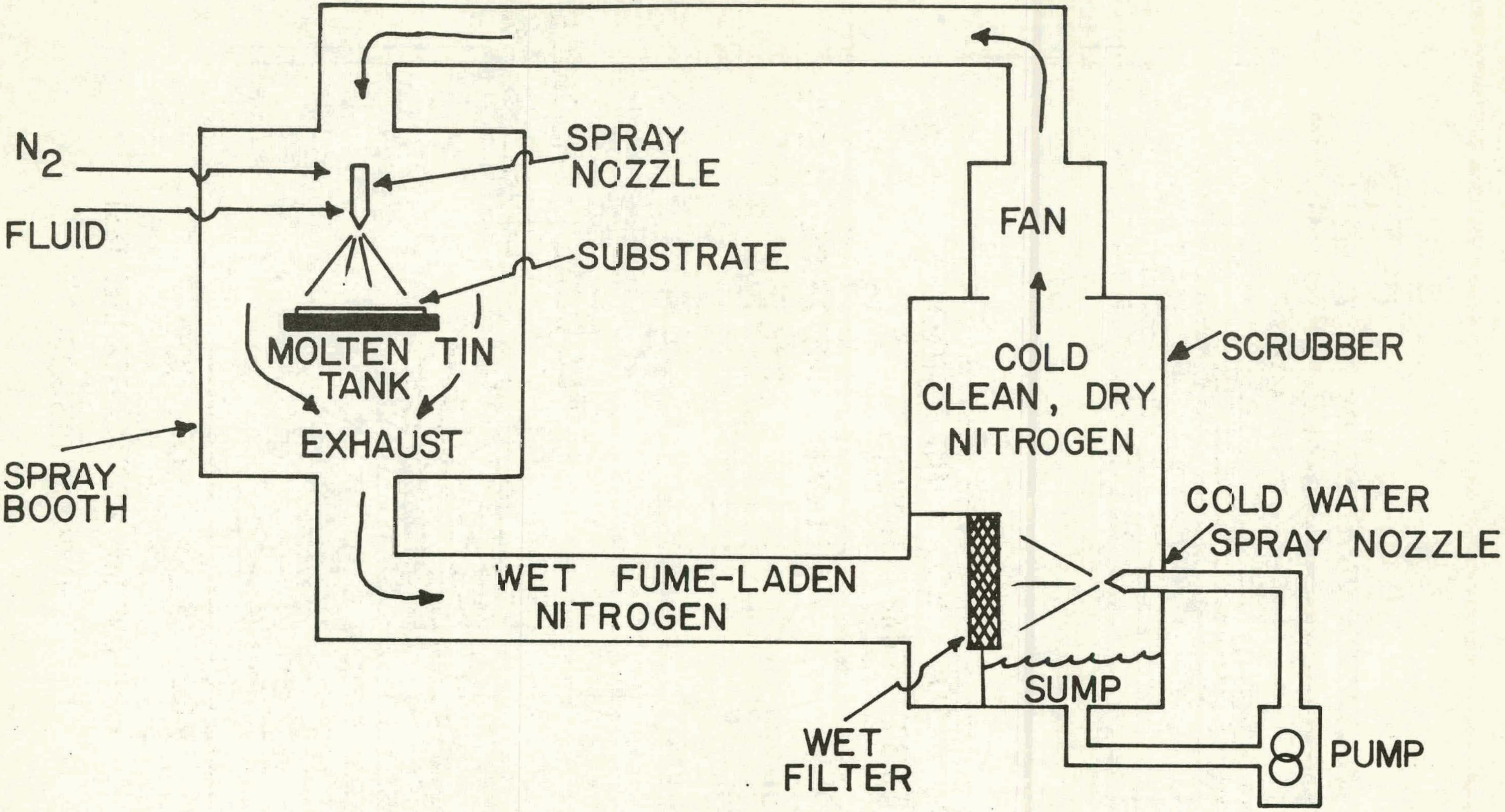
SEM photographs of films produced by the uniform droplet generator, a) and b) as deposited, c) and d) after heat treatment of 500°C for 20 min. Some grain growth can be seen. The marker is 1 μm.



ULTRASONICALLY DRIVEN NOZZLES

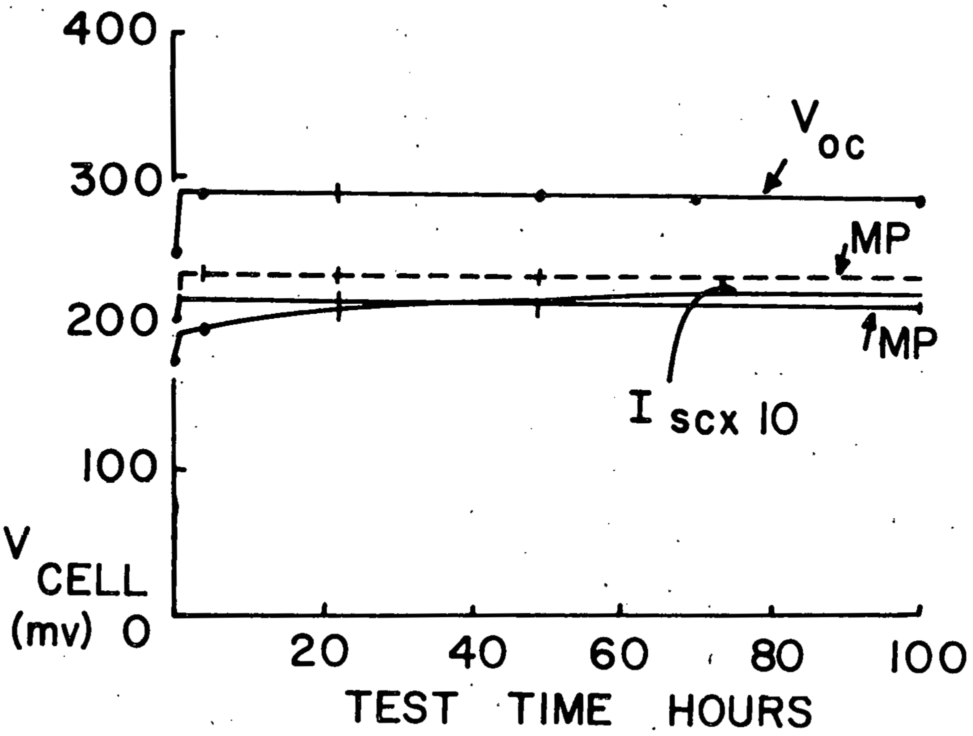
HIGH VOLTAGE DISPERSAL

AIR DISPERSAL

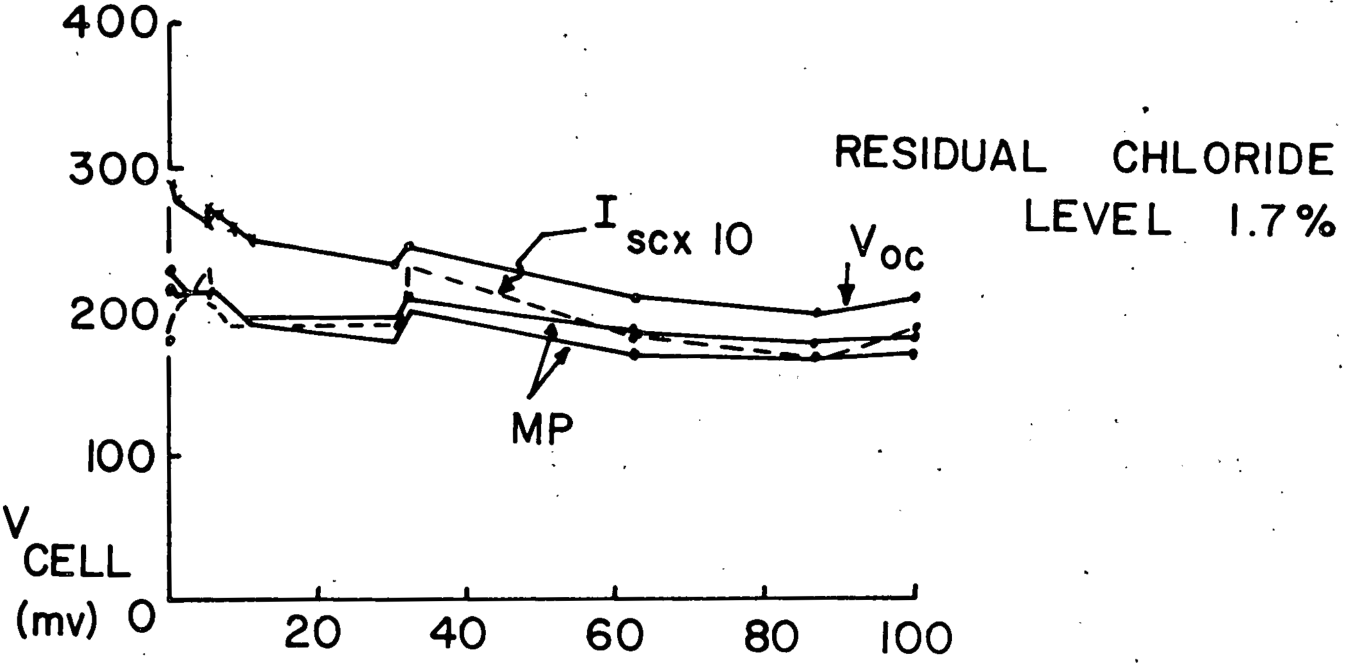


CONTROLLED ATMOSPHERE SPRAY BOOTH

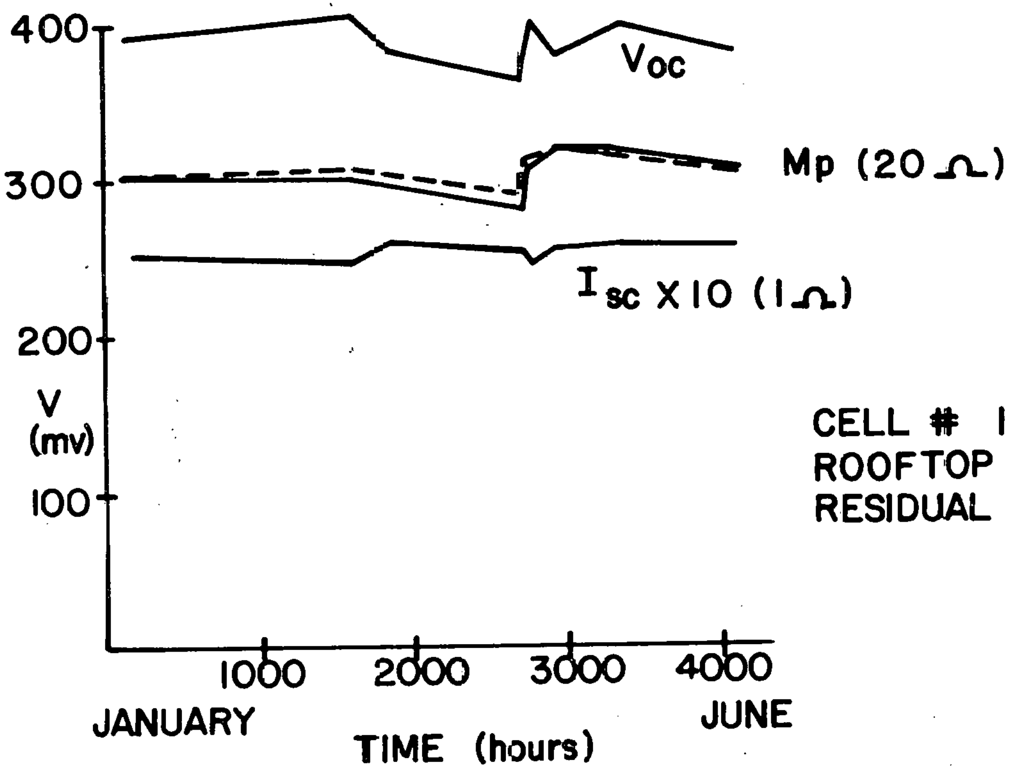
O_2 LIMIT .1%



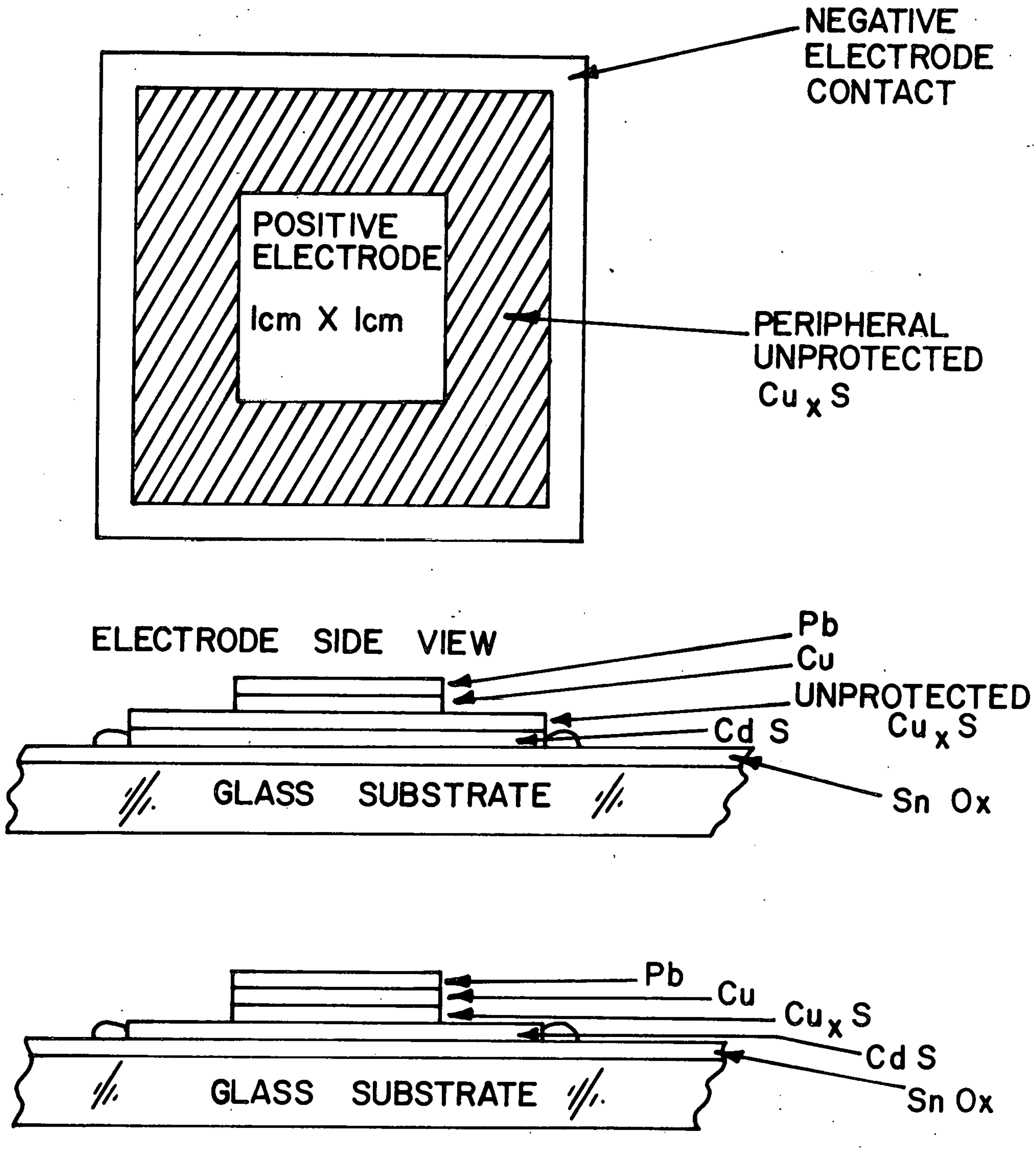
RESIDUAL CHLORIDE LEVEL
.7 %



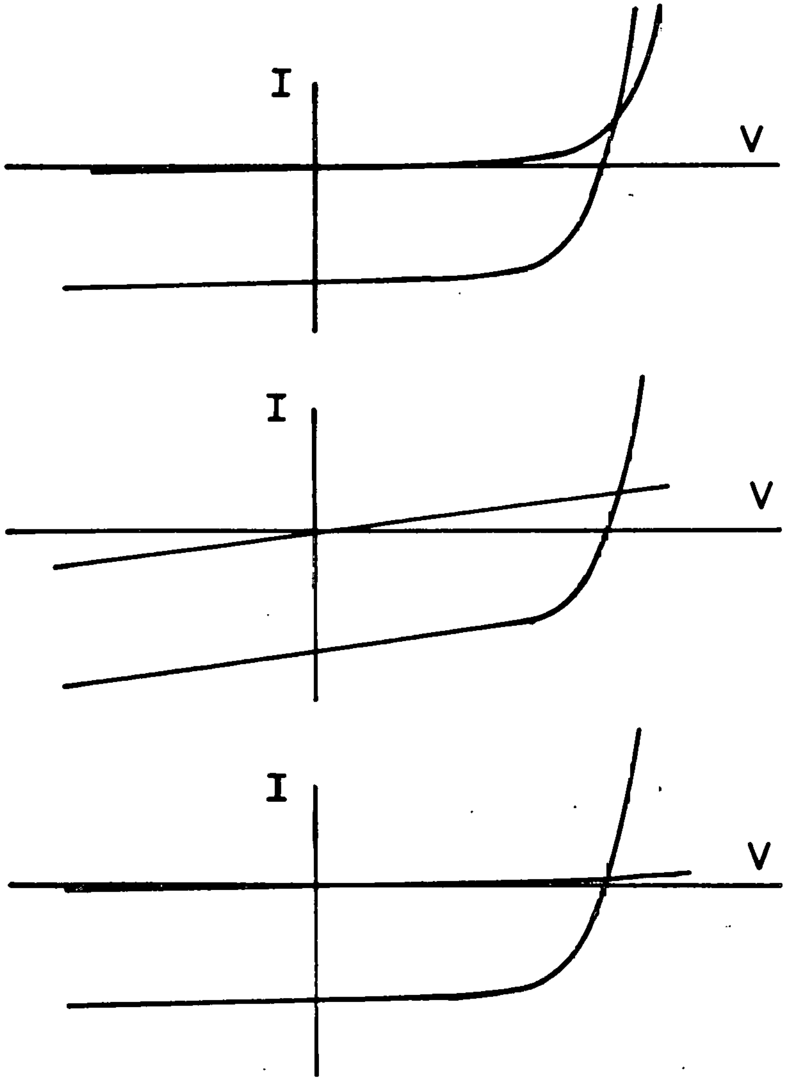
100°C ONE SUN ACCELERATED LIFE TEST
(TYPICAL RESULTS)



CELL # 11/14/75 1E
ROOFTOP LIFE TEST
RESIDUAL CHLORIDE LEVEL
.7 %



TEST CELL STRUCTURE BEFORE AND AFTER ETCHING AWAY OF PERIPHERAL Cu_xS



BEFORE TEST

AFTER TEST

AFTER TEST AND REMOVAL OF PERIPHERAL UNPROTECTED Cu_xS

TYPICAL I-V CHARACTERISTICS OF TEST CELL BEFORE AND AFTER ACCELERATED LIFE TEST (1 sun : 100 C : 100 hr)

MAJOR PROBLEMS

1. LOW V_{OC}

   PROBABLE CAUSES

   (A) GRAIN SIZE AND STRUCTURE

   (B) IMPURITIES

   (C) OXYGEN IN FILM

2. LOW MOBILITY IN FILM

PLANNED ACTIVITIES

1. INCREASE GRAIN SIZE AND ORDER
   - (A) UNIFORM DROPLET SPRAY
   - (B) REGROWTH OPTIMIZATION
2. OXYGEN-FREE PROCESSING
3. CONTINUED LIFE TESTING
   - (A) USING CNES ACCELERATED TEST AND CORRELATE WITH ROOF TEST
4. IMPURITY CONTROL
   - RECRYSTALLIZATION OF CHEMICAL COMPLEX
5. CdS-ZnS FILMS
6. MODELING OF DIODE
7. DEVELOP LARGE CELL AREA ELECTRODING PROCESS

RESEARCH DIRECTED TO STABLE HIGH EFFICIENCY CdS SOLAR CELLS

National Science Foundation

AER72 - 03478 - A04

7/1/75 - 6/30/76

$484,974

John D. Meakin

Principal Investigator
Associate Director

Institute of Energy Conversion
University of Delaware
Newark, Delaware 19711

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

I. OBJECTIVES

1) Establish analytically and experimentally the conversion efficiency limits for thin film polycrystalline cells based on the CdS/Cu_2S junction.

2) To develop the processing technology to give high efficiency cells reproducibly.

3) Establish the processes which limit usable cell lifetime.

4) Improve the efficiency of the basic CdS cell by using (CdZn)S/Cu_2S to increase the open circuit voltage.

CdS/Cu_2S Cells

The reproducible manufacture of the cell was reported at the previous Grantee's Meeting in January 1976. At that time the average efficiency of standard control cells had reached about 6% with a yield in excess of 95%. A number of engineering design changes have now been made to improve the conversion efficiency of the CdS/Cu_2S cell. In particular, grids of higher transmission were designed and manufactured. These are of two types, etched copper prebonded to Aclar and vapor deposited gold; both grids have ∿ 95% transmission. Heat treatment of laminated cells in hydrogen substantially enhanced the light generated current but with a concurrent loss of grid contact. This was reversed by relamination to give a maximum sunlight efficiency of about 7.2% and average efficiency of 6.9%. Series resistance was shown to be efficiency limiting. Cross-grid procedure with a laminated grid over an evaporated grid was developed. A series of 24 cross-grid cells were made during June 1976 with an average sunlight efficiency of 6.84% and a maximum observed efficiency of 7.64%. Since that time, the maximum achieved efficiency has been raised to 7.8%.

(CdZn)S/Cu_2S Cells

Thin films of the mixed sulfide have been made from a single source of cadmium zinc sulfide powder and from separate CdS and ZnS sources. Copper sulfide has been made on these films using the conventional wet dip process, by reaction with vapor deposited Cu_2Cl_2 and by depositing a copper layer on the film and subsequently sulfurizing Cu_2S. Open circuit voltages have been measured up to 0.68 V. In general, the short circuit current has shown negative correlation with the open circuit voltage. It has been established that the ion exchange process takes place much more slowly in the zinc rich material.

The change in barrier height for reverse electron flow has been measured using photoemission techniques and found to correspond to the observed change in open circuit voltage. The barrier height observed at 24% zinc is 1.15 eV indicating that the electron affinity of the mixed sulfide matches that of the Cu_2S at this composition.

CURRENT EFFORTS

The present efforts on the CdS/Cu_2S cell are designed to increase the efficiency in sunlight to 8.5%. An optimized evaporated grid is being developed to eliminate the necessity of cross gridding. In situ experiments to improve the quality of t Cu_2S while monitoring the short circuit current are underway. As these are perfected, antireflection coatings will be deposited.

The underlying mechanisms controlling short circuit for the mixed sulfide cell will be identified. Spectral, capacitance and electrochemical techniques are being used to identify the underlying mechanisms controlling the short circuit current.

Extensive natural sunlight testing is now underway and the correlation between atmospheric conditions, sunlight and simulated efficiencies is being developed.

Semiconductor device technology is being established to assist in diagnosis and analysis of thin film polycrystalline cells.

KEY RESULTS

- An energy conversion efficiency in sunlight in excess of 7.5% has been achieved at the Institute of Energy Conversion of the University of Delaware and validated by NASA-Lewis.
- It has been demonstrated that high efficiency thin film polycrystalline cells can be made reproducibly.
- The cell degradation mechanisms due to interaction with the atmosphere and to grid contact effects have been identified and successfully reversed.
- Open circuit voltages up to 0.68 V have been reproducibly achieved using mixed zinc cadmium sulfides.
- Techniques have been developed for increasing the short circuit current of the cell by improving the Cu_2S.

PLANNED ACTIVITY

Further efficiency enhancement of the CdS/Cu_2S cell will be achieved by improved gridding and antireflection coating to raise the short circuit current, by reducing the junction area (while maintaining overall cell size) to increase the open circuit voltage, and by reducing the semiconductor series resistance contribution to increase the fill factor.

The analytical model of the cell will be upgraded to include parameter interdependence.

Cell passivation and encapsulation studies will be initiated.

The work on mixed sulfide cells will be continued to increase short circuit current and fill factors while maintaining the enhanced open circuit voltage.

PLANNED RENEWAL

Funding will be sought to maintain the present level of cell analysis and development and to add a semiconductor technology capability to increase the analysis and diagnosis capabilities for thin film photovoltaic cells.

RESEARCH DIRECTED
TO
HIGH EFFICIENCY CdS SOLAR CELLS

NATIONAL SCIENCE FOUNDATION
AER72 - 03478 - A04

INSTITUTE OF ENERGY CONVERSION
UNIVERSITY OF DELAWARE

7/1/75 - 6/30/76
$484,974

PRINCIPAL INVESTIGATOR
JOHN D. MEAKIN

OBJECTIVES

- ESTABLISH ANALYTICALLY AND EXPERIMENTALLY CONVERSION EFFICIENCY LIMITS FOR THIN FILM POLYCRYSTALLINE CELLS BASED ON THE CdS/Cu_2S JUNCTION
- DEVELOP PROCESSING TECHNOLOGY WHICH LEADS TO REPRODUCIBLE CdS/Cu_2S CELLS
- ESTABLISH PROCESSES WHICH LIMIT CELL LIFETIME
- IMPROVE EFFICIENCY BY USING $(CdZn)S/Cu_2S$ TO INCREASE V_{oc}

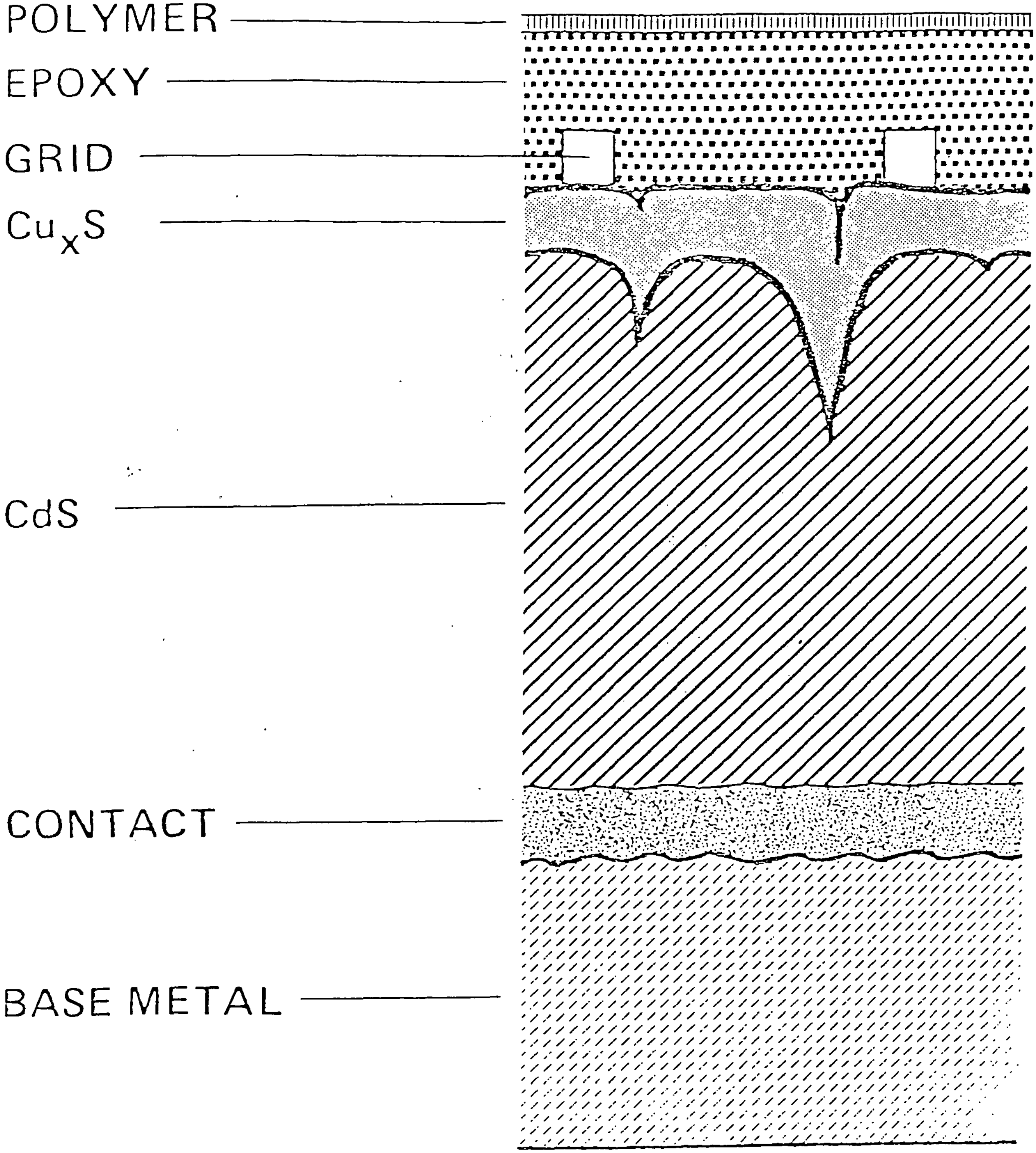
PLANNED ACTIVITIES

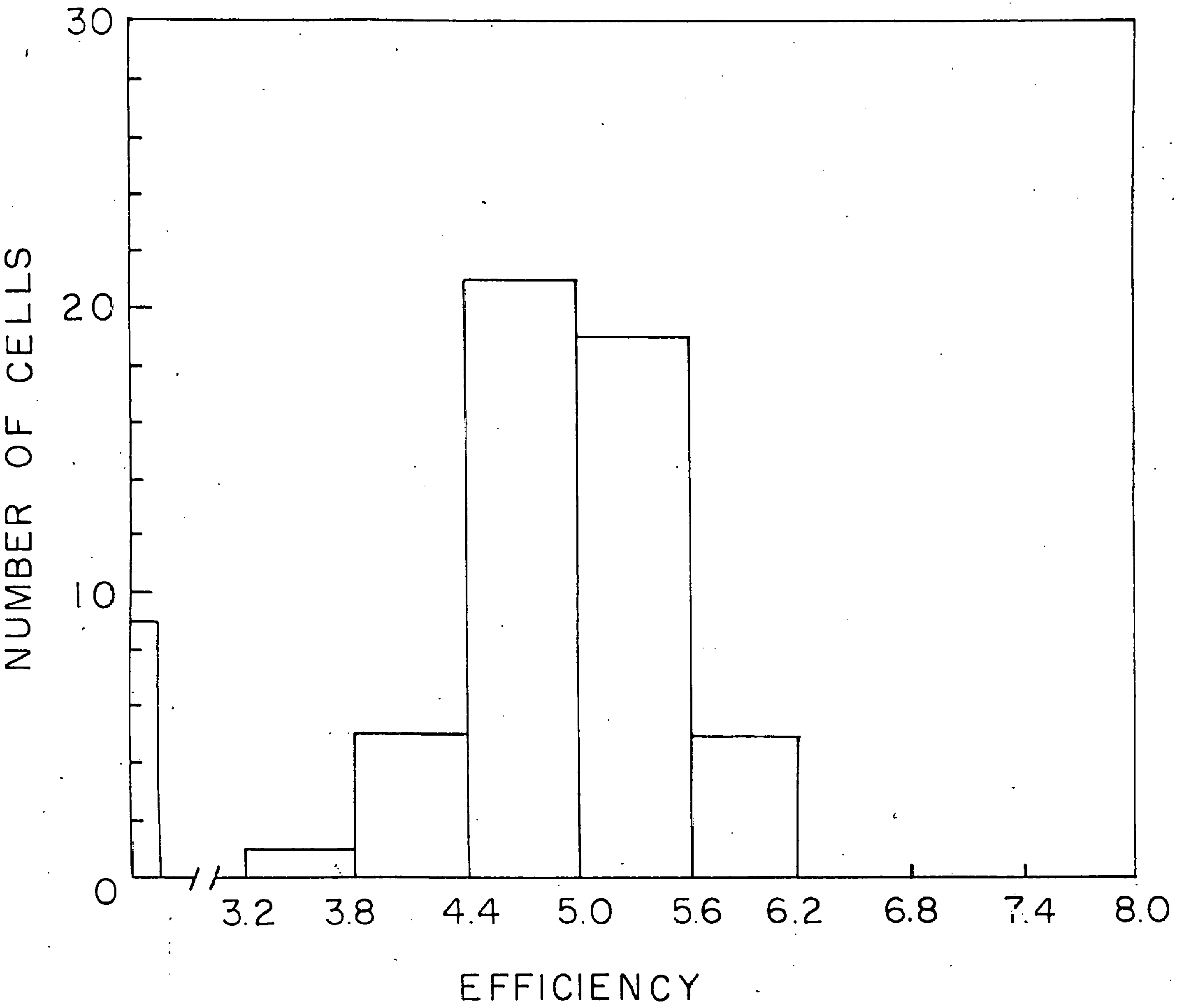
1/1/76 - 6/30/76

- INCREASE J_{sc} FOR CdS/Cu_2S CELL. DEVELOP HIGHER TRANSMISSION GRIDS.

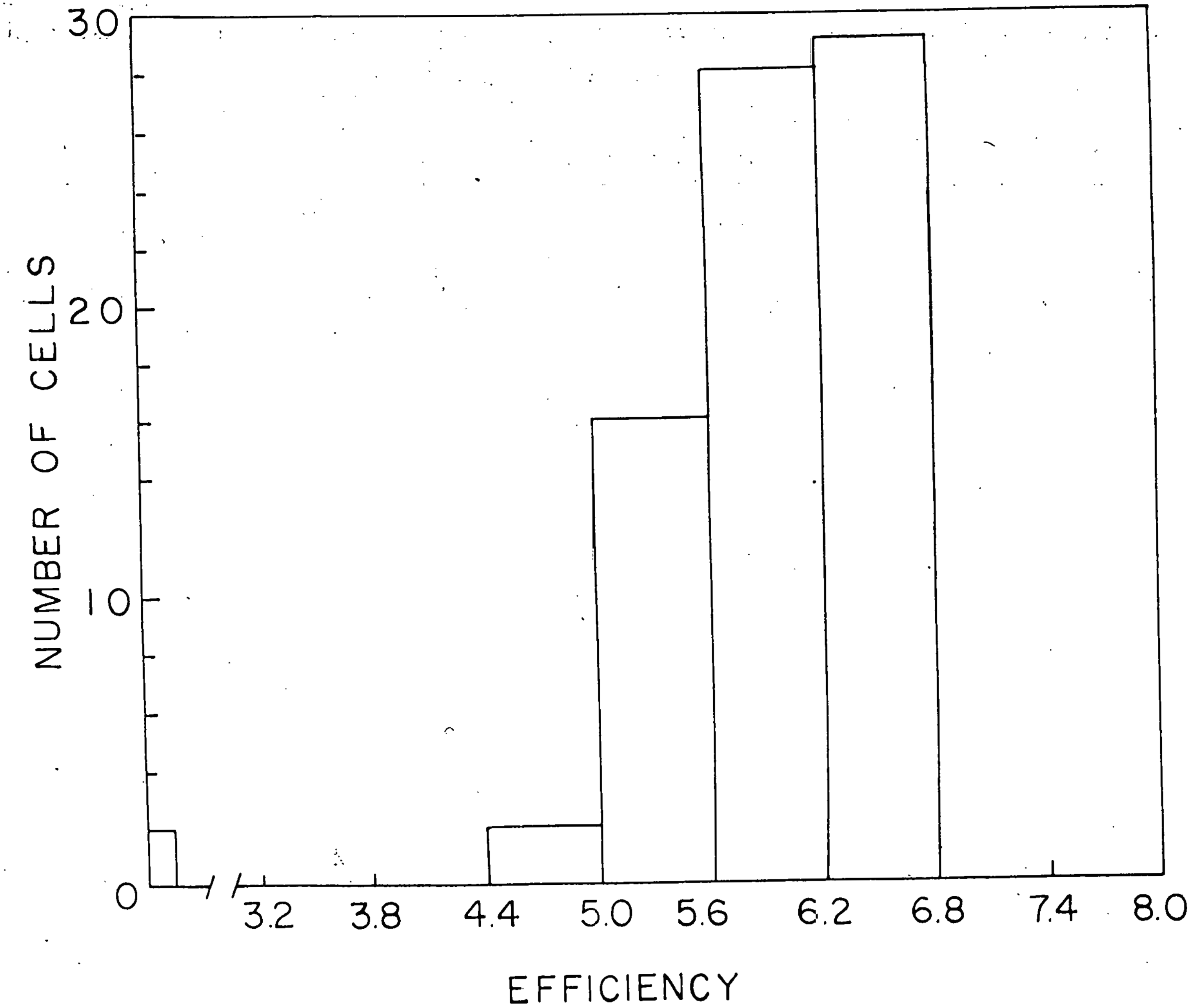
- DEVELOP REPRODUCIBLE TECHNIQUE FOR DEPOSITING UNIFORM THIN FILMS OF (CdZn)S.

- EXPLORE RANGE OF TECHNIQUES TO PRODUCE Cu_2S ON MIXED SULFIDE.

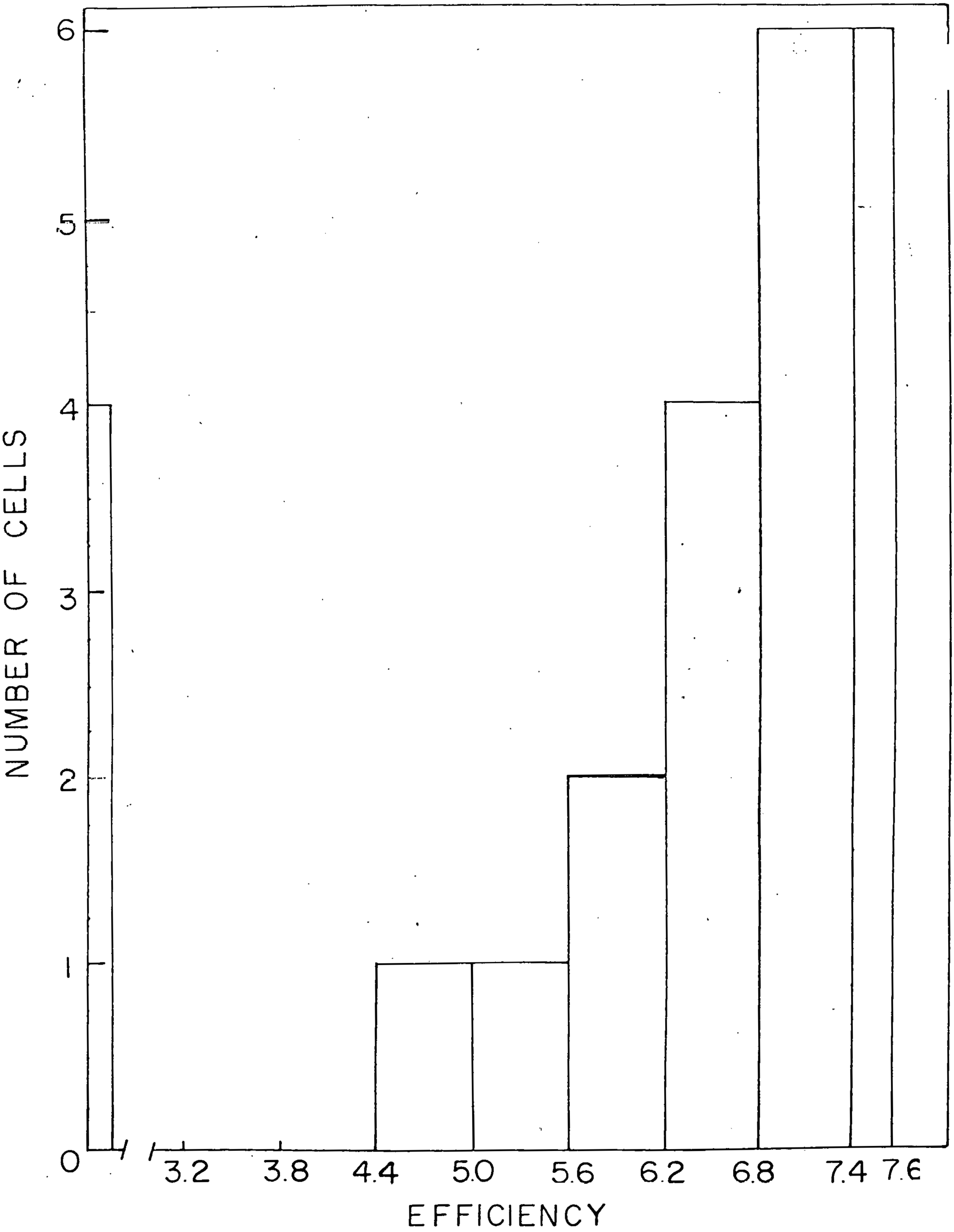

POLYMER
EPOXY
GRID
Cu_xS
CdS
CONTACT
BASE METAL



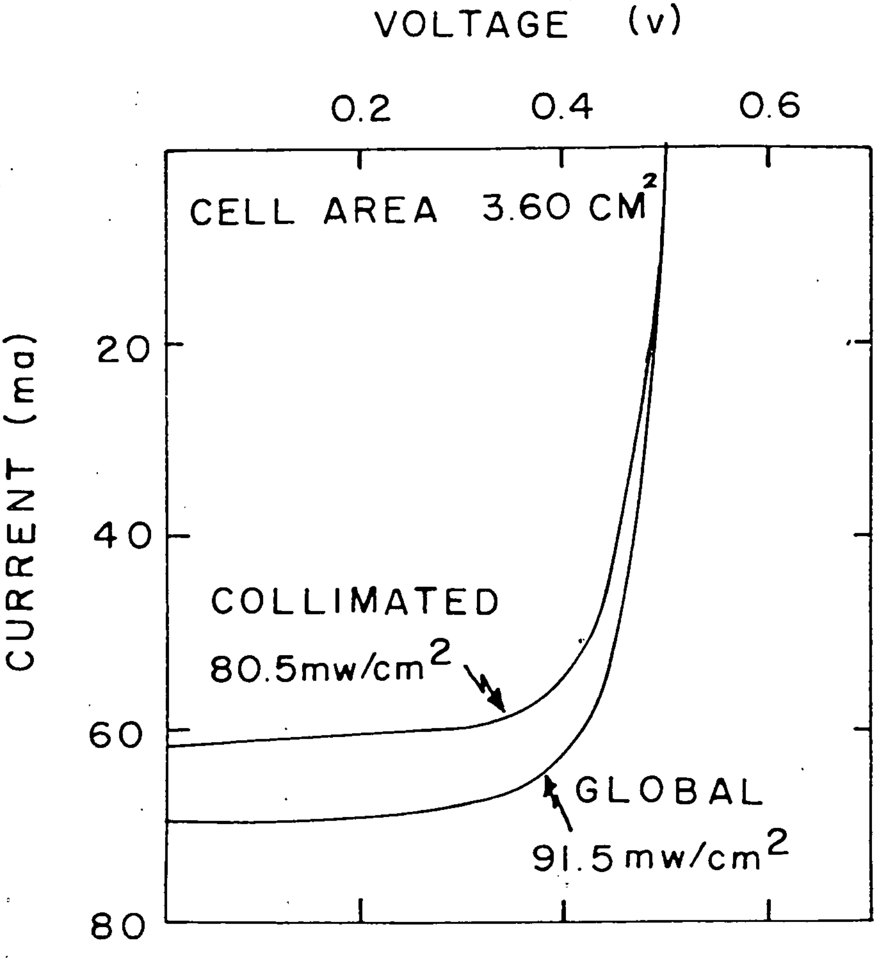
Efficiency distribution for 60 cells February 1975. Yield live cells 85%. Average sunlight based on W-I, 5.1%.



Efficiency distribution 77 monitor cells March-December 1975. 97% cells above 4.4%. Average sunlight based on W-I, 6.1%.

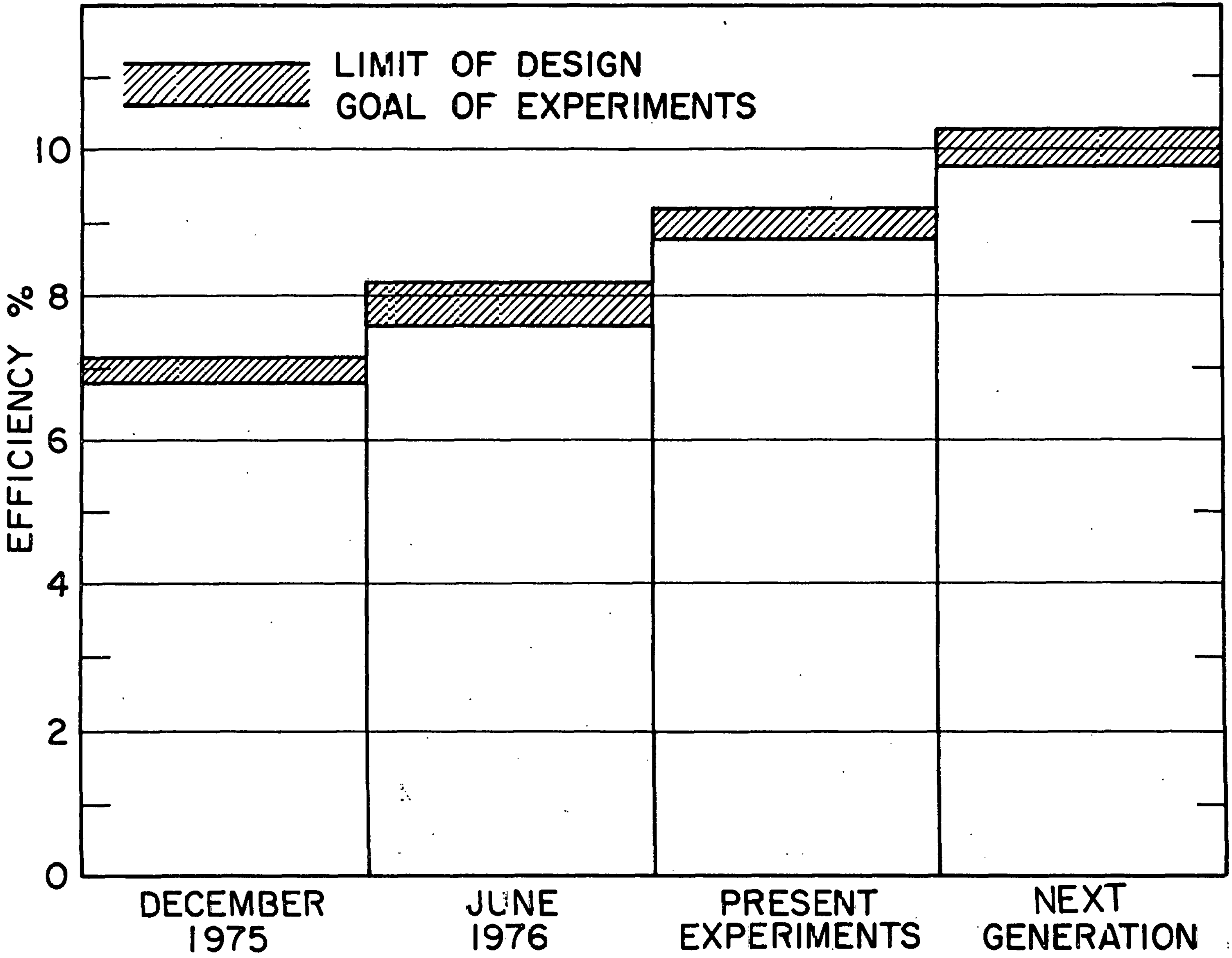


Efficiency distribution 24 cells June 1975. 83% cells over 4.4. Average sunlight based on W-I, 6.84%. Best in actual run 7.64%.



Cell 12-2 in collimated and global sunlight. Collimated efficiency 7.64%, global 7.61%.

CdS/Cu_2S CELLS



CdS/Cu_2S CELLS
KEY CELL PARAMETERS

DATE	SHORT CIRCUIT CURRENT (MA/CM^2)	OPEN CIRCUIT VOLTAGE (V)	FILL FACTOR	EFFICIENCY AM1 %
DECEMBER 1975	20	0.51	0.69	7.1
JUNE 1976	23	0.51	0.71	8.2
PRESENT EXPERIMENTS	25	0.51	0.73	9.2
NEXT GENERATION	26	0.54	0.73	10.3

CdS/Cu_2S CELLS
SHORT CIRCUIT CURRENT

	LOSS MECHANISM (%)								
			RECOMBINATION						
DATE	COVER ABSORPTION REFLECTION	GRID SHADING	SURFACE	BULK	INTERFACE	GRAIN BOUNDARY	SUBSTRATE ABSORPTION	NETT LOSS	J_{sc} AT AM1 (ma/cm^2)
DECEMBER 1975	8	19	1	15	5	1	2	42	20
JUNE 1976	8	9	1	15	5	1	2	35	23
PRESENT EXPERIMENTS	5	4	1	15	5	1	2	29	25
NEXT GENERATION	5	4	1	10	5	1	2	25	26

MAXIMUM SHORT CIRCUIT CURRENT UNDER AM1 ≈ 35 MA/CM^2

CdS/Cu_2S CELLS

OPEN CIRCUIT VOLTAGE

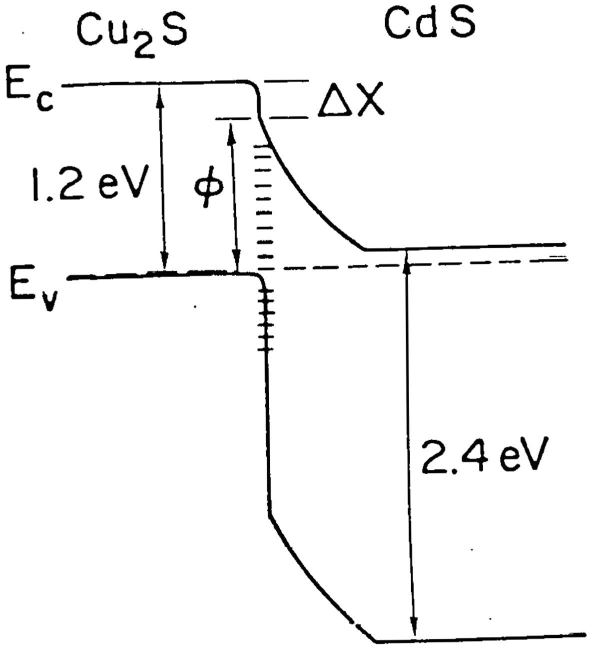
DATE	JUNCTION AREA EFFECT (V)	V_{oc} AT AM1
DECEMBER 1975	-0.06	0.51
JUNE 1976	-0.06	0.51
PRESENT EXPERIMENTS	-0.06	0.51
NEXT GENERATION	-0.03	0.54

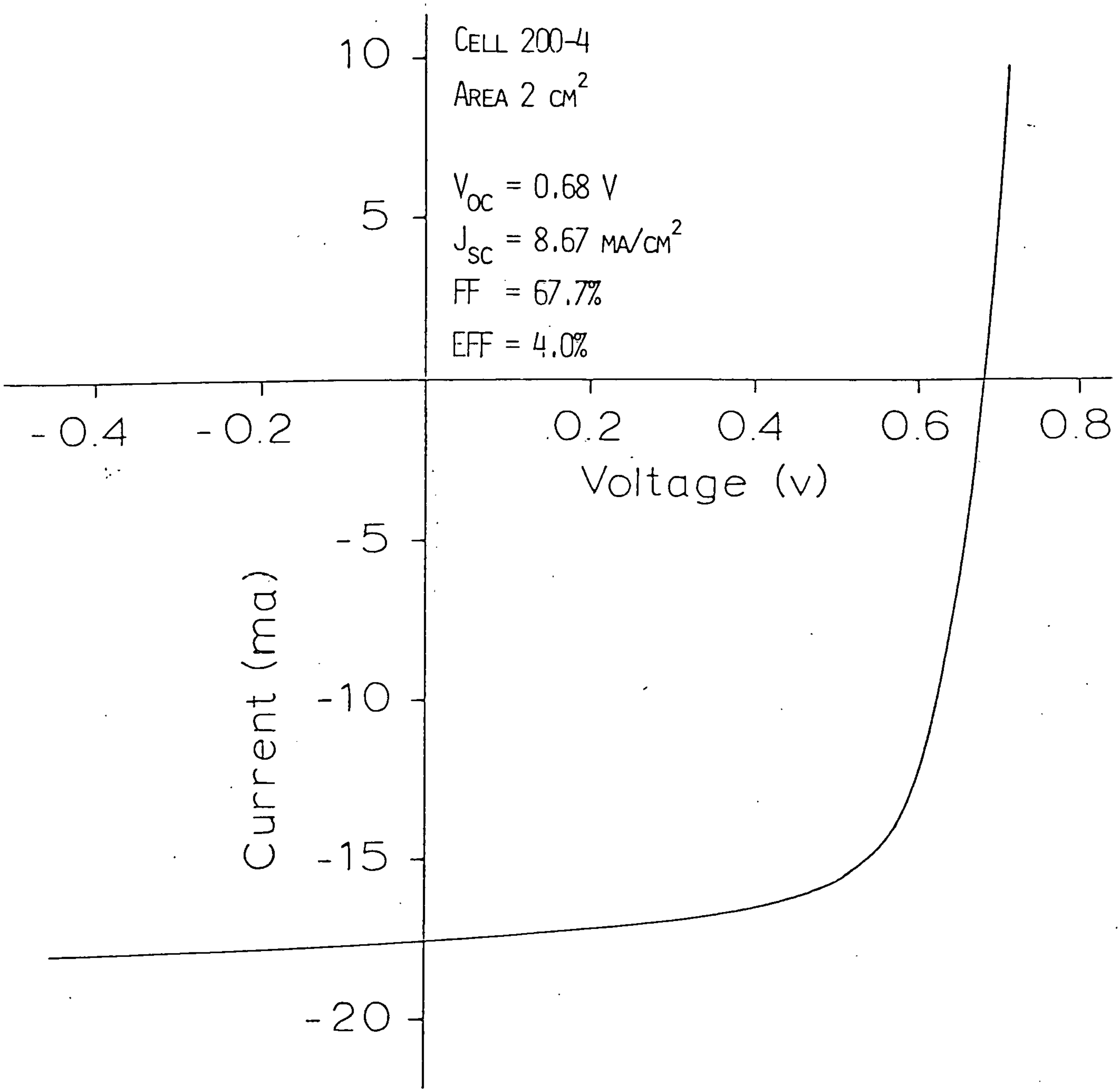
FILL FACTOR

SERIES RESISTANCE		FIELD EFFECT	NETT FILL FACTOR
Cu_2S	CdS		
-0.04	-0.04	-0.03	0.69
-0.02	-0.04	-0.03	0.71
-0.02	-0.02	-0.03	0.73
-0.02	-0.02	-0.03	0.73

OPEN CIRCUIT VOLTAGE FOR PLANAR CdS/Cu_2S JUNCTION = 0.57 V

DIODE LIMITED FILL FACTOR = 0.80


Cu_2S
CdS
E_c
ΔX
1.2 eV
ϕ
E_v
2.4 eV



I-V of one of best (CdZn)S/Cu_2S cells. Made by dry reaction with Cu_2Cl_2.

KEY RESULTS

- ENERGY CONVERSION EFFICIENCY IN SUNLIGHT IN EXCESS OF 7.5% ACHIEVED BY INSTITUTE OF ENERGY CONVERSION, UNIVERSITY OF DELAWARE AND VALIDATED BY NASA-LEWIS

- DEMONSTRATED HIGH EFFICIENCY CELLS REPRODUCIBLY

- CELL DEGRADATION MECHANISMS DUE TO ATMOSPHERIC AND GRID CONTACT EFFECTS IDENTIFIED AND REVERSED

- INCREASED OPEN CIRCUIT VOLTAGES UP TO 0.68 V REPRODUCIBLY ACHIEVED USING (CdZn)S

- J_{sc} INCREASED BY IMPROVING Cu_2S INDEPENDENTLY OF JUNCTION CHANGES

MAJOR PROBLEMS

TECHNICAL

- PRESSURE CONTACT TECHNOLOGY TENDED TO OBSCURE FUNDAMENTAL MATERIALS PROPERTIES
- DEVELOPMENT OF SIMPLIFIED CELL CONFIGURATION NECESSARY

COST

- STANDARD SEMICONDUCTOR DEVICE STUDIES COULD SUBSTANTIALLY INCREASE ANALYSIS AND UNDERSTANDING OF CELL PERFORMANCE

PLANNED ACTIVITY

- ANALYSIS DRIVEN EXPERIMENTS FOR EFFICIENCY IMPROVEMENT

- CdS/Cu_2S CELL - EFFICIENCY ENHANCEMENT

  J_{sc} BY IMPROVING GRIDDING AND A-R COATING

  V_{oc} BY REDUCING JUNCTION AREA

  FF BY REDUCING CdS SERIES RESISTANCE CONTRIBUTION

- UPGRADED ANALYTICAL MODEL TO INCLUDE PARAMETRIC INTERDEPENDENCE

- MAINTAIN REPRODUCIBILITY FOR HIGH EFFICIENCY EXPERIMENTAL CELLS

- INITIATE CELL PASSIVATION AND ENCAPSULATION STUDIES

- IMPROVE EFFICIENCY BY USING $(CdZn)S/Cu_2S$ TO INCREASE V_{oc} WHILE MAINTAINING J_{sc} AND FF

"THE FEASIBILITY OF Cu_2S/CdS THIN FILM SOLAR CELLS FOR LARGE SCALE POWER GENERATION"

NSF GRANT "CdS THIN FILM SOLAR CELLS FOR TERRESTRIAL POWER" No. AER74-14918

Aug. 1, 1974 thru July 31, 1976 - \$514,100 (Accumulative Amount)

by

F. A.Shirland, Principal Investigator
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania 15235

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

THE FEASIBILITY OF Cu_2S/CdS THIN FILM SOLAR CELLS FOR LARGE SCALE POWER GENERATION

ABSTRACT

The overall objective was the development of a terrestrial version of the CdS thin film solar cell, and a determination of its feasibility for large scale solar energy conversion. On direction of the sponsor, The National Science Foundation, the efforts at Westinghouse have been concentrated on some specific aspects of the overall problem. These were: establishing a facility for making laboratory quantities of terrestrial design cells, developing low cost gridding and encapsulating means, and determining the inherent lifetime of Cu_2S/CdS thin film solar cells in terrestrial use.

In earlier periods the space CdS thin film solar cell was re-designed to eliminate the expensive components and to make the cell suitable for long term exposure in the atmosphere. This included: a change to a low cost metal foil substrate; the conception and reduction to practice of a low cost evaporated metal grid with coarse mesh collector bus; and the conception and demonstrated feasibility of an integral glassy encapsulation applied by rf sputtering. A facility to make Cu_2S/CdS barrier layer cells in laboratory quantities was set up and gradually brought up to the previous best-state-of-the-art level. In addition, large area CdS film cells were hermetically sealed behind glass and placed on both real time and accelerated life tests. Favorable initial results were obtained from these tests.

In the current period the efforts were continued in the same areas. In cell fabrication, improvements in tooling and processing resulted in a ten-fold increase in the shunt resistance of the cells and in steadily increasing cell outputs. The efficiency of standard process cells at the end of the period ranged between 5 and 6%, compared with between 4 and 5% at the beginning of the period. Yields of acceptable quality cells were 73% of the cell starts. In the first half of 1976 a total of 112 standard process cells were fabricated. These outputs and yields are better than the previous best state-of-the-art at Clevite, and are for terrestrial design cells that are amenable to very low cost production methods.

Additional improvements were effected in the gridding and encapsulating areas. Specifically, a revised process was developed using a single component fine spaced evaporated metal grid pattern deposited through an aperture mask in combination with a new Cu_2S barrier layer heat treatment procedure. These have resulted in appreciably higher cell currents, up to 24.3 ma/cm^2, with a maximum cell efficiency of 6.6%. These values were measured under the tungsten simulator, and may be higher in direct sunlight.

On the accelerated and real time life tests, a year-and-a-half of data have been accumulated. The roof-top cells, and the accelerated test cells operating at 40°, 60° and 80°C are all giving full output. The accelerated test cells operating at 100°C are now showing a definite trend of loss of output. Extrapolation of present trends indicates many decades of useful life for encapsulated cells operating under expected terrestrial use conditions. The cells are showing changes in internal parameters which bear out these indications. The cell measurements have been verified by the Lewis Research Center of NASA.

Electron microscope studies have disclosed that conventional CdS thin films have many micron-sized flaws which can be related to the surface condition of the substrate - mainly the topography. This is the factor which probably makes necessary the 25 to 30 micron minimum CdS thickness of present high efficiency cells. Elimination of these flaws should permit CdS film thickness to be reduced several fold.

Dwg. 6371A47

CdS THIN FILM SOLAR CELLS FOR TERRESTRIAL POWER

Grant No. AER74-14918

WESTINGHOUSE ELECTRIC CORPORATION
RESEARCH LABORATORIES
PITTSBURGH, PENNSYLVANIA

With

THE UNIVERSITY OF PITTSBURGH
PITTSBURGH, PENNSYLVANIA

Period of Grant	August 1, 1974 thru July 31, 1976
Amount of Grant	$514,100
Principal Investigator	F. A. Shirland

Dwg. 6386A01

OVERALL OBJECTIVE

The Development of Very Low Cost Long Lived
Cu_2S/CdS Thin Film Solar Cells
And
A Determination of Their Feasibility for Large
Scale Solar Energy Conversion
On Earth

Dwg. 6385A93

PLANNED ACTIVITY – LAST SIX MONTHS

1 – Continue Efforts to Improve Cell Fabrication by Better Tooling and Better Process Control. Emphasis on Achieving Reproducibility

2 – Complete Development of Low Cost Grid System

3 – Complete Development of Integral Passivation – Encapsulation Means

4 – Continue Accelerated and Real Time Life Testing

5 – Continue Basic Studies With Emphasis on Role of Oxygen and the Heat Treating Process

Dwg. 6385A95

PROGRESS

1 — Cell Fabrication

Improved Tooling	For Substrate Preparation, CdS Film Deposition, Barrier Formation, and Heat Treatment — Has Yielded Cleaner More Uniform Deposition From Multiple Sources, More Uniform Temperature Control During Deposition, and Better Optimization of Etching and Barrier Formation
Improved Processing	For Substrate Preparation, CdS Film Deposition, and Barrier Formation — Has Yielded Better Structured CdS Films With Fewer & Smaller Flaws

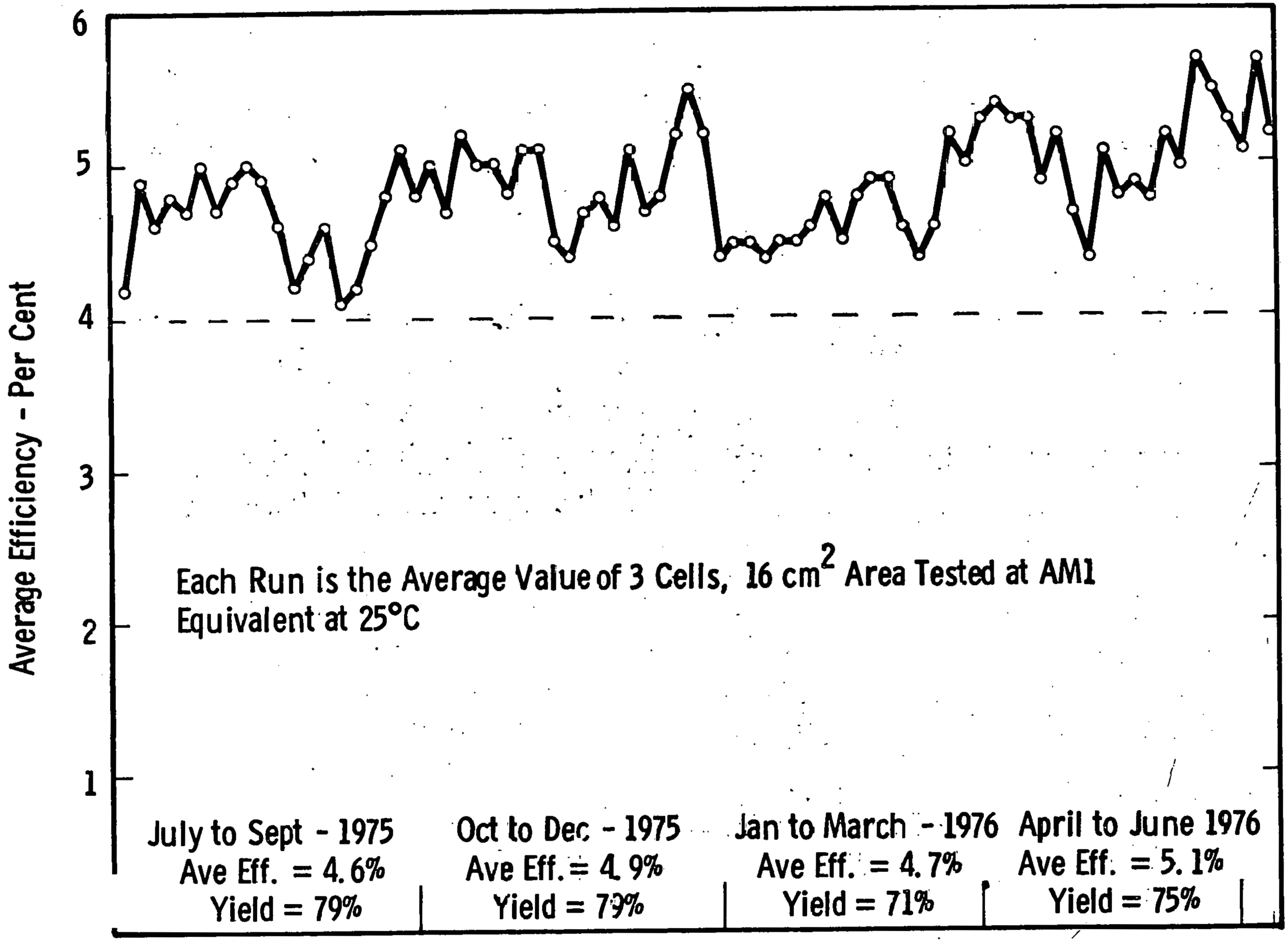
Results:

Steadily Improving Shunt Characteristics (An Order of Order of Magnitude Better Than Earlier Cells)

Steadily Improving Cell Out Puts

Curve 686202-A

STANDARD PROCESS RUNS
CdS THIN FILM SOLAR CELLS
AT WESTINGHOUSE RESEARCH LABS
JULY 1975 THROUGH TO JULY 1976



Each Run is the Average Value of 3 Cells, 16 cm^2 Area Tested at AM1 Equivalent at 25°C

July to Sept - 1975
Ave Eff. = 4.6%
Yield = 79%

Oct to Dec - 1975
Ave Eff. = 4.9%
Yield = 79%

Jan to March - 1976
Ave Eff. = 4.7%
Yield = 71%

April to June 1976
Ave Eff. = 5.1%
Yield = 75%

Dwg. 6385A94

PROGRESS

2 — Gridding

Developed Revised Low Cost Grid System —

A Single Component Metal Grid Contact Vacuum Deposited Through an Aperture Mask at Low Temperature, in Combination With:

Post Barrier Vacuum Drying and
Barrier Vacuum Annealing Process

Advantages:

Higher Light Transmission — 95%
Elimination of Coarse Collector Grid
Elimination of Two Process Steps
Higher Short Circuit Current Levels

Dwg. 6385A90

NEW PROCESS CELLS
Vacuum Evaporated Grids — Revised Heat Treatment

Cell No.	OCV V	J mA/cm^2	Eff %	Fill %	Area cm^2
422 – 3a	.482	22.9	6.6	59	1.6
422 – 3b	.490	21.8	5.7	53	1.9
422 – 3c	.458	18.9	5.7	64	4.0
422 – 5d	.460	21.4	5.8	59	3.78
422 – 9	.445	24.3	5.8	53	4.1
433 – 3	.445	20.3	5.1	55	4.0
442 – 2a	.445	18.9	5.3	62	1.75
442 – 3b	.470	18.0	5.8	68	2.0
443 – 3a	.455	23.3	4.7	44	3.96
443 – 6a	.465	20.9	5.9	59	4.1
444 – 4	.465	21.0	5.6	57	1.0
444 – 4b	.467	23.8	5.7	52	3.69
445 – 4a	.460	24.2	5.7	50	1.78
445 – 4b	.460	21.4	5.7	58	1.25
446 – 2	.480	23.1	5.4	49	1.2

Dwg. 6385A98

PROGRESS

3. Encapsulation

Developed Revised Encapsulation —

Passivation SiO Layer Next to Cu_2S

Applied by Thermal Evaporation

Sealing Si_3N_4 Layer Over SiO

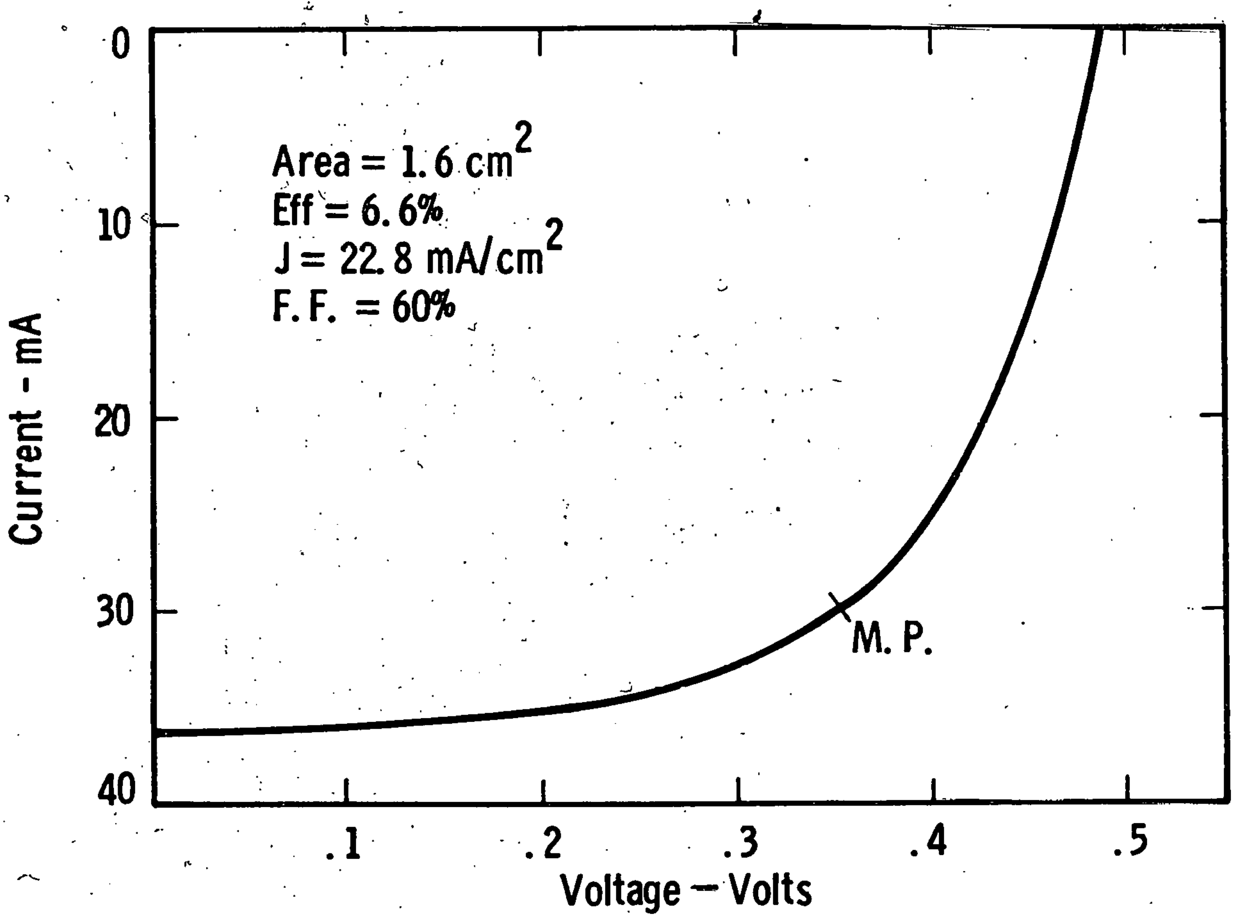
Applied by rf Sputtering

Cells Give Efficiencies of 4.7 to 6.6% and Current Densities of 16 to 24 ma/cm^2

Process Ready for Inclusion in Standard Cell Fabrication

Curve 686204-A

I-V CURVE
OF HIGHEST EFFICIENCY CELL
FABRICATED BY NEW PROCESS



Dwg. 6385A92

PROGRESS

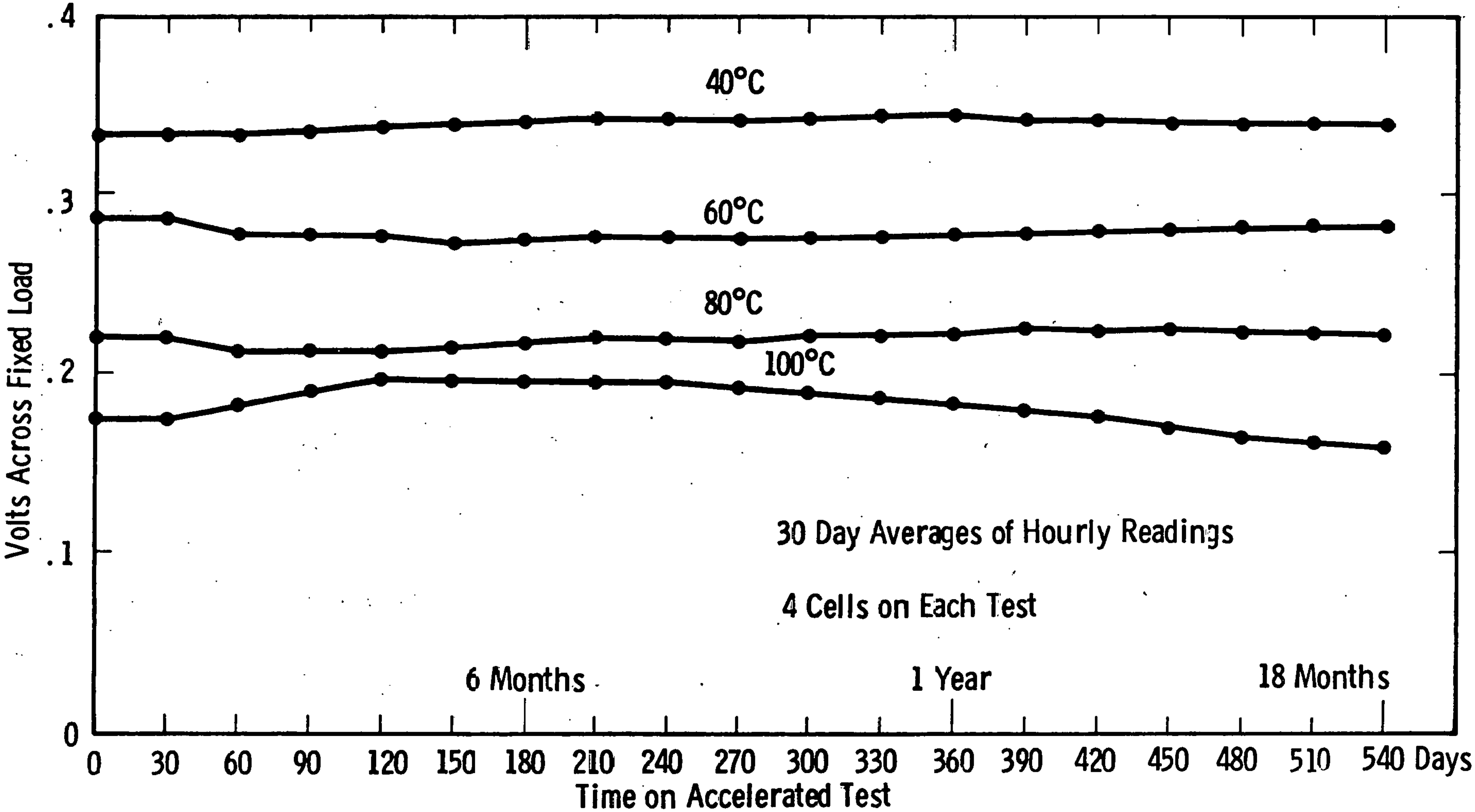
4 – Life Testing

Accelerated Life Test – Completed 18 Months of AM1 Equivalent Exposure of Encapsulated CdS Cells on 50% Duty Cycle at 40°, 60°C, 80°C and 100°C

Real Time Test – Completed 17 Months of Roof – Top Exposure of Encapsulated CdS Cells in Direct Sunlight

Curve 686208-A

IN-SITU OUTPUT DATA
ACCELERATED LIFE TEST
OF
ENCAPSULATED CdS THIN FILM SOLAR CELLS



Dwg. 1684B05

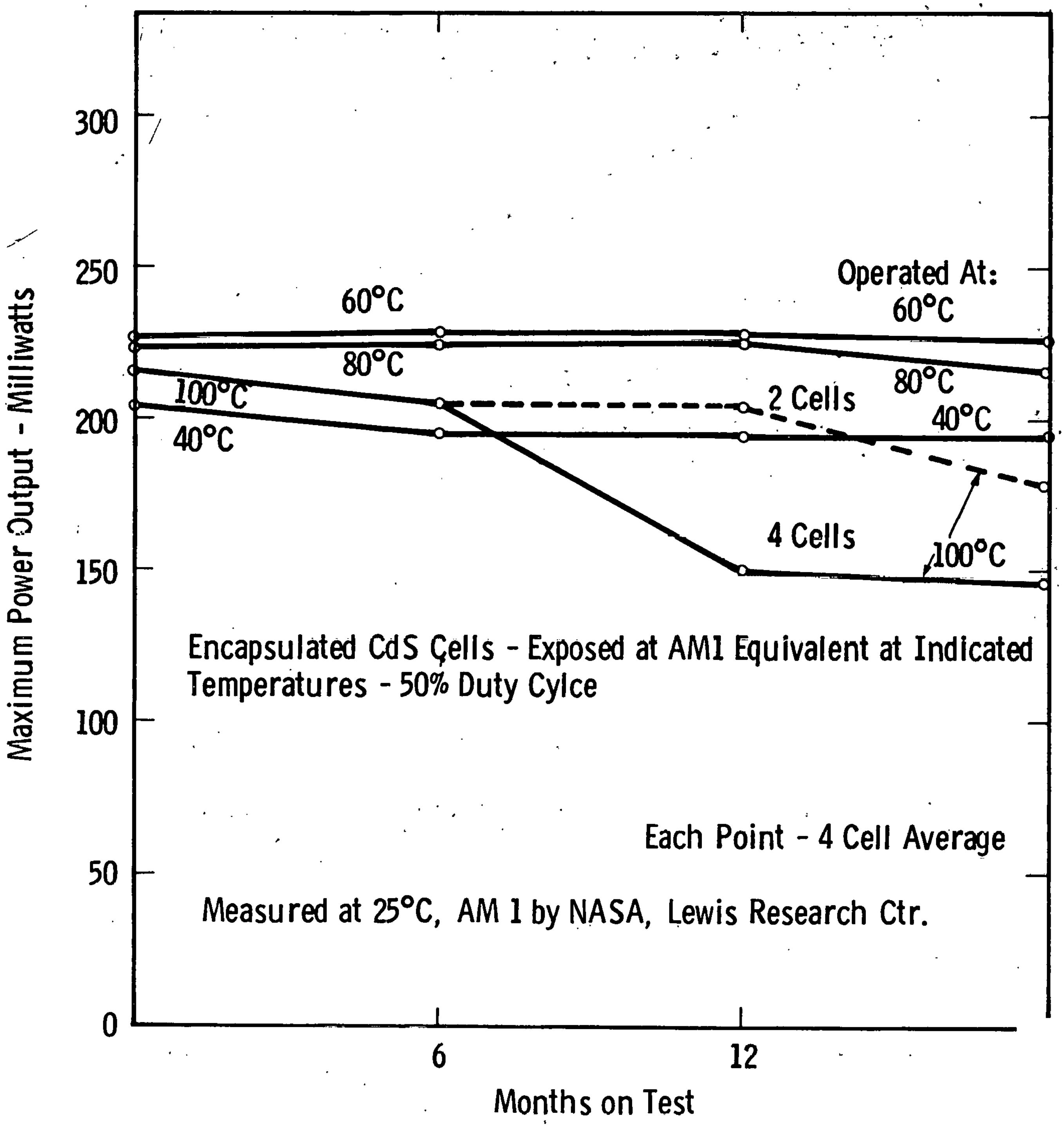
AVERAGE PARAMETERS OF LIFE TESTED CELLS VS TIME & TEMP OF TEST

(Measured at AM1, 25°C by NASA, Lewis)

	40°C				60°C				80°C				100°C			
	0	6 Mos	12 Mos	18 Mos	0	6 Mos	12 Mos	18 Mos	0	6 Mos	12 Mos	18 Mos	0	6 Mos	12 Mos	18 Mos
Voc	.476	.475	.476	.475	.475	.482	.480	.476	.474	.481	.481	.470	.473	.465	.446	.449
I_{sc}	.639	.628	.624	.633	.692	.700	.708	.720	.689	.712	.745	.765	.670	.753	.638	.659
M. P.	.203	.196	.196	.196	.227	.229	.229	.227	.224	.226	.226	.217	.217	.206	.151	.147
F. F.	67.5	65.6	66.0	65.3	69.1	68.0	67.4	66.1	68.7	66.1	63.2	60.4	68.6	58.8	50.9	48.8
R_s	.047	.062	.112	.085	.048	.079	.059	.073	.050	.068	.107	.110	.052	.126	.173	
R_{SH}	403	232	206	150	418	248	293	224	841	455	725	350	509	389	118	342
C	1.47	1.45	1.45	1.49	2.28	2.28	2.26	2.25	2.04	2.01	1.96	1.92	2.14	1.40	1.30	0.90

Curve 686205-A

MAXIMUM POWER OUTPUT
VS
TIME ON ACCELERATED LIFE TEST



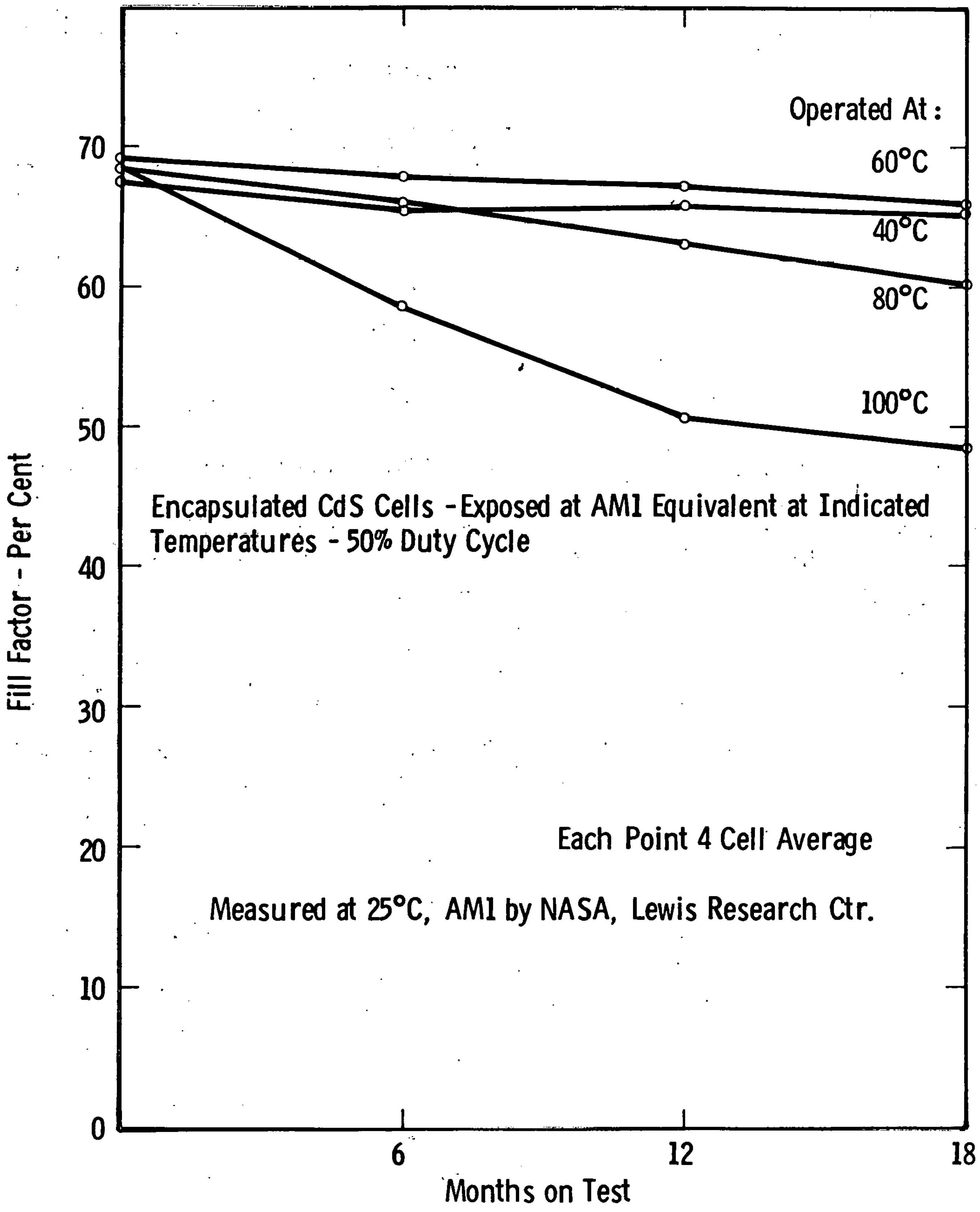
Encapsulated CdS Cells - Exposed at AM1 Equivalent at Indicated Temperatures - 50% Duty Cylce

Each Point - 4 Cell Average

Measured at 25°C, AM 1 by NASA, Lewis Research Ctr.

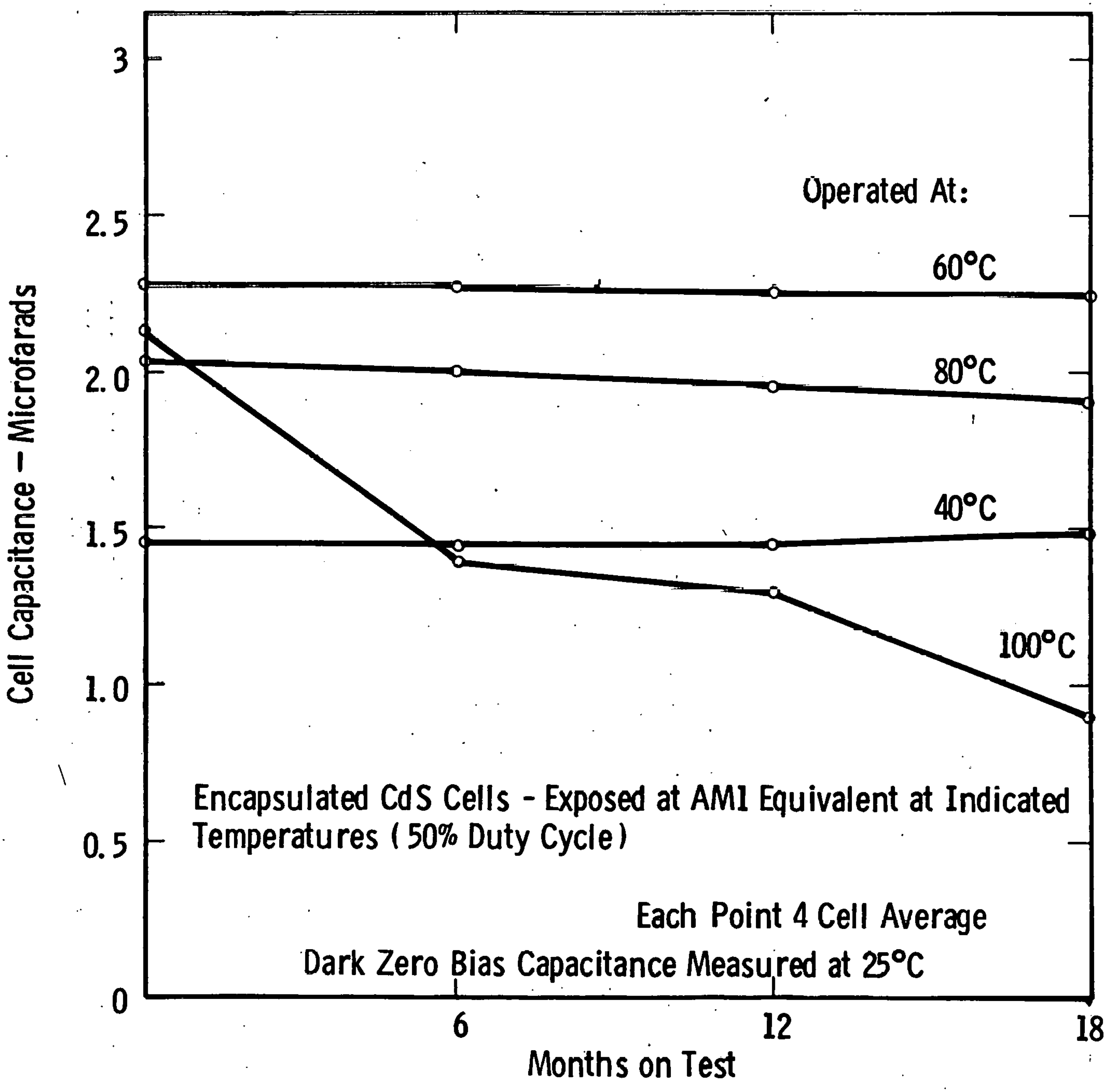
Curve 686206-A

FILL FACTOR
VS
TIME ON ACCELERATED LIFE TEST

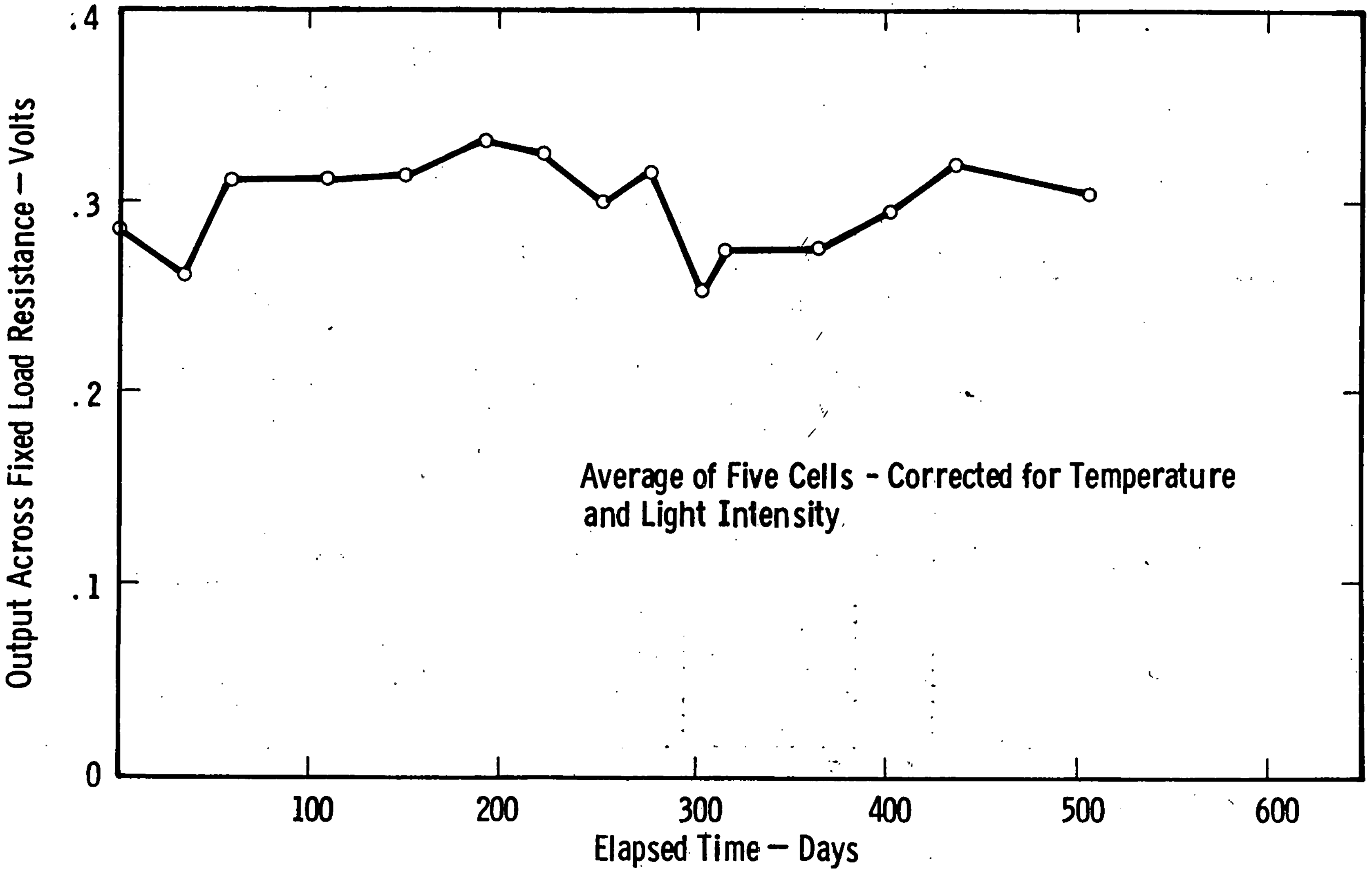


Curve 686203-A

CAPACITANCE
VS
TIME ON ACCELERATED LIFE TEST



Curve 686207-A



REAL TIME OUTDOOR SUNLIGHT TEST OF ENCAPSULATED CdS THIN FILM SOLAR CELLS

Dwg. 6385A91

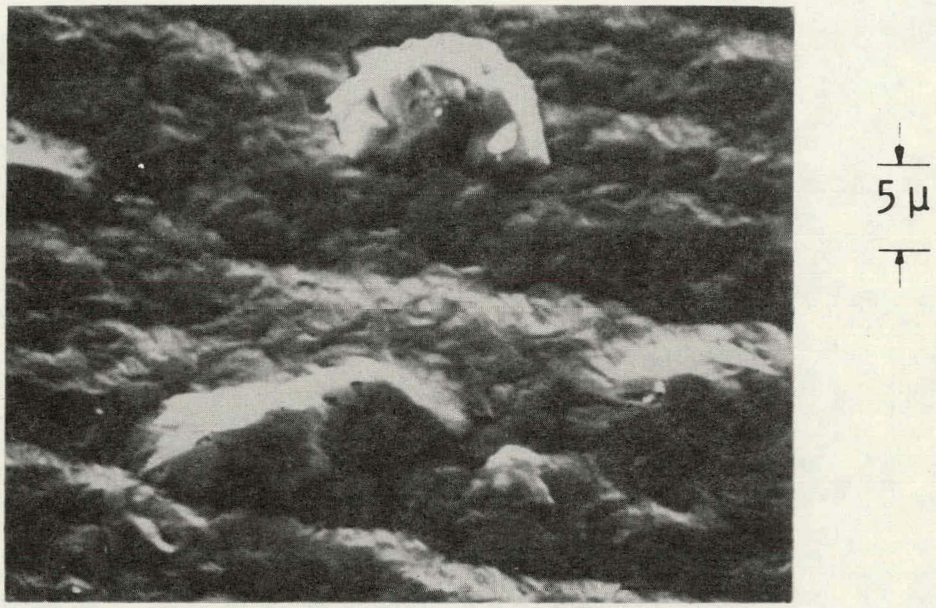
PROGRESS

5 — Basic Studies

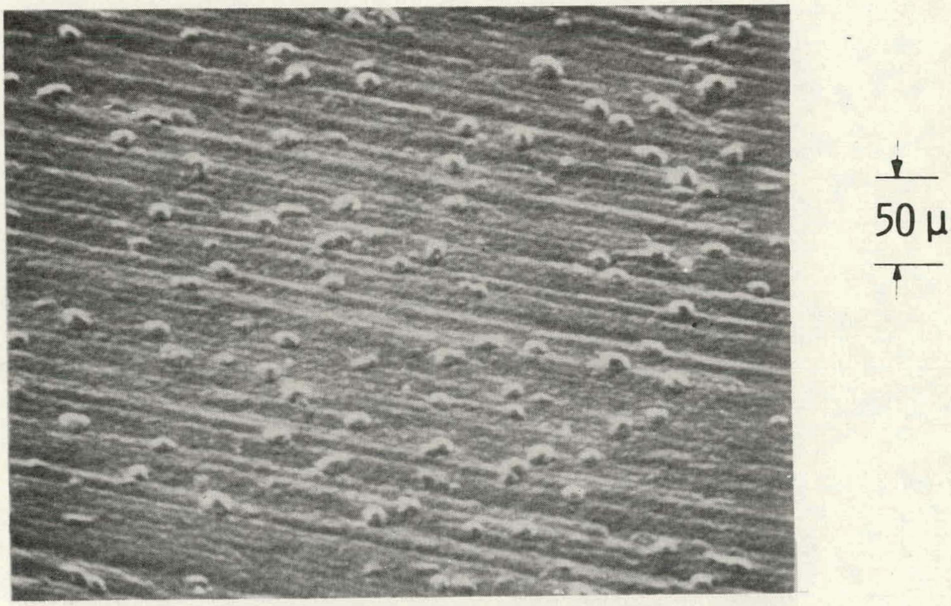
SEM Examinations of Anomalous Features of CdS Films are Leading to a Better Understanding of the Influence of Substrate Topology on CdS Film Structure

This Should Result in Better Quality CdS Films, Freer of Defects and Higher Output Cells With Higher Yields

SEM PHOTOGRAPHS OF CdS FILM, AS EVAPORATED, SHOWING GROWTH ANOMALIES

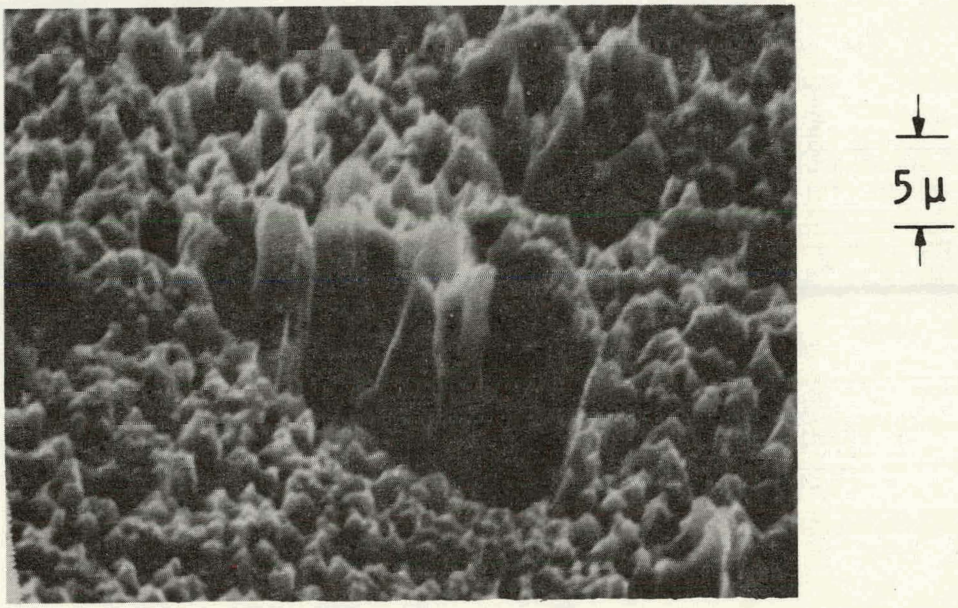


b — 2000X 45° Tilt

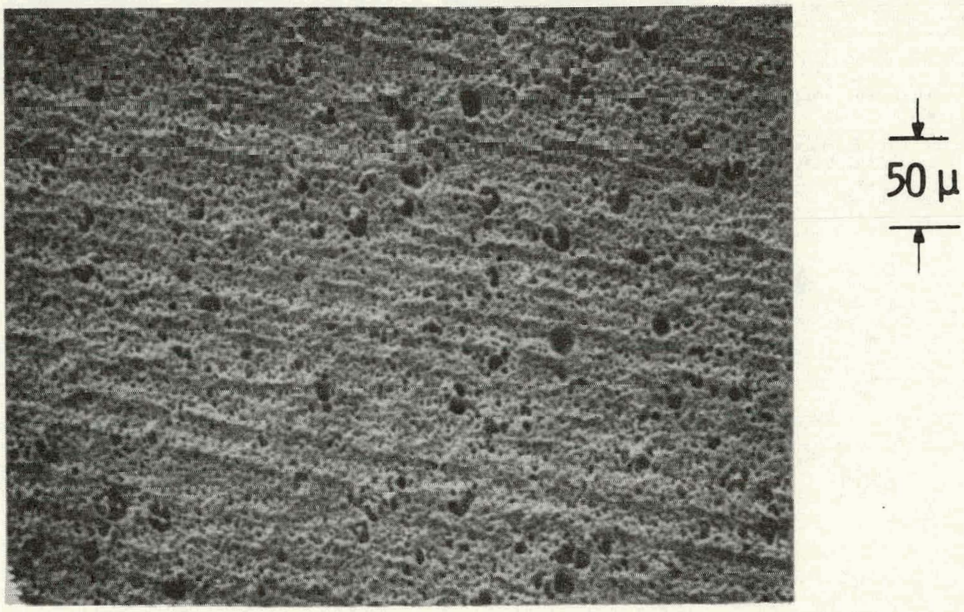


a — 200X 45° Tilt

SEM PHOTOGRAPHS OF CdS FILM, AFTER ETCHING IN HC1, SHOWING HOLES LEFT BY GROWTH ANOMALIES RUN 373-7A

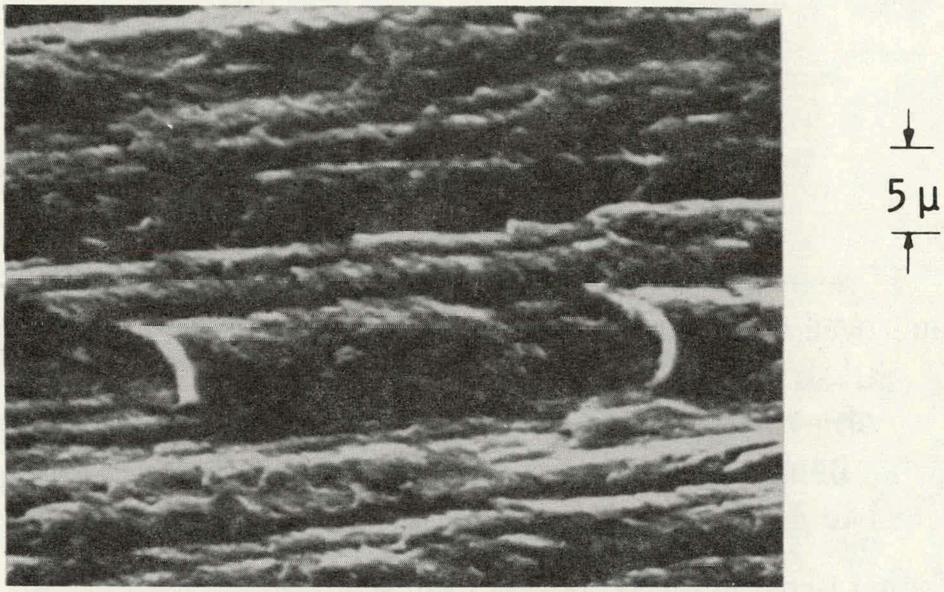


b — 2000X 37-1/2° Tilt

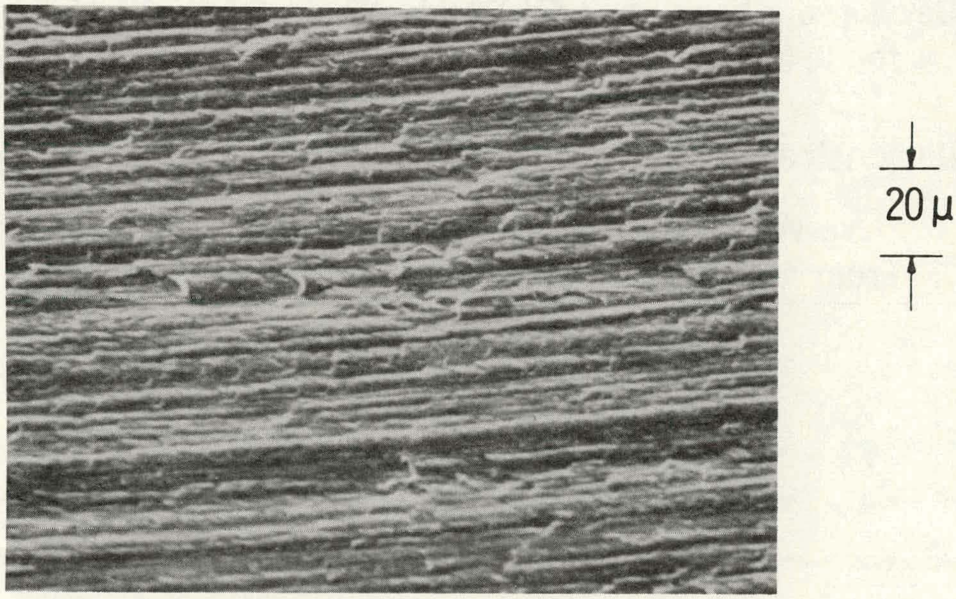


a — 200X 0° Tilt

SEM PHOTOGRAPHS OF SMOOTH SURFACE OF ELECTROFORMED COPPER FOIL, HNO_3 ETCHED



b – 2000X 45° Tilt



a – 500X 45° Tilt

Dwg. 6385A96

SUMMARY OF KEY RESULTS

1. Improved Cell Processing — Particularly in Areas of Substrate Preparation and CdS Film Evaporation — Achieved Reproducibility and Steadily Increasing Outputs as Demonstrated by Full Year of Standard Process Runs With 71 to 79% Yields of Cells Between 4 and 6% Efficiency
2. Solved Problem of Major Cost Component of CdS Cell by Developing Very Low Cost Grid System — i. e. — Evaporated Metal Grid Contact That Does Not Depress Cell Output & That is Suitable for Continuous All Vacuum Processing
3. Developed a Very Low Cost Passivating — Encapsulating Layer for Protecting Cu_2S From Atmospheric Contamination
4. Demonstrated That Cu_2S/CdS Barrier Layer Thin Film Cells Have Very Long Lifetimes in Terrestrial Use When Protected From Atmospheric Contamination

Dwg. 6385A97

MAJOR PROBLEMS

Technical –

Elimination of Growth Anomalies in CdS Film Deposition Needed in Order to Achieve Higher Output Cells From Thinner CdS Films

Improved Minority Carrier Lifetime in Cu_2S Needed in

Order to Achieve Higher Currents and Cell Output Levels From Thicker Cu_2S Co-Planar Barrier Layers on Thinner CdS Films

More Extensive Lifetime Testing of Improved Design Cells is Needed

More Extensive Basic Studies Needed in Order to Expedite Process & Design Improvements & Lead to Higher Outputs

More Extensive Engineering & Tooling Efforts Needed to Improve State-of-Cell-Fabrication-Art Faster

Dwg. 6385A99

RECOMMENDED ACTIVITY NEXT 6 MONTHS

1. Increase Cell Efficiency to > 8% By:

   a – Increasing SCC to > 20 ma/cm^2 by Improving Photon Absorption and Charge Collection

   b – Increasing OCV to > .50 Volts by Selective Doping

   c – Increasing FF to > 70% by Reducing Series Resistance by Selective Doping

2. Operate Improved Laboratory Cell Fabrication Facility Including New Low Cost Gridding and Integral Encapsulation Processes

3. Continue Accelerated & Real Time Life Tests and Include Latest Design Cells. Indentify and Characterize Degradation Modes

APPLIED RESEARCH ON II-VI COMPOUND MATERIALS FOR HETEROJUNCTION SOLAR CELLS

NSF AER 75-16379

September 1, 1975 - August 31, 1976

$ 56,400

Alan L. Fahrenbruch
Research Associate
Department of Materials Science and Engineering
Stanford University
Stanford, California 94305

Professor Richard H. Bube, Principal Investigator

Presented at the
National Solar Photovoltaic Program Review Meeting

August 3-6, 1976

Orono, Maine 04473

SUMMARY

I. OBJECTIVES

The long term objective of this grant is the preparation and investigation of heterojunction solar cells based on several II-VI compound systems suitable for large scale terrestrial application. Our immediate objectives during the past six months have been the detailed characterization of the n-CdS/p-CdTe cell, application of ITO transparent conducting contacts to optimize current collection, and the development of the collection function approach to analyze photo-generated carrier loss mechanisms. Exploration of other II-VI heterojunctions, particularly n-ZnSe/p-CdTe, has been pursued as well.

II. PREVIOUS ACTIVITY

Previous activity has centered around the deposition of II-VI films by close-spaced vapor transport (CSVT) and vacuum evaporation on single crystal II-VI substrates. CdS deposition has produced epitaxial layers of controlled resistivity on single crystal p-CdTe giving well characterized solar cells with solar efficiencies of 5-6%.

III. CURRENT EFFORTS

In the past 6 months we have increased the efficiency of the n-CdS/p-CdTe cell from 5.2 to 7.9% (solar simulation, 85 mW/cm^2). This improvement has been primarily due to the deposition of an indium-tin oxide (ITO) conducting layer as a transparent front electrode on the CdS film. This ITO layer reduces the distributed series resistance loss, increasing the fill factor from 55% to 66% and the open circuit voltage V_{oc} from 0.59V to 0.63V. Increases in J_{sc} were realized by the use of partial antireflection coatings which decreased the front reflection from $\sim$17% to $\sim$6% and provided an additional improvement in efficiency. See Figure 1.

Using electron-beam induced current techniques, the minority carrier diffusion length L_D in the p-CdTe crystal substrate of the cell discussed above was measured. A value of $\sim$0.4 µm was obtained for the bulk which appears to increase in the depletion layer near the junction (Figure 2). This increase is due to enhancement of L_D by the junction field.

The existence of the high quantum efficiencies observed ($\sim$75% averaged over the band gap "window" - corrected for reflection) with such a small L_D implies a considerably larger optical absorption coefficient $\alpha(\lambda)$ than expected from literature data. Data for $\alpha(\lambda)$ calculated from L_D and the spectral response of the cell above are shown in Figure ~~2~~3. This is a very favorable result for thin film cells where the L_D is limited by grain size and most of the light must be absorbed within L_D for useful collection.

Preliminary research on the n-ITO/p-CdTe heterojunction has produced promising results. Large V_{oc} (0.66V) and low J_o (10^{-10} - 10^{-9} A/cm^2) have been observed. Fill factors are small, however, and a large reverse bias is necessary to collect the maximum current ($\sim$23 mA/cm^2 at -4 V bias has been observed under solar simulation). The advantages of this cell are the inherently high V_{oc}, large band gap window (1.47 to 3 eV), and simplicity of fabrication.

A number of heterojunctions were made by close-spaced vapor transport techniques (n-CdSe/p-CdTe, n-ZnSe/p-CdTe, n-CdTe/p-ZnTe, and n-ZnSe/p-ZnTe) and new values of electron affinity for CdSe (4.58 eV) and ZnTe (3.73 eV) were found - both referenced to the CdTe value. These junctions have low quantum efficiencies, the current transport being limited by insulating layers of the junction caused by interdiffusion at the high substrate temperatures used.

Because of the large bandgap of ZnSe (2.67 eV) and the large diffusion potential of the CdTe/ZnSe cell it shows definite promise of being the highest efficiency binary II-VI combination if sufficient quantum efficiency can be obtained. Our results show that ZnTe (bandgap = 2.3 eV) or CdSe (bandgap = 1.7 eV) interlayers are formed near the junction by alloying at the high deposition temperatures used in CSVT. This conclusion is supported by the spectral response curves in Figure 4 for a choice of ZnSe or CdTe as the substrate crystal. These layers severely limit current transport and thus the low quantum efficiencies obtained so far are not representative of a true CdTe/ZnSe junction. The use of vacuum evaporation for the deposition of n-ZnSe will permit lower substrate temperatures and avoid the interdiffusion problem.

Vacuum evaporation of ZnSe with coevaporation doping of In has yielded adherent films on glass with excellent optical properties. The resistivity of these films is high however (> 10^8 Ωcm) and several different doping schemes are being tried (e.g., coevaporation with Ga and excess Zn).

A CdTe/CdS solar cell made by solution spraying the CdS film onto a single crystal p-CdTe substrate gave 6.4% solar efficiency (uncorrected for reflection loss) indicating good properties for these films.

IV. SUMMARY OF KEY RESULTS

The key results of the last 6 months are summarized on page 15. Perhaps the most important result is the measurement of a very short diffusion length (0.4μm) in a n-CdS/p-CdTe cell with very high quantum efficiency (>75%). The high absorption constant implied by these measurements is a very favorable result for future thin film cells, making thinner films with smaller grain size feasible.

V. FUTURE PLANS

Future work includes characterization of 18 n-CdS/p-CdTe cells which have been prepared with epitaxial films of CdS with bulk resistivity ranging from 0.002 to 0.6 Ωcm. These will be investigated with respect to variation in heat-treatment conditions. Other work includes the control of resistivity of ZnSe films and the preparation of n-ZnSe/p-CdTe heterojunctions and their characterization. Control of evaporation and resistivity of p-CdTe films will be followed by more work on making ohmic contact to this material. It is felt that making contacts to the freshly evaporated p-CdTe film surface (without breaking vacuum) will provide new insights into this problem.

APPLIED RESEARCH ON II-VI COMPOUND MATERIALS FOR HETEROJUNCTION SOLAR CELLS

NSF AER 75-16379

Department of Materials Science and Engineering
Stanford University
Stanford, California 94305

September 1, 1975 - August 31, 1976

$ 56,400

Professor Richard H. Bube
Principal Investigator

PROJECT OBJECTIVES

PREPARATION AND INVESTIGATION OF HETEROJUNCTION SOLAR CELLS BASED ON SEVERAL II-VI COMPOUND SYSTEMS SUITABLE FOR LARGE-SCALE TERRESTRIAL APPLICATION.

SUMMARY OF ACTIVITIES FOR PAST 6 MONTHS

- * CHARACTERIZATION AND OPTIMIZATION OF n-CdS/p-CdTe SOLAR CELLS
- * CONTROL OF VACUUM EVAPORATION OF ZnSe FILMS
- * INITIAL CHARACTERIZATION OF n-ZnSe/p-CdTe CELLS (CSVT)
- * PREPARATION OF SOLUTION SPRAYED CdS FILM CELLS
- * INITIAL CHARACTERIZATION OF OTHER II-VI CELLS
  - n-CdSe/p-ZnTe
  - n-CdSe/p-CdTe
  - n-ITO/p-CdTe

OPTIMIZATION OF n-CdS/p-CdTe CELLS

* INCREASED EFFICIENCY WITH ITO CONTACTS

Preparation	V_{OC}	J_{SC}	ff	Reflection Loss	η_S
Initial	0.59 V	13.9 mA/cm^2	55%	∿17%	5.2%
ITO	0.62	14.4	∿	∿12	(7.4)
ITO + Glycerol	0.633	16.1	65.8	∿ 6	7.9

* MINORITY CARRIER DIFFUSION LENGTH L_D BY EBIC

0.4 μm in CdTe; 0.43 μm in CdS films

* COLLECTION FUNCTION ANALYSIS ($L_D \overset{\sim}{\sim} W_D$)

- Low L_D with $\bar{\eta}_Q \overset{\sim}{-} 80\%$ implies high $\alpha(\lambda)$
- $H(V) = g(V)h(V)$ from spectral response

  $g(V)$ ∿ effective L_D, Loss ∿14%

  $h(V)$ ∿ interfacial recombination,

  → $S \sim 10^7$ cm/sec, Loss ∿20%

* ANALYSIS OF CELLS WITH VARIATION OF HEAT TREATMENT

18 cells with $0.003\ \Omega\text{cm} < \rho_{CdS} < 0.6\ \Omega\text{cm}$ now being analyzed.

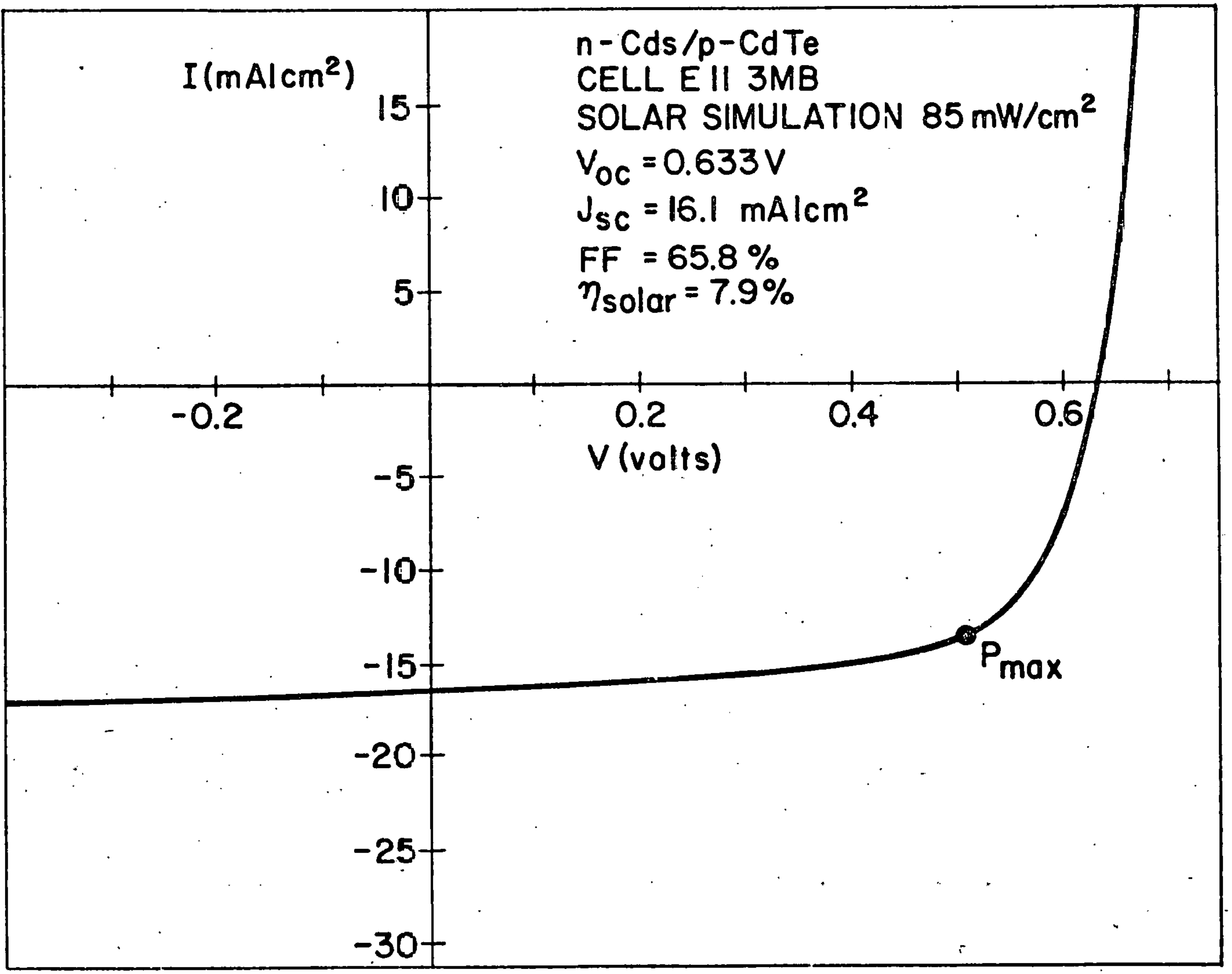


Figure 1. Current density vs voltage for n-CdS/p-CdTe cell.

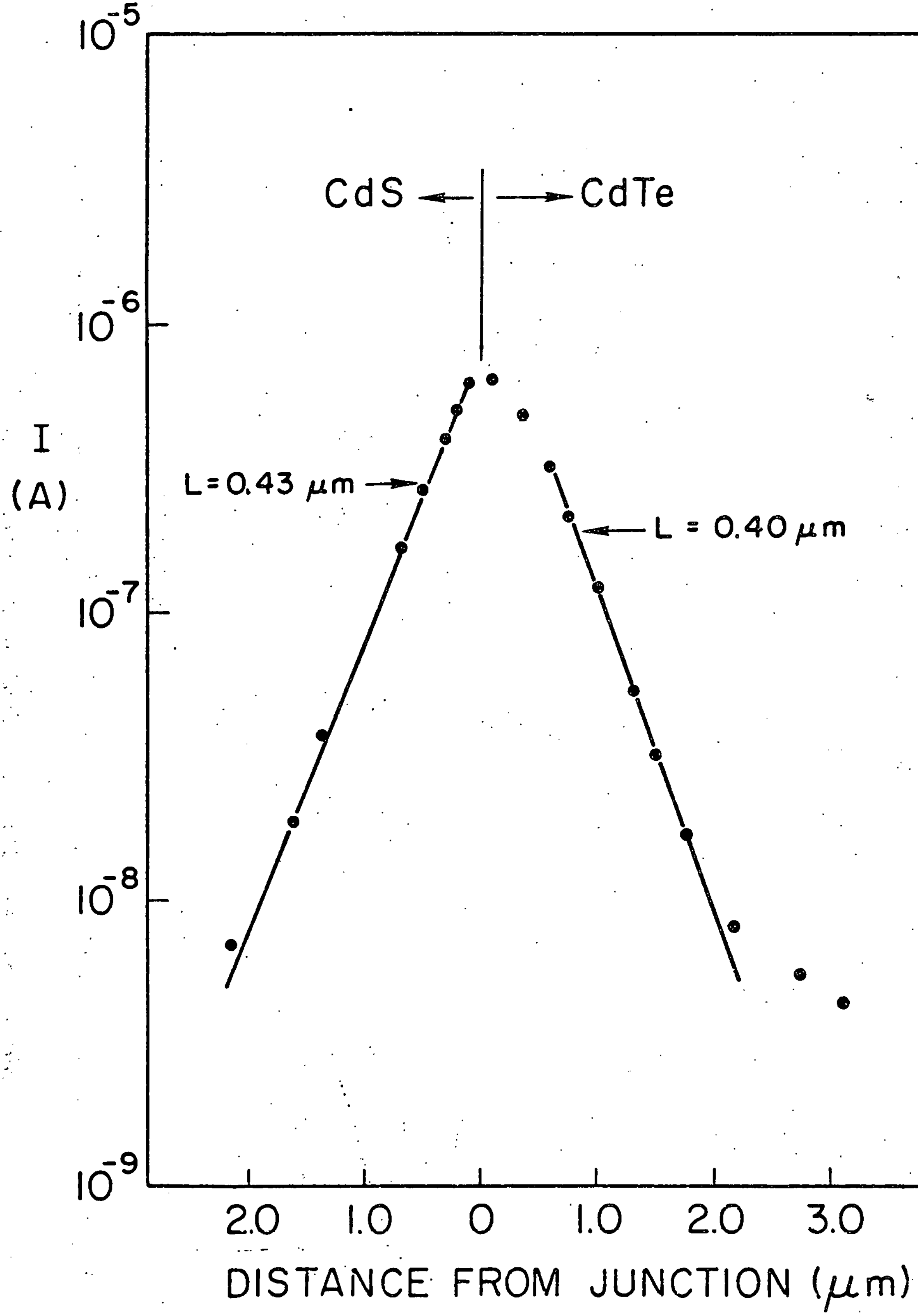


Figure 2. Plot of the electron beam induced current as a function of position for the E11-3MB solar cell.

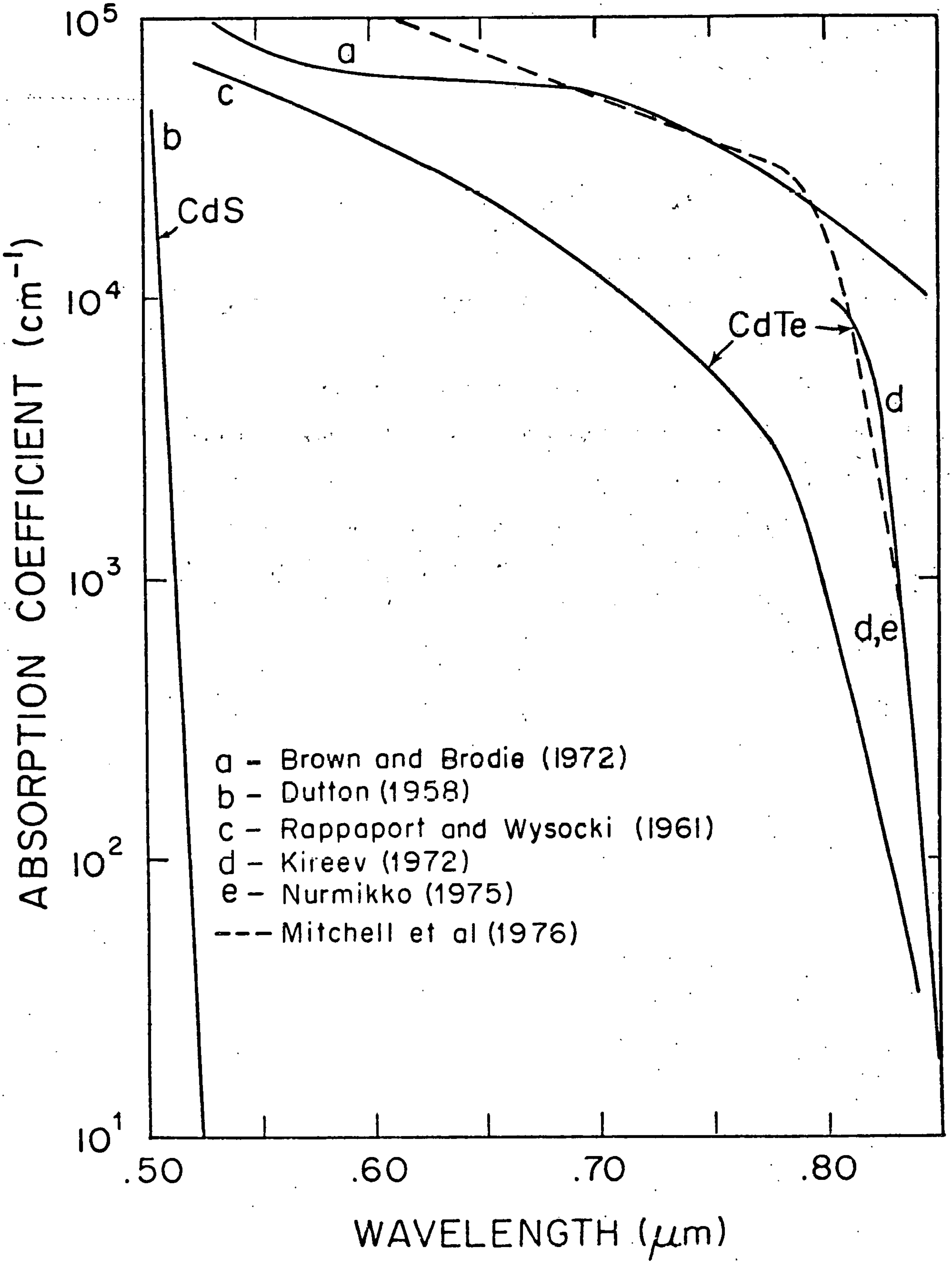


Figure 3. Optical absorption constant for CdTe.

CHARACTERIZATION OF n-ZnSe/p-CdTe CELLS

* DEPOSITION CONDITIONS - CSVT

- On single crystal substrates of CdTe and ZnSe
- In H_2 at $\approx$ 500°C

* INTERDIFFUSION DOPING → CdSe OR ZnTe LAYERS

Low η_Q - not representative of true binary junctions

* VACUUM EVAPORATION OF ZnSe

Glass substrates at 300°C, 0.2 μm/min, with In.
Very good optical properties, $\rho_\beta > 10^8\ \Omega\text{cm}$
Ga, Zn coevaporation now being tried.

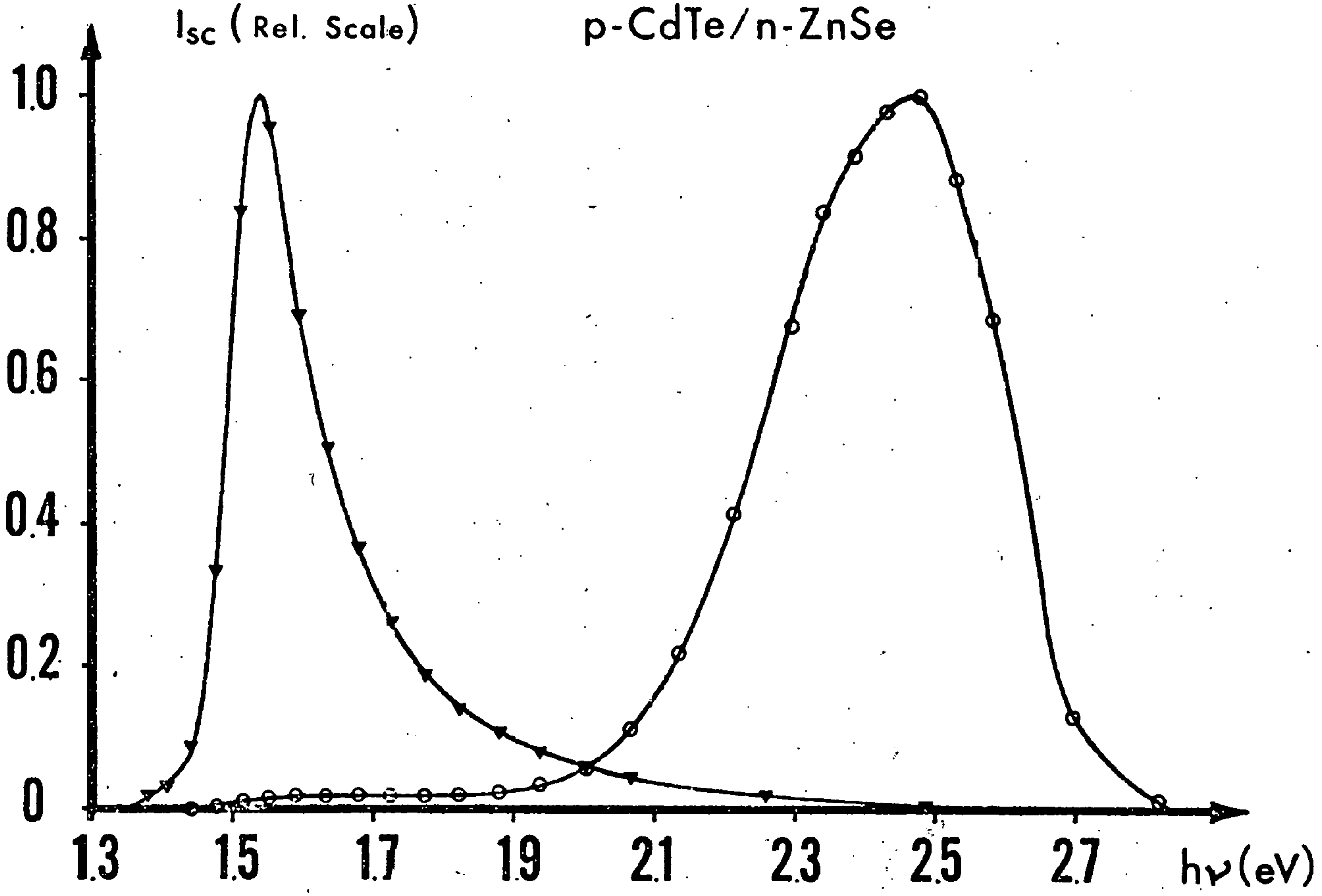


Figure 4. Spectral response of short-circuit current for cells M-1 (low energy peak) and Q-1.

OTHER HETEROJUNCTIONS

* SOLUTION SPRAYED CdS FILMS ON p-CdTe

Substrate Temp.	V_{OC}	J_{SC}	η_S
400°C	0.725 V	10.5 mA/cm^2	5.5%
460°C	0.53	17.2	6.6

* n-CdSe/p-ZnTe
n-CdSe/p-CdTe
n-ZnSe/p-CdTe

CSVT
For CdSe $\chi = 4.58$ eV
For ZnTe $\chi = 3.73$ eV relative to χ for CdTe

* n-ITO/p-CdTe HETEROJUNCTIONS

High J_L, Large V_{OC} (0.66 V), Low ff

SUMMARY OF KEY RESULTS

* PRODUCTION OF 7.9% EFFICIENT CdS/CdTe CELL

* CONTROL OF ITO SPUTTERED TRANSPARENT CONDUCTING FILMS

* MEASUREMENT OF L_D IN p-CdTe BY EBIC

* MEASUREMENT OF $\alpha(\lambda)$ IN CdTe

* DEVELOPMENT OF COLLECTION FUNCTION MODEL TO ANALYZE S, α, L_D, AND V_D

* INITIATION OF ZnSe EVAPORATION

* n-ITO/p-CdTe CELL

* PREPARATION OF 6.6% EFFICIENT SOLUTION SPRAYED CdS CELL

PLANNED ACTIVITY FOR NEXT 6 MONTHS

- CHARACTERIZATION OF 18 CdS/CdTe CELLS WITH VARIATION OF ρ_{CdS} AND T_{HT}
- PREPARATION OF n-ZnSe/p-CdTe CELLS
- CONTROL OF p-CdTe EVAPORATION
- FURTHER WORK ON SPRAYED CdS FILM CELLS
- RELATED WORK
  - Ohmic contact studies by ion implantation on p-CdTe
  - Ohmic contact studies on thin film p-CdTe
  - Further work on n-ITO/p-CdTe cell
- BEGINNING OF ALL THIN FILM CELL PREPARATION

PLANNED RENEWAL

- * SUPPORT SHIFTED TO MATERIALS SCIENCE PROGRAM OF ERDA
- * CONTINUED INVESTIGATION OF II-VI HETEROJUNCTIONS AND THE Cu_2S/CdS CELL
- * RESEARCH INCLUDES BASIC STUDIES ON JUNCTION PROPERTIES, OHMIC CONTACT FORMATION, AND PREPARATION OF ALL THIN FILM CELLS.

INVESTIGATION OF THIN FILM SOLAR CELLS BASED ON Cu_2S AND CERTAIN TERNARY COMPOUNDS

NSF/RANN/SE/GI-38102X - AER73-07784-A02

GRANT PERIOD: 1 July 1973 - 30 June 1976

TOTAL FUNDING THREE YRS: $268,300

FUNDING 1 July 1975 - 30 June 1976: $91,000

PRINCIPAL INVESTIGATOR: J. J. LOFERSKI
PROFESSOR OF ENGINEERING
ORGANIZATION: BROWN UNIVERSITY
PROVIDENCE, R.I. 02912

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

August 3 - 6, 1976
University of Maine at Orono
Orono, Maine 04473

PROGRAM PARTICIPANTS: J. Shewchun, A. Wold, R. Arnott, E. A. DeMeo
H. L. Hwang, C. C. Wu, E. E. Crisman
R. Beaulieu

1. OBJECTIVES:

The objective of this project has been the investigation of thin film solar cells based on Cu_2S and ternary compounds of the type $CuInS_2$ and $CuInSe_2$ for large-scale terrestrial solar energy utilization. Specific goals include the fabrication and testing of 1) metal-semiconductor photovoltaic cells consisting of Cu_2S on Cu or other metals, 2) metal-semiconductor cells involving $CuInS_2$ on metals, 3) heterojunction cells involving $CuInS_2$ on Cu_2S, 4) homojunction cells of $CuInS_2$, and 5) heterojunction cells of Cu_2S on single crystal Si and CdS.

The motivation for the program arose as follows. At the time the original proposal was written (1972), it was known that most of the solar photons absorbed in the thin film Cu-Cd-S cell were absorbed in the Cu_xS layer formed on its surface by the "Clevite" process, in which a CdS film was dipped in a cuprous ion solution and Cu^+ ions substituted for the Cd^{++} ions to form a thin film (~ 2000Å) whose composition was approximately Cu_2S. This process did not lead to reproducible results; there was a large variation in efficiency of cells produced by the process. Furthermore, the "as-produced" cells were usually of poor quality; it was only after the cells had been subjected to post-fabrication treatments like heat-treatment in air or the "Cu-treatment" in air that efficiencies rose into an acceptable range of 4 to 5 % and sometimes even up to 8%. It was hypothesized that high efficiency (this usually meant high short circuit current) required that the Cu_xS layer be chalcocite which has a composition range from $x=2.000$ to $x=1.995$ at room temperature. If the layer had a composition $x \sim 1.96$ which was assumed to be djurleite, the current was reported to be an order of magnitude smaller than for a chalcocite film.

Our objective was to develop a method for producing chalcocite or any member of the Cu-S system in a controllable fashion. The method chosen was a simple one, adaptable to inexpensive large scale fabrication of cells. Films of Cu would be deposited on any substrate like CdS, Si, etc. The film would then be heated in H_2S at temperatures between 150 and 300°C. Any desired member of the Cu-S system would be producible by this technique. (Sulfurization should also be adaptable to the formation of thin films of $CuInS_2$ and of CdS.) The thin films produced in this fashion should in principle lead to high efficiency Cu-CdS cells since any desired composition or composition profile would be achievable. In addition since the chalcocite could be produced on any substrate, it should be possible to make solar cells based on p-type chalcocite on other semiconductors like Si as well as Shottky barrier cells on metal substrates. The combination of chalcocite with Si was especially attractive because chalcocite and Si have nearly equal energy gaps but chalcocite is a direct gap semiconductor. This combination could lead to improved thin film Si cells because most of the photon absorption would occur in the few thousand angstroms of chalcocite and the demands on diffusion length in silicon would be minimal.

The interest in the ternary chalcopyrite semiconductors $CuInS_2$ and $CuInSe_2$ arose because they can be made both n- and p-type by adjusting the chalcogenide content; consequently homojunctions can be fabricated from them. They are direct gap semiconductors and have energy gaps favorable for efficient solar energy conversion. One of them $CuInS_2$ has two elements in common with Cu_2S and it was hoped that good cells could be made by combining these two semiconductors. The sulfurization process could be used to produce such cells from metal films.

II PREVIOUS ACTIVITIES:

A number of these objectives were achieved. The sulfurization process was developed so that thin films of chalcocite were readily produced on a variety of substrates including silica and glass slides, cadmium sulfide single crystals and thin films, and silicon single crystals. That the films were chalcocite was confirmed by x-ray analysis on thick films (more than 0.5 micron thick) and by cathodoluminescence on films thin as 0.2 micron.

It was established that cathodoluminescence (CL) could be used for identification of thin films of chalcocite. Of all the members of the Cu-S system, only those films whose x-ray diffraction pattern indicated that they were mainly chalcocite luminesced. It was found, however, that distinct differences can exist in the shapes, positions and intensities of the CL spectra. In particular, those chalcocite films produced on CdS crystals by the chemical substitution methods, i.e., by the Philips (Fig 1) and the Clevite processes (Fig 2) exhibit CL spectra distinctly different from the spectra of "pure" specimens produced by sulfurization of Cu, (Fig 3) by chalcocite mineral, evaporated Cu_2S and synthesized Cu_2S powder compressed into bars. While the shape of the "pure" chalcocite spectrum is stable with time, the shape of the CL spectrum of the topotaxial chalcocite films changes with time though it was never seen to assume the form of pure chalcocite CL spectra. The intensity of the pure chalcocite CL spectrum varied over a wide range for samples prepared by the same method.

Heat-treatment and copper treatment affected the intensity of the CL spectra but did not affect the shape.

It is well known that luminescence is sensitive to the small variations in the chemical impurity and structural defect content of the luminophor. Here then was a phenomenon which could be used to monitor changes in chalcocite films on a finer scale than is possible from observation of current-voltage characteristics of cells. We set out to exploit this phenomenon in the expectation that it would provide a systematic approach to the improvement of thin film Cu-Cd-S cells and to the fabrication of other kinds of solar cells based on Cu_2S.

We have also grown some $CuInS_2$ crystals by the Bridgman method. We established that the cathodoluminescence spectra of sulfur-saturated (and therefore, p-type) and sulfur-deficient (and therefore, n-type) $CuInS_2$ were distinctly different and therefore that CL spectra could be used to monitor conductivity type changes in thin films of $CuInS_2$. We attempted without success to make photovoltaic cells from these single crystals.

We have also successfully fabricated photovoltaic cells on CdS crystals with chalcocite layers produced on them by sulfurization. We have compared these cells with cells made by the Clevite and Philips processes. We found that the AM1 open circuit voltages achieved in these cells were comparable (0.45 to 0.50V) but that the maximum value of I_{sc} attainable in the sulfurized cells (about 2%) (Fig 4) was lower than that achieved in Clevite cells (about 3%) which in turn had lower values of I_{sc} than Philips process cells (about 4%).

We also fabricated p-Cu_2S/n-Si (single crystal) cells by evaporating "pure" Cu_2S onto the Si and by sulfurizing Cu on Si. The efficiency of the former was up to about 2%; of the cells made by sulfurization did not exceed 1% efficiency.

Attempts to make Shottky barrier cells from thin films of Cu sulfurized on aluminum and copper substrates did not succeed. No evidence of a rectifying barrier was between p-Cu_2S and the metal was observed.

III DESCRIPTION OF PROGRESS DURING PAST SIX MONTHS

a) Cathodoluminescence Studies

1) Until now we have reported that of the various members of the Cu-S system, only chalcocite luminesces. According to Mulder's absorption curves, (Fig 5) djurleit and diginite are

also semiconductors and they should luminesce, but their luminescence bands should be displaced toweard shorter wavelengths because their bandgaps are larger than that of chalcocite. We have observed luminescence from a film whose x-ray diffraction pattern indicates that it is the tetragonal phase (composition approximately $Cu_{1.96}S$); the peak is around 0.9μ (Fig 6). We never did succeed in producing djurleite by sulfurization of Cu; we have observed either chalcocite, the tetragonal phase which according to Cook is not stable below 90°C (Fig 7) or diginite. The CL spectrum of the tetragonal phase transforms into the chalcocite form after sulfurization.

ii) We have observed a correlation between the intensity of CL, the conductivity of the films and the free carrier absorption. Figure 8 shows the intensity vs conductivity for a group sulfurized Cu films on silica substrates. Figures 9 and 10 show the correlation between intensity and free carrier absorption in a sample subjected to heat treatment. The CL intensity is greatest when the infrared transmission is greatest, i.e., when the free carrier concentration is smallest. At least two models (outlined in Fig 11) could account for a dependence of the CL intensity on conductivity. In the first conductivity changes cause shifts in the Fermi level which ultimately affect the minority carrier lifetime and therefore, the luminescence intensity which is proportional to lifetime. In the second, the increased conductivity is attributed to the increases in acceptor concentration. If a significant fraction of the recombination occurs via the acceptors and if this recombination is non-radiative, the CL intensity will drop and it will be a linear function of conductivity. The data of Fig 8 has been replotted on a linear scale in Fig 12. The low conductivity samples exhibit a variation of CL intensity which does not fit the linear model; however, the possibility of a correlation exists. No such agreement with the first of the two models was possible.

iii) Heat treatment in air or in vacuo which is known to improve I_{sc} of solar cells leads to a decrease in CL intensity as shown in Figs 9 and 10. Copper treatment in vacuum increases the CL intensity while Cu treatment in air has the opposite effect. If it is assumed that CL intensity is highest in samples which are most nearly pure chalcocite, then these experiments imply that the improvement in photovoltaic output of Cu-Cd-S cells after heat treatment or Cu-treatment must be attributed to other changes in the cell. Figure 12a suggests such possible changes. Both treatments require the presence of oxygen. Since copper oxides have forbidden gaps larger than chalcocite, structures like those shown in this figure could result from these treatments. Both of them reduce surface recombination losses and both should lead to an increase in I_{sc}.

iv) Figure 13 suggests a model which could account for the observed difference in the CL spectra of "pure" chalcocite and chalcocite produced by substituting copper for cadmium in CdS. The broadened band, with a maximum shifted toward longer wavelengths could be a superposition of two bands; the longer wavelength band of the pair could arise as a result of radiative recombination via a defect level. We have examined the CL spectra of "pure" chalcocite powder specimens deliberately doped with cadmium and chlorine, since both of these elements are probably present in chalcocite derived from CdS by chemical substitution. Another possible source of the spectral distortion is the topotaxial nature of the films on CdS; none of the other chalcocite samples is under any stress like the chalcocite in intimate contact with the CdS.

v) The highest efficiencies (~4%) we have observed in p-Cu_2S/n-CdS cells were those observed in cells produced by the Philips process. Examination of spectral response curves showed that these cells had far more response in the chalcocite absorption region than do sulfurized cells. Grain size and/or topotaxiality may account for this difference. It is also possible that the dry process films have a larger minority carrier diffusion length than sulfurized films. Note, however, that the highest CL intensity-which should be proportional to lifetime - observed thus far is that encountered from sulfurized samples. However this pure, unstressed chalcocite does not make the best solar cells.

vi) We have continued fabricating p-chalcocite/n-Si (single crystal) cells in hopes of increasing their efficiency and their area. The chalcocite layer is evaporated on a Si wafer. Efficiencies up to 4% have been measured on cells having areas of about 0.5 cm^2; however, cells of 4 cm^2 area had efficiencies no higher than about 2%. These cells do not have antireflection coatings. Contact problems are a factor and so is reproducibility of films. The thickness of the chalcocite on our best cells is about 900 Angstroms, i.e., these are not simple Schottky barrier cells on silicon. We have not been able to demonstrate conclusively that the chalcocite is contributing significantly to the I_{sc} of this type of cell.

vii) After consultation with Dr. W. Giriat of the University of Merida, Venezuela, we have grown thin platelet single crystals of $CuInS_2$ by vapor transport in a sealed tube. The transporting agent is iodine.

IV SUMMARY OF KEY RESULTS

i) Films whose x-ray diffraction spectra indicate that they are chalcocite can exhibit wide variations in CL intensity as well as distinct differences in the shape and positions of CL bands. Such differences can potentially be correlated with variations in lifetime, resistivity, impurity content and structural perfection of the films. These parameters can have profound effect on the efficiency of Cu-Cd-S cells and on any cells made from chalcocite.

ii) Cu-Cd-S cell produced on CdS single crystal substrates by the Philips process seem to have higher efficiencies (about 4%) than those of cells produced by the Clevite process or by sulfurization. However, the high efficiency (8%) reported by Philips has not been observed. This may be related to the "quality" of the CdS substrate as TeVelde of Philips has reported.

iii) p-chalcocite/n-Si cells with efficiencies of 5% are certainly achievable and approaching 10% are potentially achievable. This heterostructure cell could be useful for realization of acceptable efficiency polycrystalline Si cells.

iv) Most of our work has focused on Cu_2S and cells made from it. Only a modest effort has been expended on $CuInS_2$. Groundwork has been laid for an investigation of the photovoltaic effect in both single crystal and thin film cells based on it. Because of the attractive characteristics of $CuInS_2$ for solar cells, continued work could lead to valuable results.

V) FUTURE PLANS

If funding were available, we would like to continue the cathodoluminescence studies to identify those characteristics of chalcocite which are truly crucial to the reproducible fabrication of Cu-Cd-S cells. We would like an opportunity to complete an assessment of the chalcocite-silicon cell. We would propose a further exploration of the Philips process with emphasis shifted to the production of high quality CdS crystals by epitaxial growth on Ge crystals. We would like to intensify our investigation of $CuInS_2$ and of photovoltaic cells made from it.

INVESTIGATION OF THIN FILM SOLAR CELLS BASED ON Cu_2S AND CERTAIN TERNARY COMPOUNDS

NSF/RANN/SE/GI-38102X - AER 73-07784-A02

GRANT PERIOD: 1 JULY 1973 - 30 JUNE 1976

TOTAL FUNDING THREE YRS.: $268,300
FUNDING 1 JULY 1975 - 30 JUNE 1976:
$91,000

PRINCIPAL INVESTIGATOR: J.J. LOFERSKI
PROFESSOR OF ENGINEERING
ORGANIZATION: BROWN UNIVERSITY
PROVIDENCE, RI 02912

PRESENTED AT NATIONAL SOLAR PHOTOVOLTAIC
PROGRAM REVIEW MEETING
AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

OBJECTIVES

FABRICATION AND TESTING OF SOLAR CELLS BASED ON Cu_2S AND TERNARY COMPOUNDS OF THE TYPE $A^{I}B^{III}C_2^{VI}$ LIKE $CuInS_2$ and $CuInSe_2$

SPECIFICALLY THE FOLLOWING STRUCTURES WERE TO BE INVESTIGATED

a) SHOTTKY BARRIER CELLS OF Cu_2S AND $CuInS_2$ WITH Cu AND OTHER METALS

b) p-Cu_2S/n-Si HETEROJUNCTIONS

c) p-Cu_2S/n-CdS HETEROJUNCTIONS IN WHICH Cu_2S IS PRODUCED BY VARIOUS METHODS WITH ATTENTION FOCUSED ON SULFURIZATION PROCESS

d) $CuInS_2$ SINGLE CRYSTAL HETEROJUNCTIONS

e) p-Cu_2S/n-$CuInS_2$ HETEROJUNCTIONS

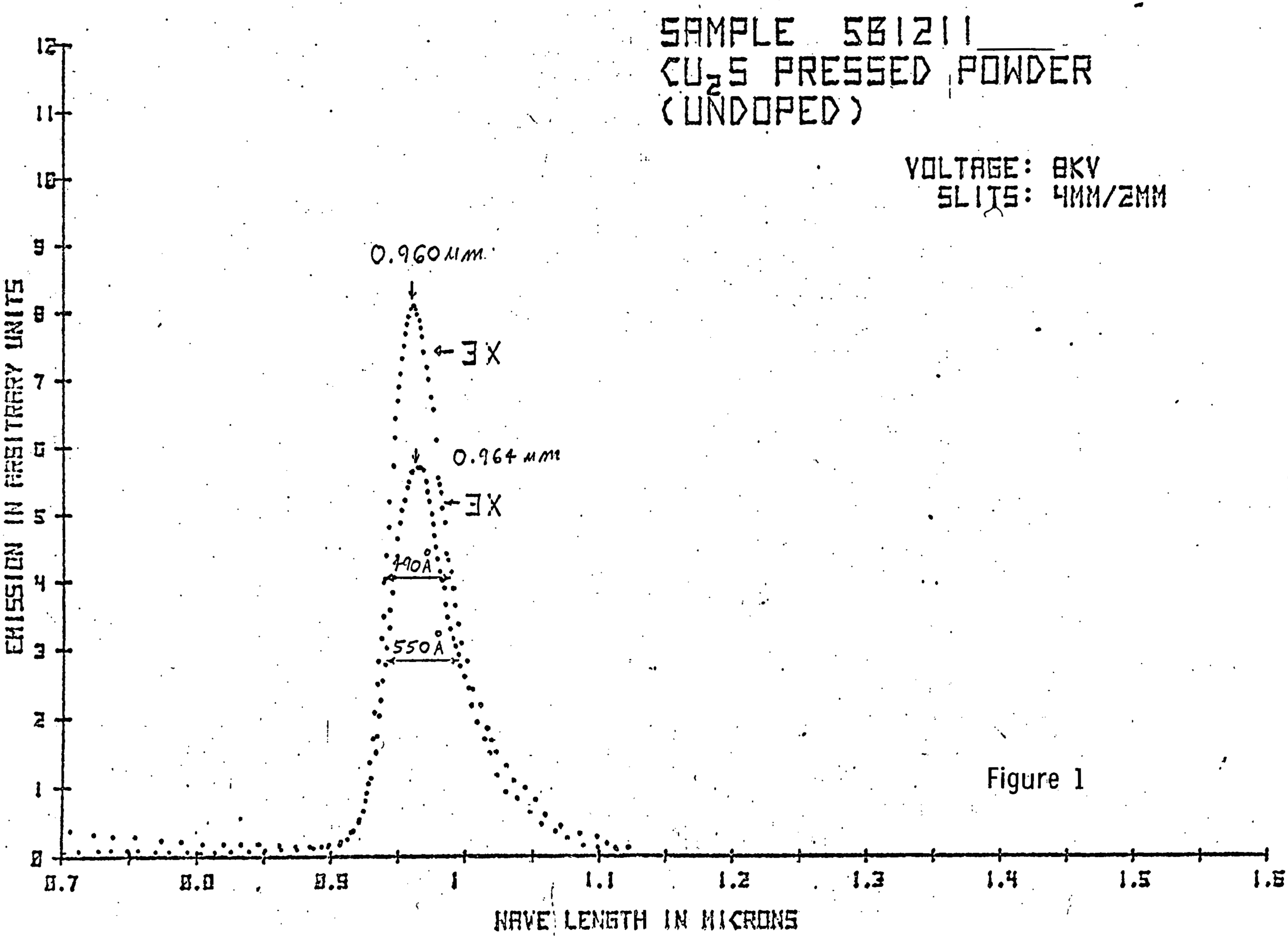

SAMPLE 5B1211
(CU$_2$S PRESSED POWDER
(UNDOPED)
VOLTAGE: 8KV
SLITS: 4MM/2MM
0.960 μm
←3X
0.964 μm
←3X
490 Å
550 Å
EMISSION IN ARBITRARY UNITS
0
1
2
3
4
5
6
7
8
9
10
11
12
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
WAVE LENGTH IN MICRONS

Figure 1

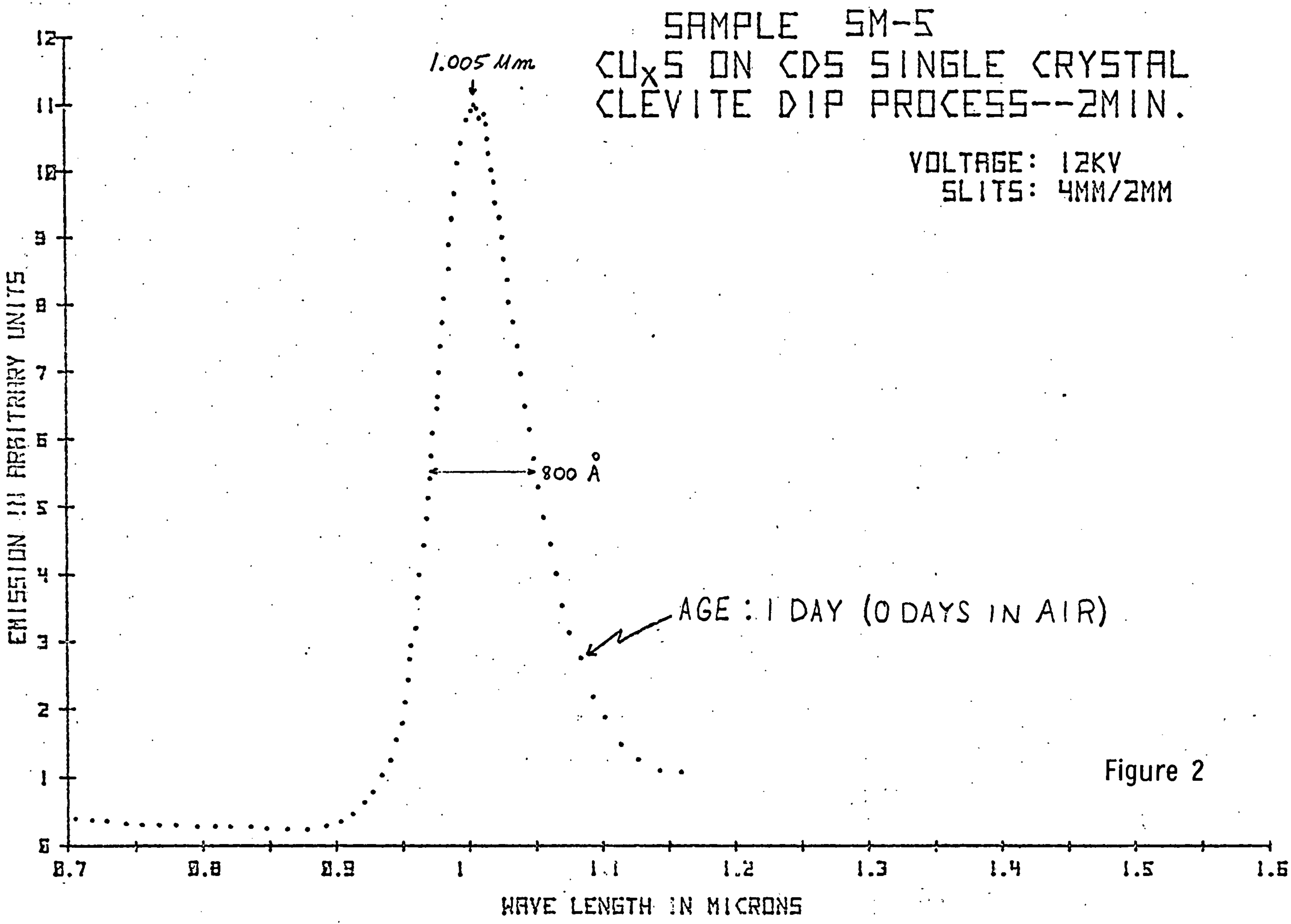
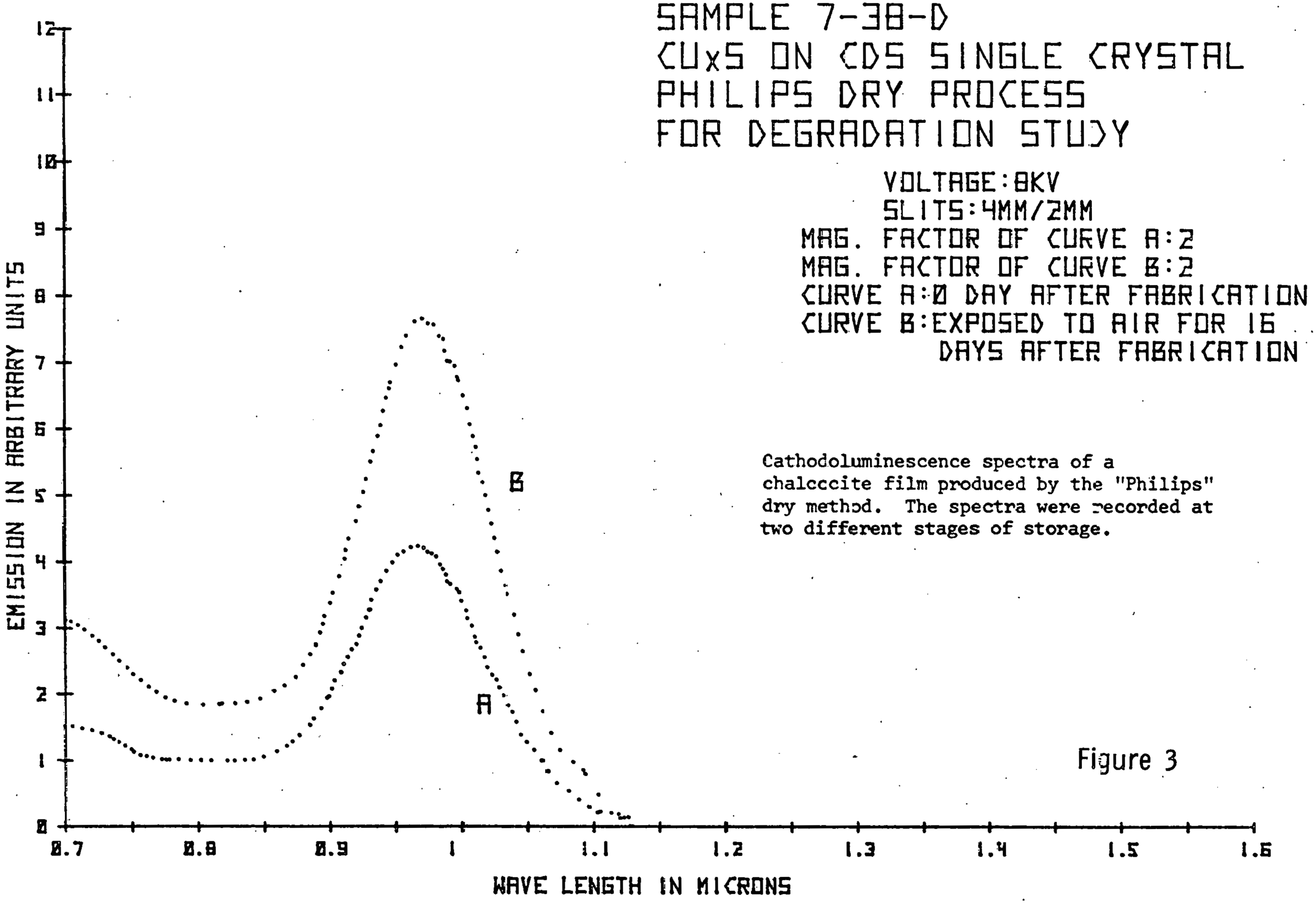
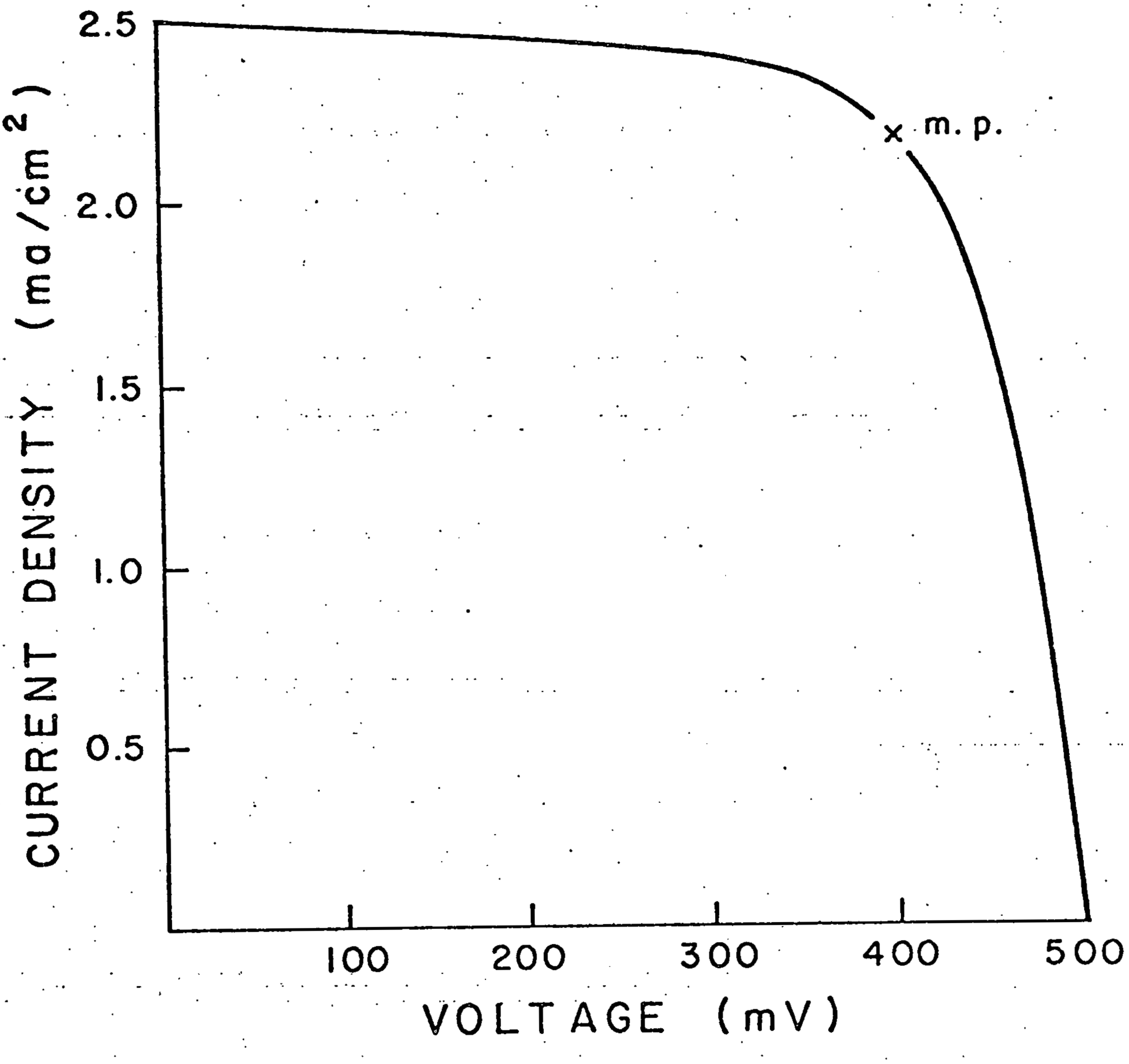

SAMPLE SM-5
CU$_X$S ON CDS SINGLE CRYSTAL
CLEVITE DIP PROCESS--2MIN.
VOLTAGE: 12KV
SLITS: 4MM/2MM
1.005 μm
800 Å
AGE : 1 DAY (0 DAYS IN AIR)
EMISSION IN ARBITRARY UNITS
0
1
2
3
4
5
6
7
8
9
10
11
12
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
WAVE LENGTH IN MICRONS

Figure 2



Cathodoluminescence spectra of a chalcocite film produced by the "Philips" dry method. The spectra were recorded at two different stages of storage.

Figure 3



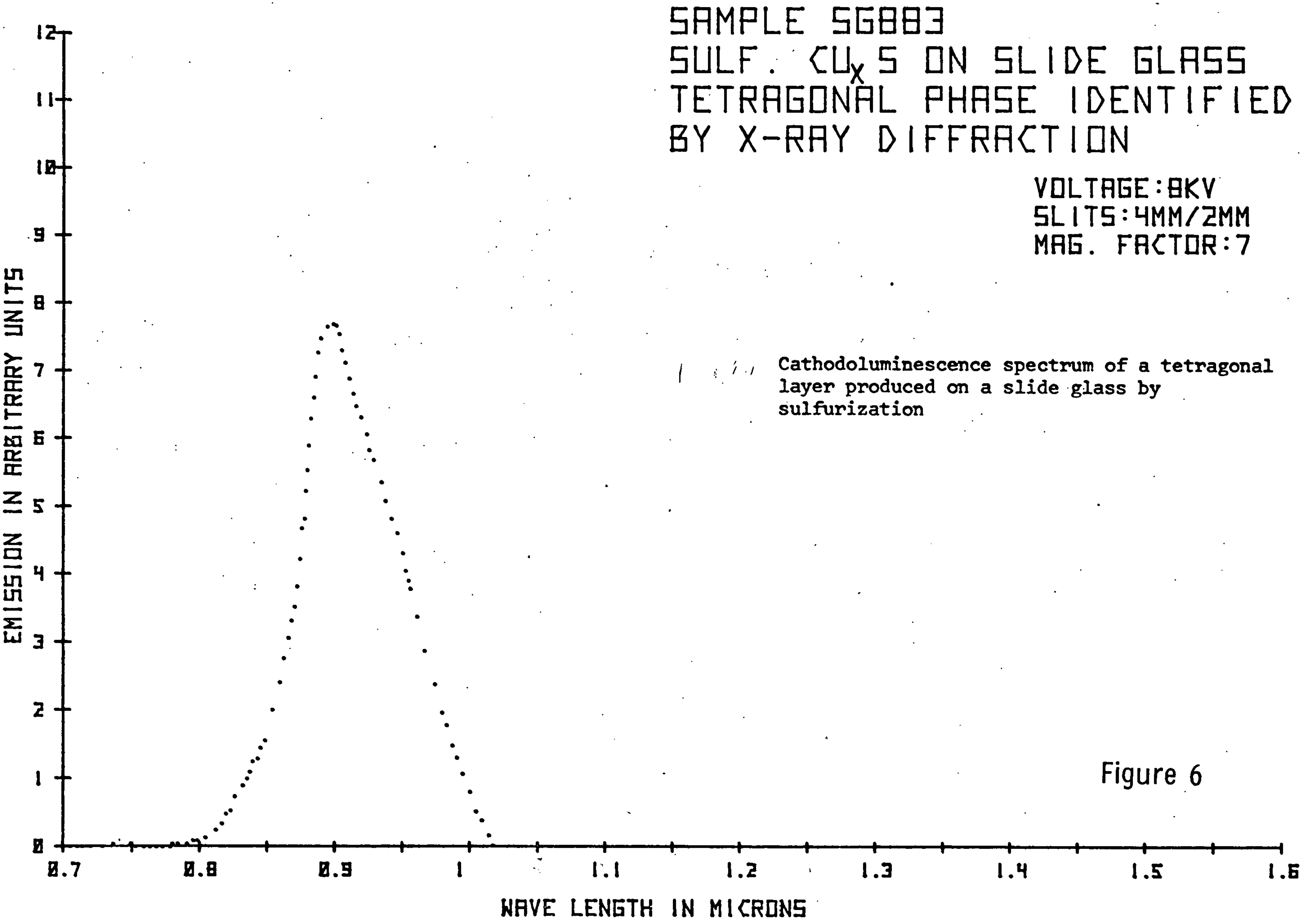
AMI illuminated I-V characteristic of an "as-fabricated" Cu_xS/CdS cell produced on single crystal CdS substrate by sulfurization. The Cu film for sulfurization is about 700 Å thick

Figure 4

PLANNED ACTIVITY DURING PAST SIX MONTHS

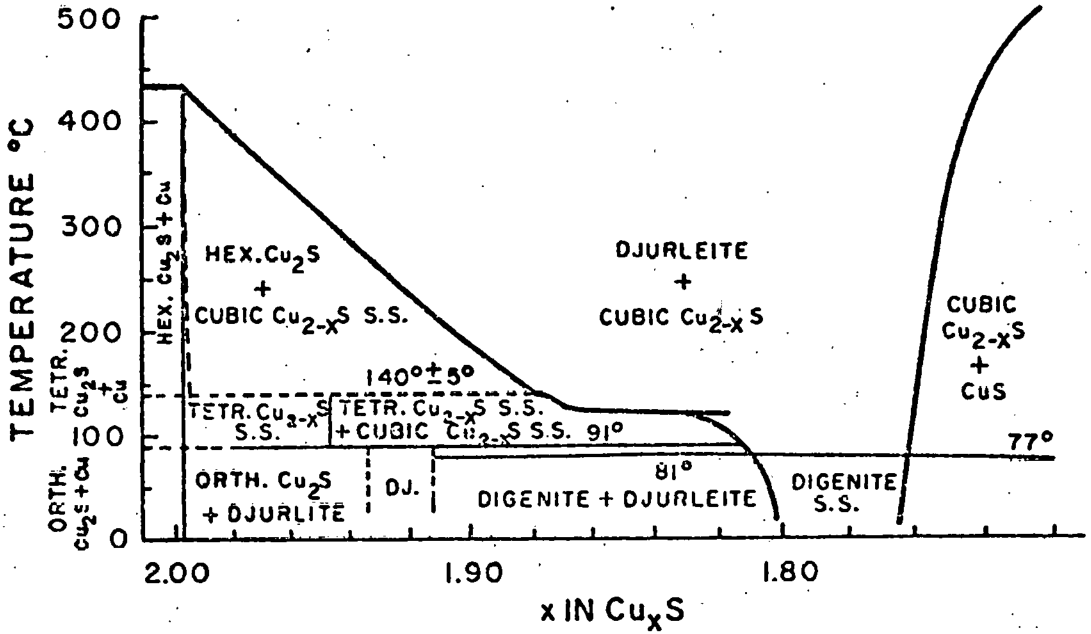
- CONTINUE COMPARISON OF CELLS MADE BY SUFURIZATION OF Cu LAYERS DEPOSITED ON CdS SINGLE CRYSTALS AND CELLS MADE BY THE CLEVITE AND PHILIPS PROCESSES
- FURTHER DOCUMENTATION AND INTERPRETAION OF DIFFERENCES IN THE CATHODOLUMINESCENCE SPECTRA OF Cu-S LAYERS PRODUCED BY VARIOUS PROCESSES AND OF CHANGES IN THESE SPECTRA CAUSED BY CELL POST FABRICATION "TREATMENTS".
- ATTEMPT OPTIMIZATION OF p-CHALCOCITE/n-Si (SINGLE CRYSTAL) CELLS
- GROW $CuInS_2$ CRYSTALS BY VAPOR PHASE TRANSPORT IN A CLOSED SYSTEM

Figure 5

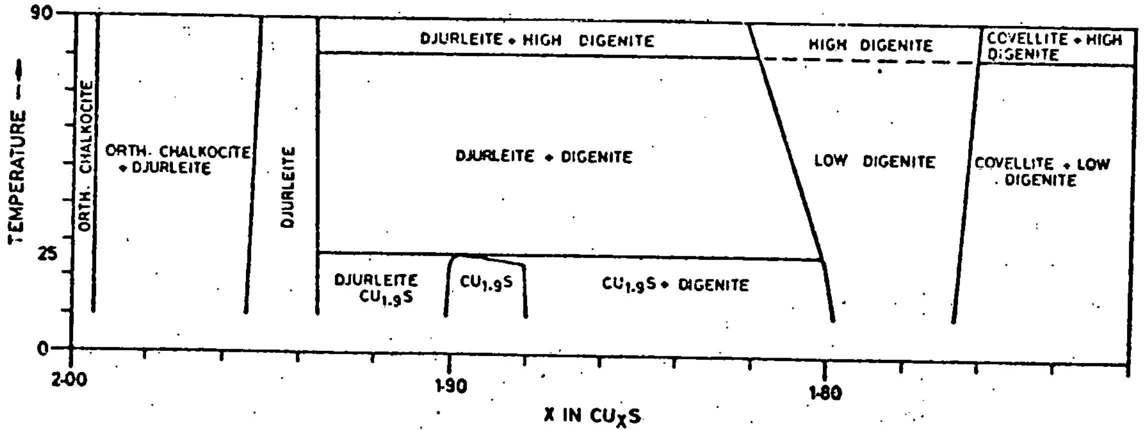


Cathodoluminescence spectrum of a tetragonal layer produced on a slide glass by sulfurization

Figure 6

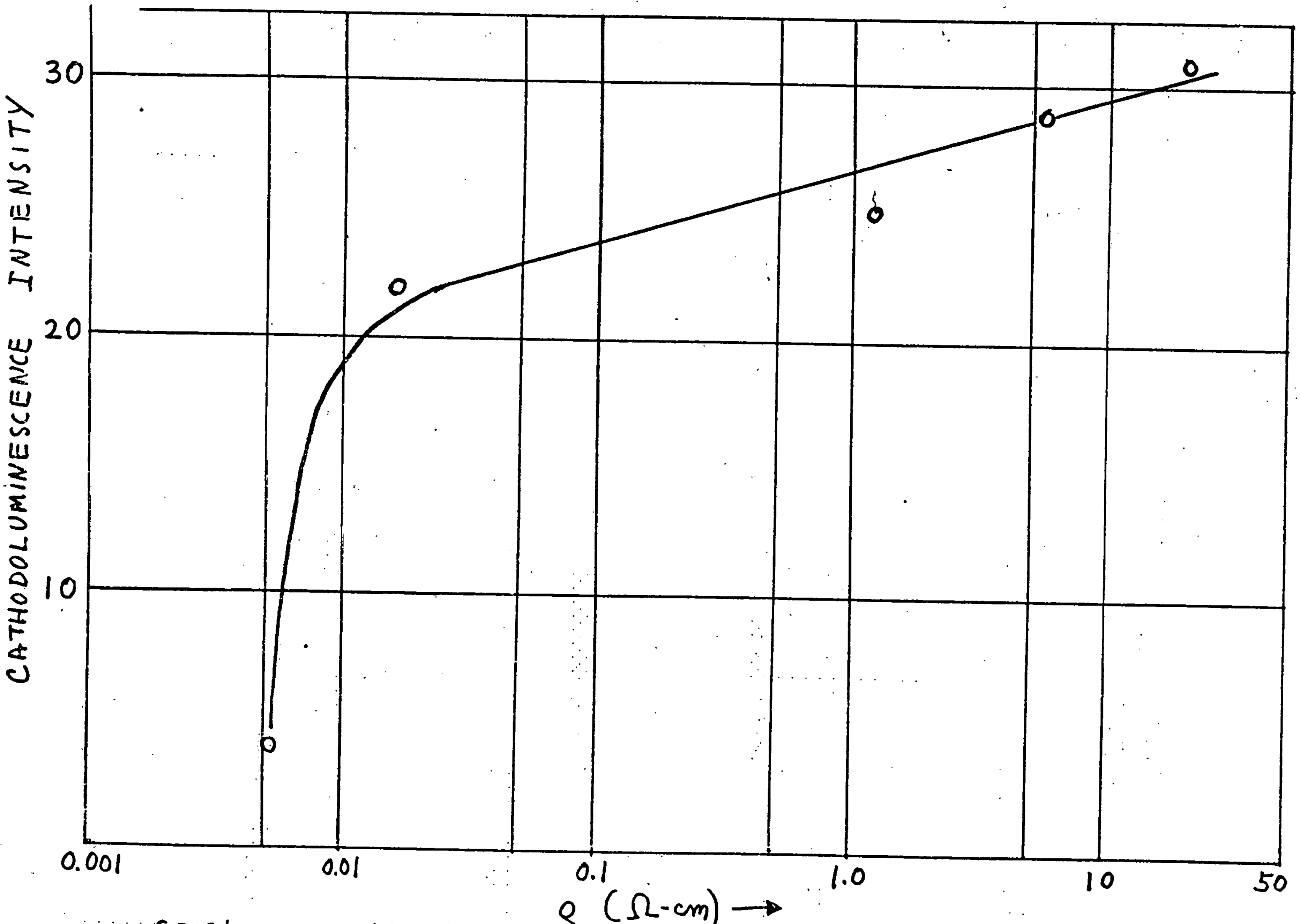


Phase diagram from $Cu_{2.00}S$ to $Cu_{1.72}S$ according to Cook

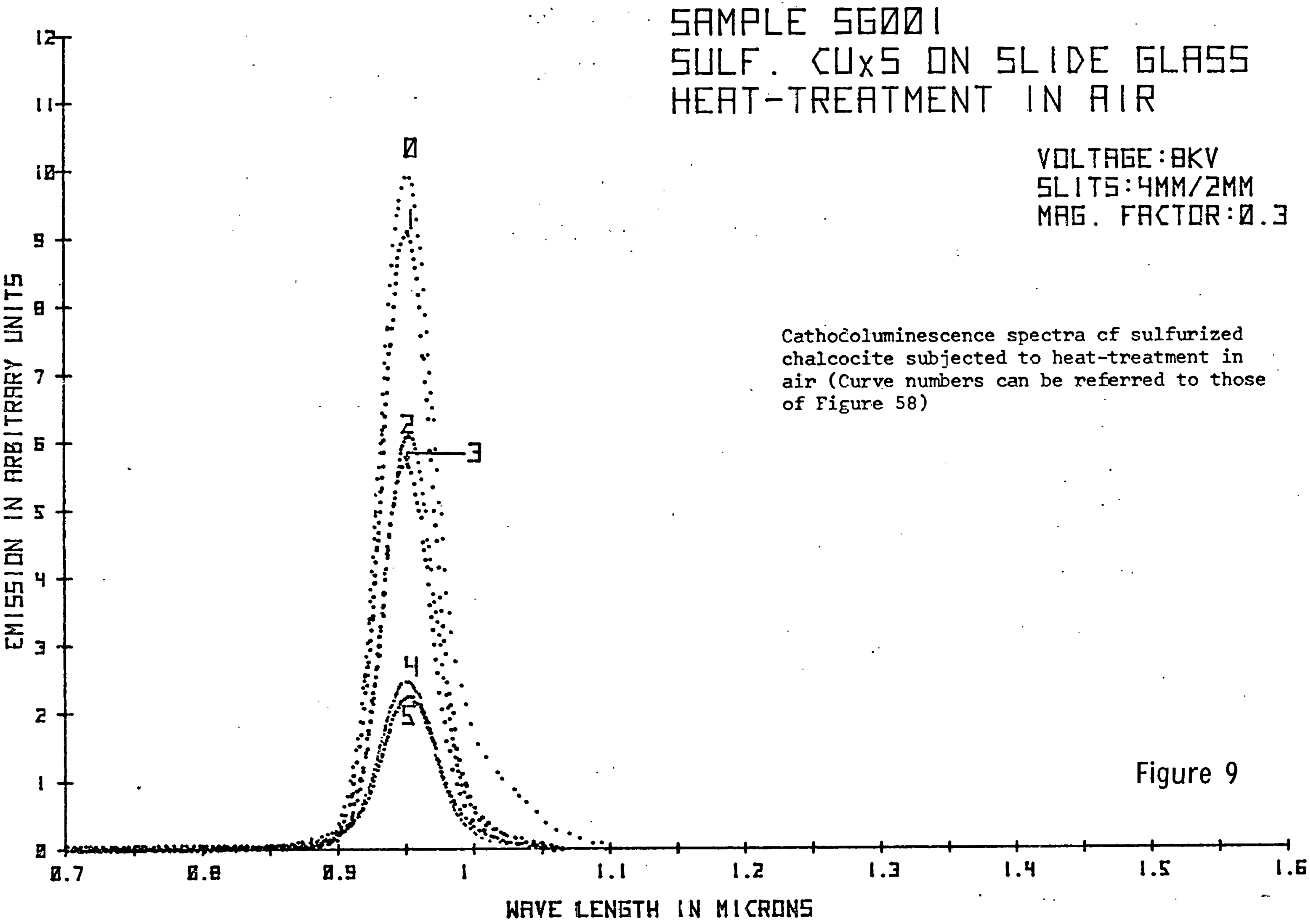


Low-temperature Cu-S phase diagram according to Mathiew et al.

Figure 7

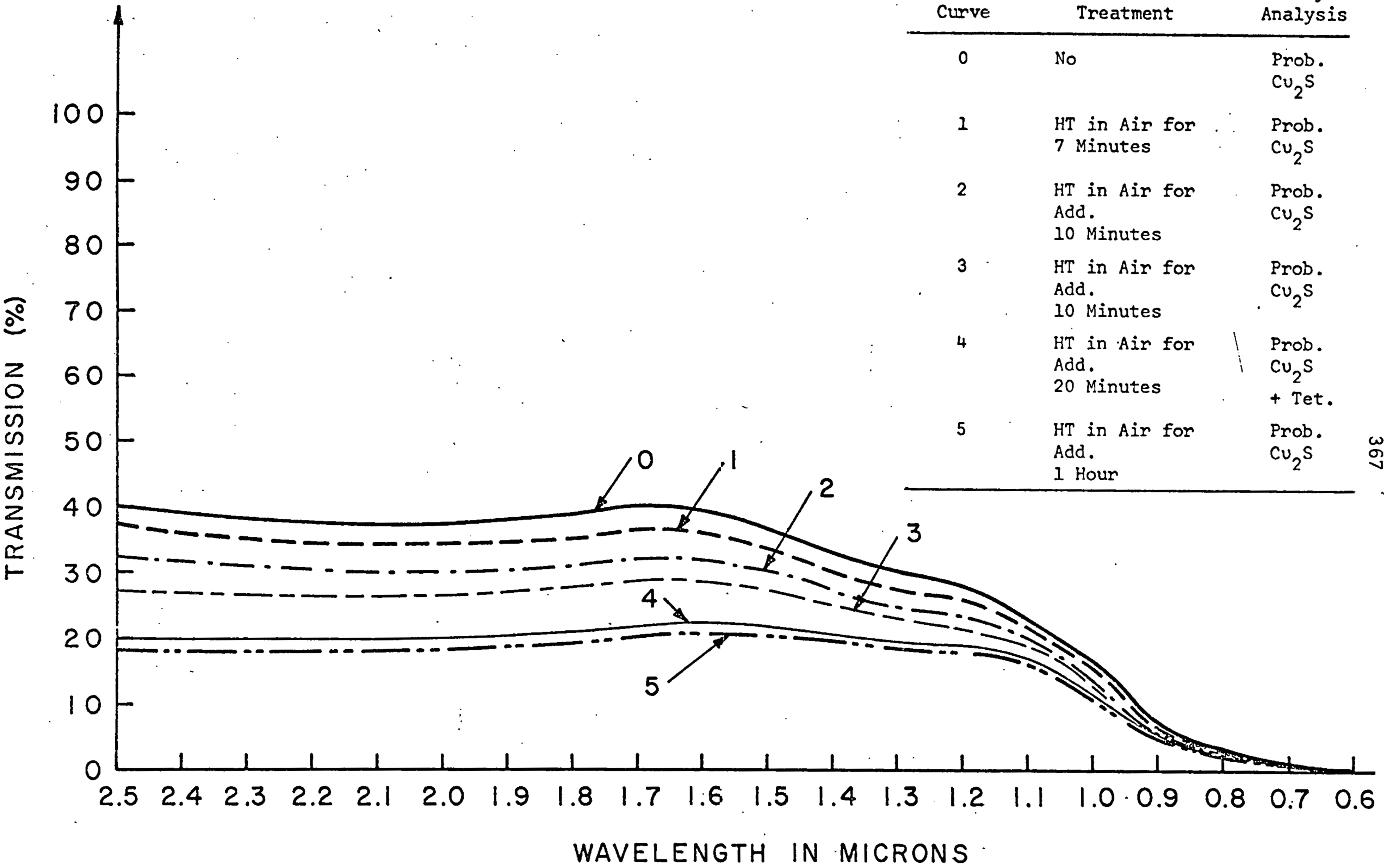


CATHODOLUMINESCENCE INTENSITY OF CHALCOCITE vs ρ. Figure 8



Cathocoluminescence spectra cf sulfurized chalcocite subjected to heat-treatment in air (Curve numbers can be referred to those of Figure 58)

Figure 9



SG 001

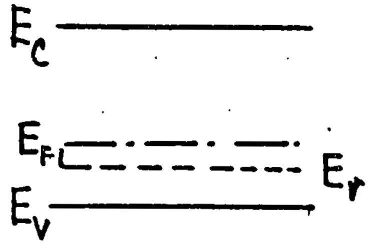
Curve	Treatment	X-Ray Analysis
0	No	Prob. Cu_2S
1	HT in Air for 7 Minutes	Prob. Cu_2S
2	HT in Air for Add. 10 Minutes	Prob. Cu_2S
3	HT in Air for Add. 10 Minutes	Prob. Cu_2S
4	HT in Air for Add. 20 Minutes	Prob. Cu_2S + Tet.
5	HT in Air for Add. 1 Hour	Prob. Cu_2S

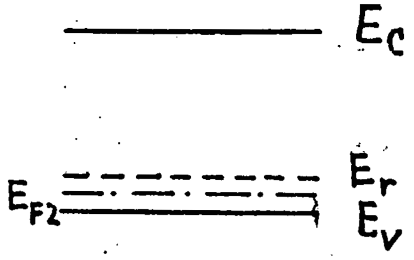
Figure 10

MODELS WHICH COULD ACCOUNT FOR $I_{CL}(\rho)$

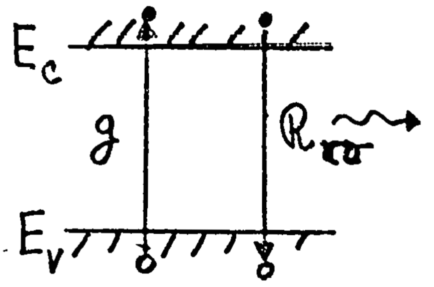
a) DIFFUSION LENGTH L CHANGES BECAUSE OCCUPANCY FACTOR $f(E_r - E_F)$ CHANGES

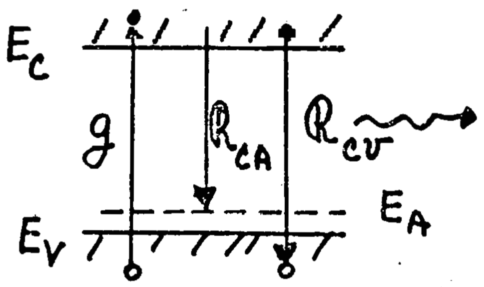
$$\frac{1}{\tau} = \sigma_c N_r v f(E_r - E_F)$$





b NEW RECOMBINATION PATHS ARE INTRODUCED WHEN ρ *decreases* i.e. N_A INCREASES





$$I \propto (R_{cv} - R_{CA}) \propto I_0(1 - kN_A) \propto I_0(1 - k'\sigma)$$

Figure 11

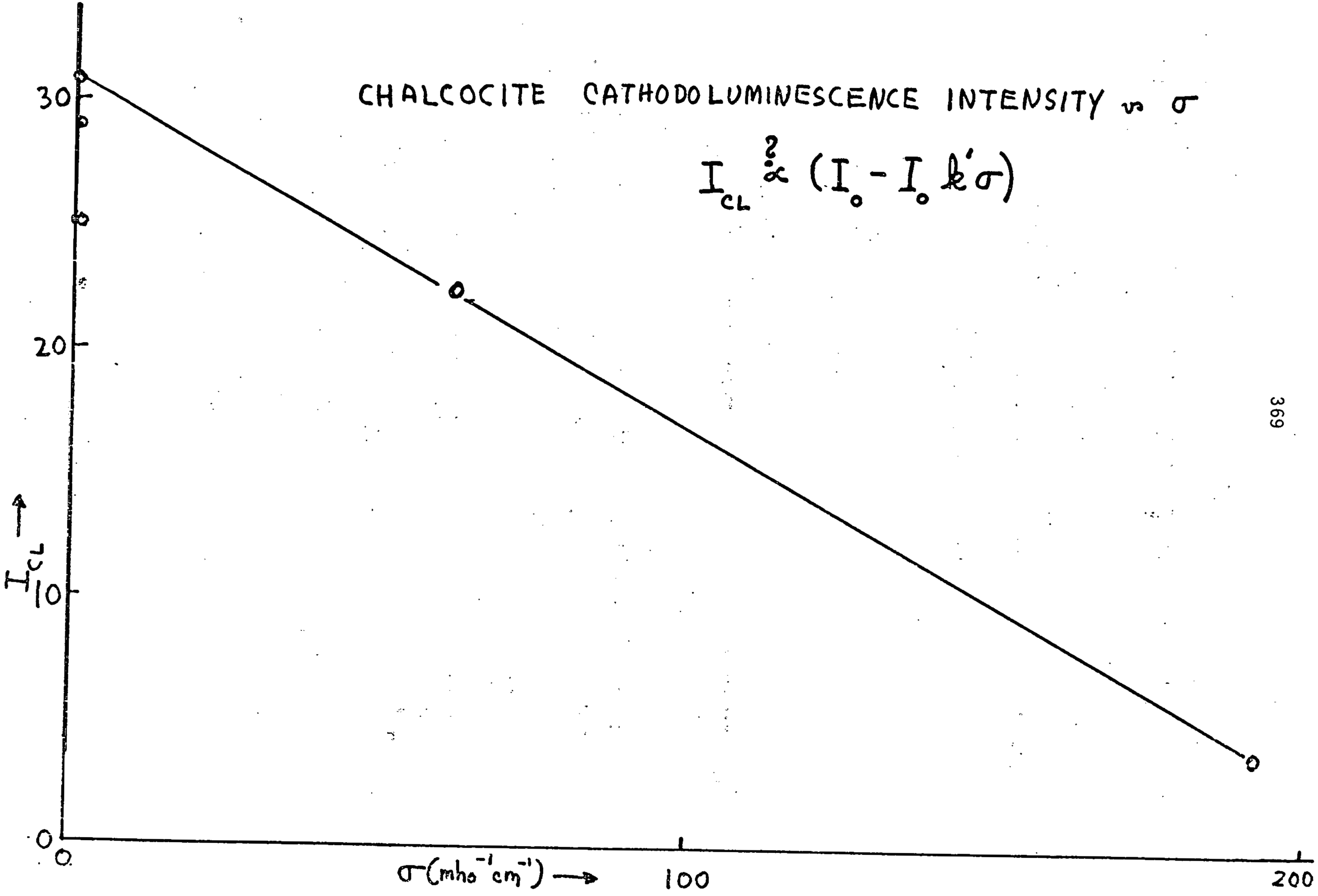
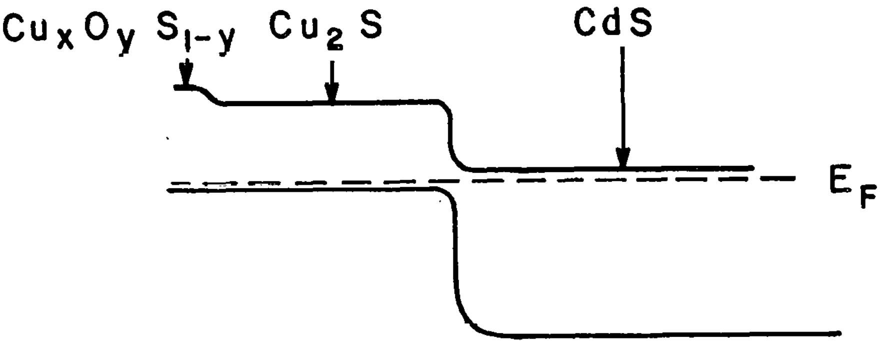
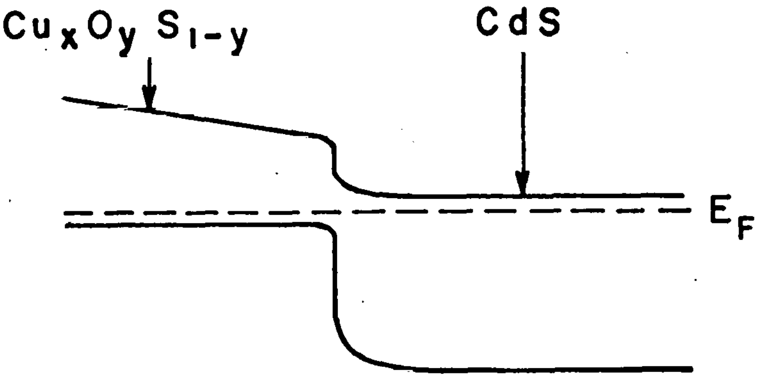

CHALCOCITE CATHODOLUMINESCENCE INTENSITY vs σ
$I_{CL} \overset{?}{\propto} (I_o - I_o k'\sigma)$
30
20
10
0
I_{CL} →
0
100
200
σ (mho⁻¹ cm⁻¹) →

Figure 12



A model of Cu_2S/CdS cells proposed to explain the increase in I_{sc} after copper-treatment in air

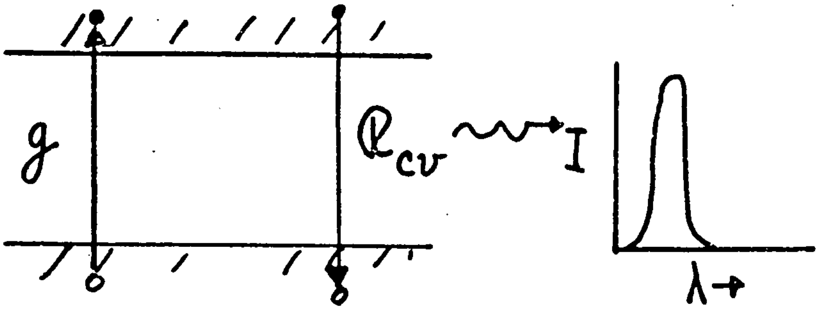


Second model of Cu_2S/CdS cells proposed to explain the increase in I_{sc} after copper-treatment in air

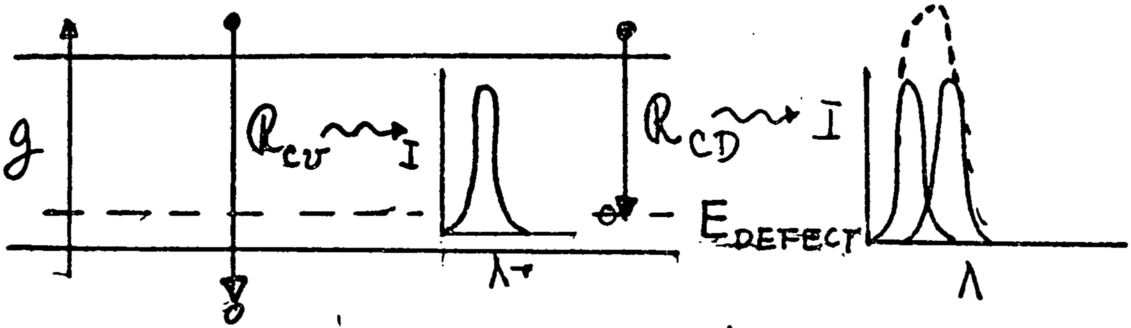
Figure 12a

MODEL WHICH COULD ACCOUNT FOR DIFFERENT CL BAND SHAPES OF "PURE" Cu_2S AND Cu_xS DERIVED FROM CdS

"PURE" Cu_2S



Cu_xS PRODUCED BY CHEMICAL SUBSTITION OF Cu^+ FOR Cd^{++}



DEFECT COULD BE Cd^{++}, Cl^+ etc OR STRUCTURAL DEFECT ARISING FROM LATTICE MISMATCH

Figure 13

KEY RESULTS

- CATHODOLUMINESCENCE (CL) PROVIDES A POWERFUL TOOL FOR STUDYING IMPORTANT PROPERTIES AND PHENOMENA IN THIN FILMS USED IN SOLAR CELLS

- COMPARISON OF Cu-Cd-S CELLS IN WHICH Cu_xS LAYER IS PRODUCED BY VARIOUS METHODS SHOWS THAT EVEN THOUGH SULFURIZED FILMS ARE "PUREST" CHALCOCITE THEY DO NOT PRODUCE BEST SOLAR CELLS

- p-CHALCOCITE/n-Si CELLS WITH $\eta_{max} \sim 4\%$ ($0.5 cm^2$) HAVE BEEN FABRICATED. THIS HETEROSTRUCTURE COULD BE USEFUL FOR THIN FILM Si CELLS

- GOOD QUALITY $CuInS_2$ CRYSTALS HAVE BEEN GROWN BY BRIDGMAN AND VAPOR PHASE TRANSPORT METHODS

PROPOSED FUTURE WORK

- COMPLETE CL STUDIES OF CHALCOCITE TO ESTABLISH CORELATIONS WITH DOPING IMPURITIES, Cu VACANCIES, ETC. AND τ, σ, N_A AND N_r. EXTEND OBSERVATIONS TO HE TEMPERATURE
- COMPLETE ASSESSMENT OF p-Cu_2S/n-Si CELL
- EXPLORE HIGH η Cu-Cd-S CELLS PRODUCED BY PHILIPS PROSESS ON "HIGH QUALITY" EPI-CdS CRYSTALS
- CONTINUE WORK ON $CuInS_2$ SOLAR CELLS

FUNDING LEVEL: ~$90,000/annum

TERNARY COMPOUND THIN FILM SOLAR CELLS

NSF/RANN Grant AER 75-19576

Period of Grant: September 1, 1975 - August 31, 1976

Value: $34,900

Renewal: September 1, 1976

Value: $80,000

Lawrence L. Kazmerski
Principal Investigator
Department of Electrical Engineering
University of Maine at Orono
Orono, Maine 04473

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

ABSTRACT

The purpose of this program is the investigation of ternary (I-III-VI_2) semiconductor thin films and the application of these compounds in photovoltaic devices. The specific objectives have included: (1) The growth and characterization of the ternary thin films, giving priority to $CuInS_2$, $CuInSe_2$ and $CuInTe_2$ because of their suitable properties;[1] (2) The demonstration of homojunction viability for $CuInS_2$ thin films; and, (3) The demonstration of heterojunction viability for $CuInX_2$ (X = S, Se and Te) with other semiconductors.

The activity-to-date for this program is summarized in the accompanying figures. This activity has centered around the growth and characterization of the three ternary compounds, the study of defects in the chalcopyrite system, the first demonstration of a $CuInS_2$ homojunction, the continued characterization of the $CuInSe_2$/CdS heterojunction and the investigation of several other heterojunctions (e.g. $CuInS_2$ on Si). The primary results with respect to device work have focused on the $CuInS_2$ homojunction and $CuInSe_2$/CdS heterojunction. The first thin film $CuInS_2$ photovoltaic junction has been produced with a 1.07% efficiency, and is shown in Fig. 7. This structure was grown completely in-situ with the p-layer grown first. This was accomplished by controlling the sulfur partial pressure in the system using a two source technique.[2] A p-type film occurs if the material is not sulfur deficient.

Two types of $CuInSe_2$/CdS heterostructures have been produced.[3] The Mode I device is illuminated through the ternary, and the Mode II device, through the CdS. The light characteristics for the "best" of each of these

devices is shown in Fig. 8 (i.e. Mode I: 4.%, Mode II: 5.7%). The spectral response of a typical device has been included in Fig. 9, showing two cutoff regions associated with the CdS ($\lambda = 0.58\mu$) and $CuInSe_2$ ($\lambda = 1.28\mu$) respectively.[3]

An Auger analysis of the junctions has been performed to determine failure modes. Fig. 11 shows a depth profile of a good junction, indicating an abrupt change from CdS to $CuInSe_2$. Fig. 12, however, shows a junction which has been annealed at 400°C for 2 hours. The diffusion of the Cd into the $CuInSe_2$ is apparent, but little diffusion of Cu into CdS can be noticed. The Cd problem had been predicted[4], and it appears that the chalcopyrite lattice does hold the Cu sufficiently tight at least for this treatment.

The major problem to-date is the control of ternary film stoichiometry. This has a significant effect on device production and performance. This problem is to receive primary attention over the next 6 months. The Cd diffusion problem will undergo further investigation.

The key results for this reporting period include:

(1) Thin Films:
  a. Photoconductivity Measurements (Figs. 1-3)
  b. Auger Analyses (Figs. 11, 12)
  c. $CuInTe_2$ growth, characterization
  d. Defects Studies (Figs. 4-6)

(2) Devices:
  a. $CuInSe_2$/CdS Thin Film Heterojunction, 5.7%(Figs. 8-10)
  b. Auger Analyses (Figs. 11, 12)
  c. $CuInS_2$ Thin Film Homojunction, 1.07%(Figs. 7, 7a)
  d. Other Heterojunctions (e.g. $CuInS_2$ films on single crystal silicon) (Fig. 13)

[1] See, for example, L.L. Kazmerski (Ed) "Ternary Compound Thin Film Solar Cells" First Quarter Report, NSF-RA-N-75-232, January, 1976.

[2] L.L. Kazmerski, M.S. Ayyagari and G.A. Sanborn, J. Appl. Phys. 46, 4865 (1975).

[3] L.L. Kazmerski, F.R. White and G.K. Morgan, "Thin Film $CuInSe_2$/CdS Heterojunction Solar Cells". To appear Appl. Phys. Lett. (August 15, 1976).

[4] B. Tell, S. Wagner and P.M. Bridenbaugh, Appl. Phys. Lett. 28, 454 (1976).

OBJECTIVES

1. The Growth and Characterization of Ternary Compound Thin Films - Emphasizing $CuInS_2$, $CuInSe_2$ and $CuInTe_2$.
2. Demonstration of Homojunction Viability for $CuInS_2$ Thin Film Solar Cells.
3. Demonstration of Heterojunction Viability for $CuInX_2$ (X = S, Se and Te) With Other Semiconductors. (e.g. Thin Film $CuInSe_2$/CdS Solar Cell.)

ACTIVITY-TO-DATE

PLANNED ACTIVITY	PROGRESS
1. $CuInS_2$ Thin Films	
a. Thin Film Growth	a. n,p type films on glass, metals (Au,Al,Pt), carbon, NaCl
b. Identification, Structural Characterization	b. X-ray diffraction, electron diffraction, Auger Electron Spectroscopy (Crystallography, Grain Size Data, preferred growth, orientations
c. Electrical Characterization	c. Measurement of μ, σ, n Temperature dependences Photoconductivity, Spectral Response Photoconductive decay times Energy Gap Dependence on Temperature
d. Recrystallization, Annealing	d. Grain growth data: Argon, Nitrogen, H_2S Atmospheres Carrier type changes on annealing
2. $CuInS_2$ Homojunction Solar Cell	
a. Diode Growth and Characterization	a. In-situ and anneal-produced diodes (iv characteristics)
b. Photovoltaic Demonstration	b. Initial production of thin film (n on p) $CuInS_2$ Device (characterization)
	c. Auger Analysis of Device
3. $CuInSe_2$ Thin Films	
a. Thin Film Growth	a. n-type (as grown) on glass, Au, Pt, Carbon, NaCl
b. Identification, Structural Characterization	b. X-ray diffraction, electron diffraction, TEM, Auger Investigations (Grain size data, preferred growth, orientations, defects)
c. Electrical Characterization	c. Measurement of μ, σ, n;Temperature dependences; Photoconductive decay data; Energy Gap Dependence on Temperature Photoconductivity; Spectral Response
d. Recrystallization	d. Argon and H_2Se atmospheres Carrier type changes ($n \rightarrow p$)

4. CuInSe$_2$/CdS Heterojunction	
a. Junction Demonstration	a. Mode I: CuInSe$_2$/CdS Mode II: CdS/CuInSe$_2$ (Electrical Characterization in Dark and Light)
	b. Auger Analysis of Device
	c. Consideration and Demonstration of Possible Device Problems
	d. Spectral Response Measurement
5. Other Heterojunctions	a. n-CuInSe$_2$ (Film) on p-Si (Single Crystal
	b. n-CuInSe$_2$ (Film) on p-Si(polycrystalline
	c. n-CuInS$_2$ (Film) on p-Si (Single Crystal)
	d. p-CuInS$_2$ (Film) on n-Si (Single Crystal)
	e. n-CuInTe$_2$ (Film) on p-Si (Single Crystal
6. CuInTe$_2$ Thin Films	
a. Growth and Characterization	a. Growth on Glass, Carbon (n-type), Contacts Measurement of μ, σ, n Temperature Dependence of Electrical Properties Electron Diffraction, X-ray Diffraction Analyses, Auger
	b. Photoconductivity Measurements Spectral Response Data Energy Gap (Temperature Dependence)
7. Defects	
a. Categorization of Defects in Chalcopyrite System	a. Dislocations, Stacking Faults, Grain Boundaries Observation under TEM

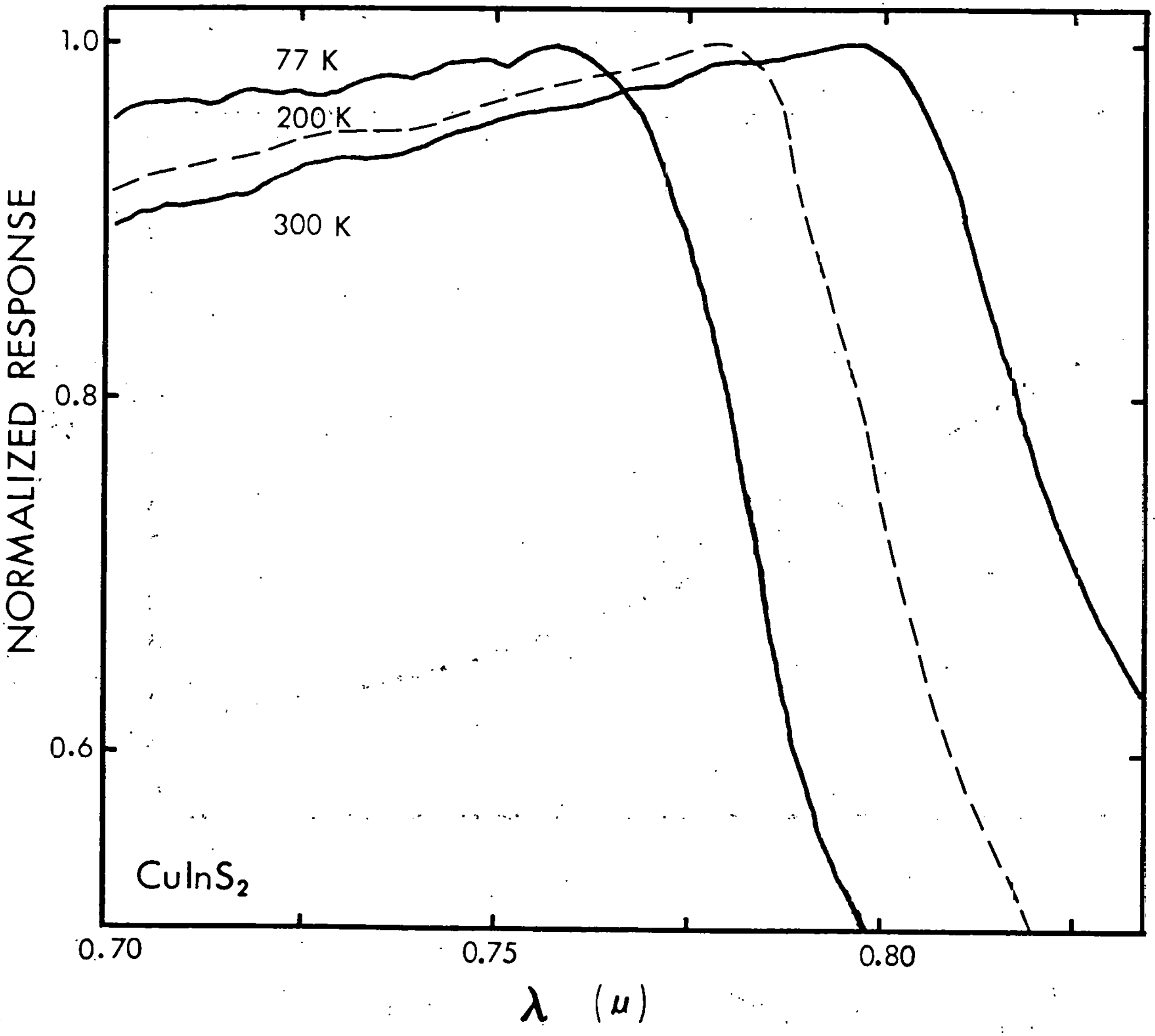


Fig. 1 Spectral Response Characteristics for CuInS$_2$ Film.

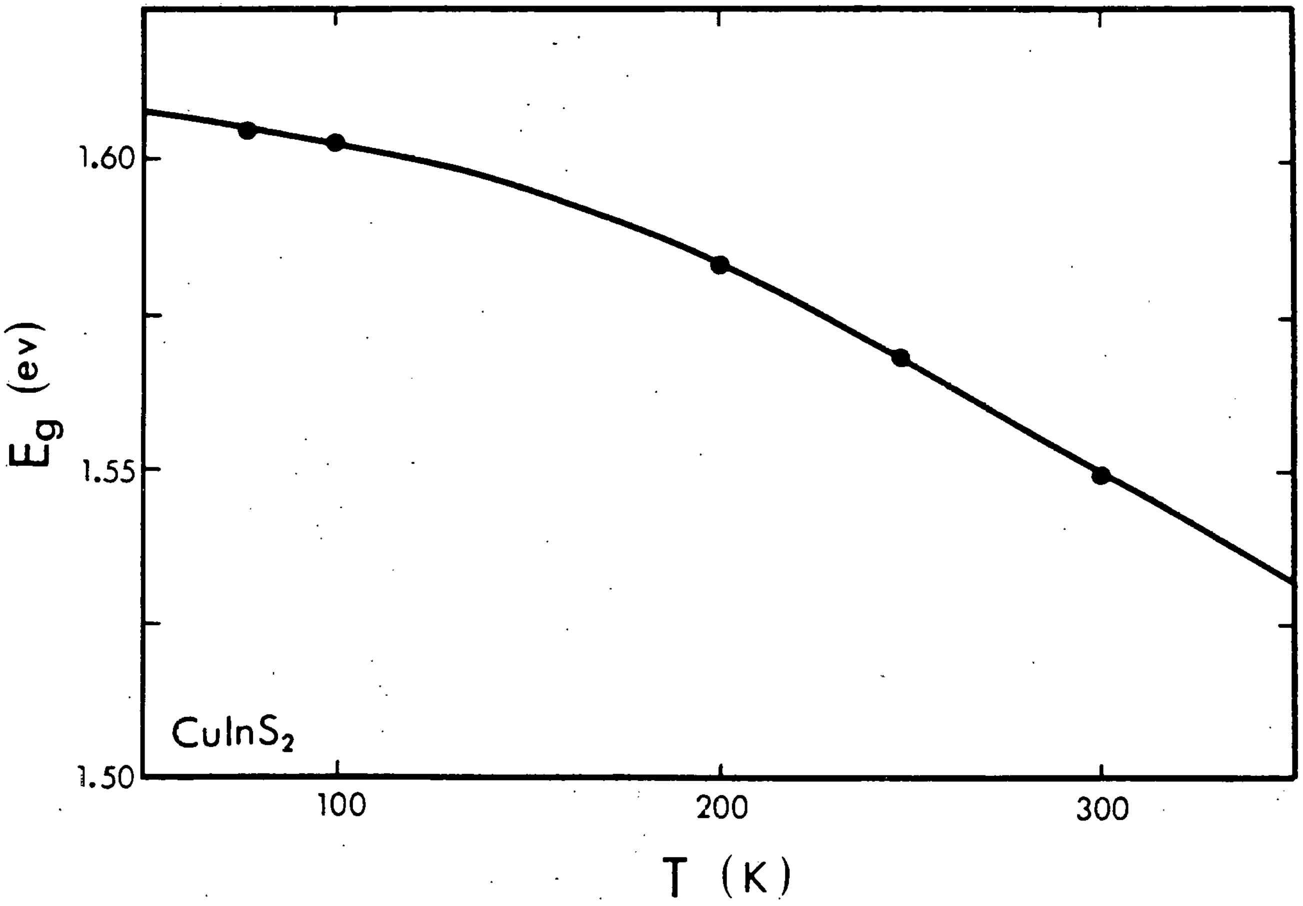


Fig. 2 Experimental Dependence of Energy Gap on Film Temperature.

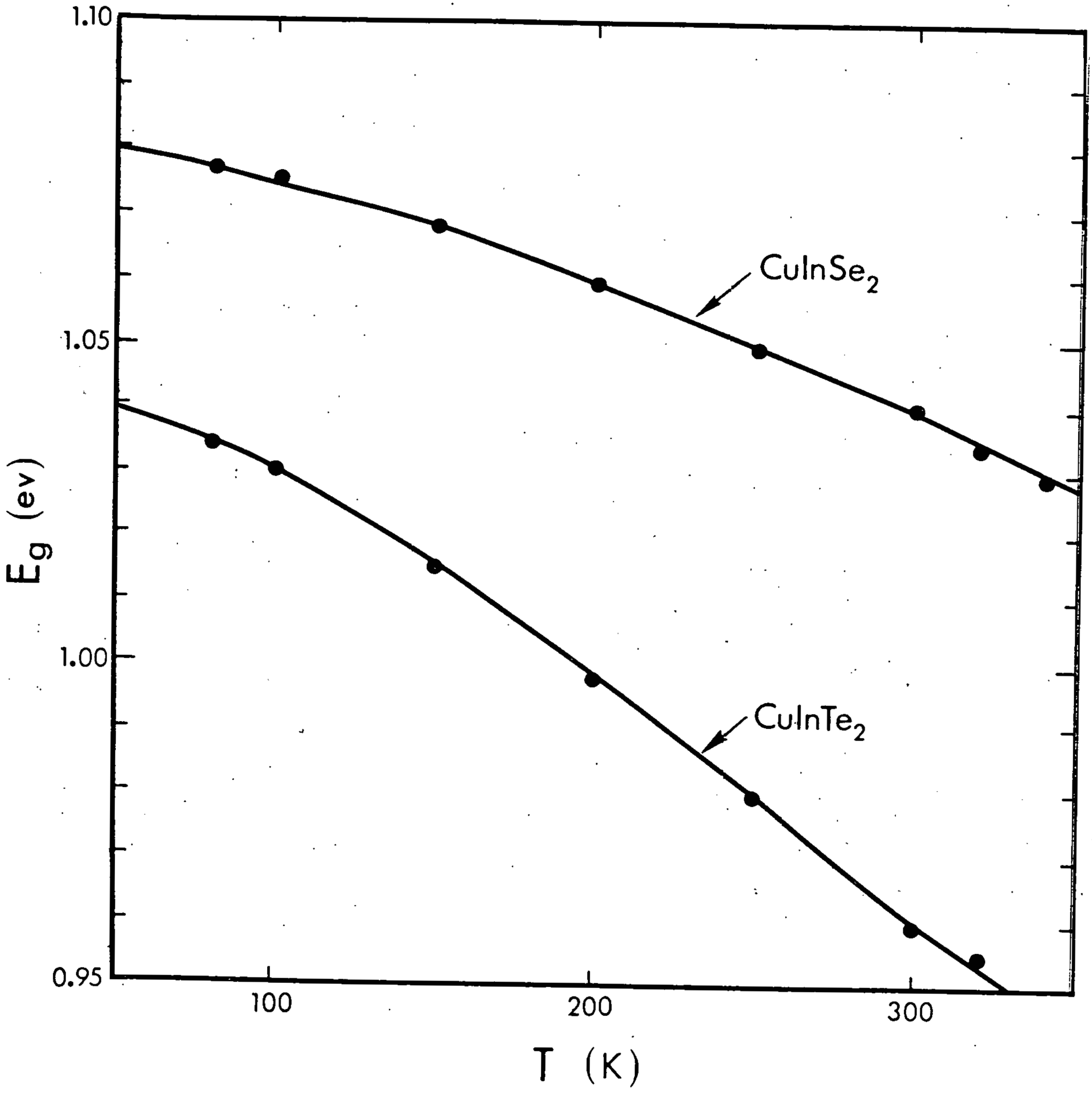


Fig. 3 Experimental Dependence of Energy Gap on Film Temperature.

Table I. Comparison of Various Energy Gap Parameters for Ternary Compound Thin Films.

	$CuInS_2$	$CuInSe_2$	$CuInTe_2$
$E_{g_{300K}}$ (eV)	1.55	1.04	0.96
E_{go} (eV)	1.62	1.08	1.05
β (eV/K)	4.3×10^{-4}	$(2.39 \times 10^{-4})^a$ $(1.5 \times 10^{-4})^b$	$(4.6 \times 10^{-4})^a$ $(3.2 \times 10^{-4})^b$
α (K)	231.54	201.98	185.78

a. Measured, This Study.

b. Single Crystal Value. See Ref. 13.

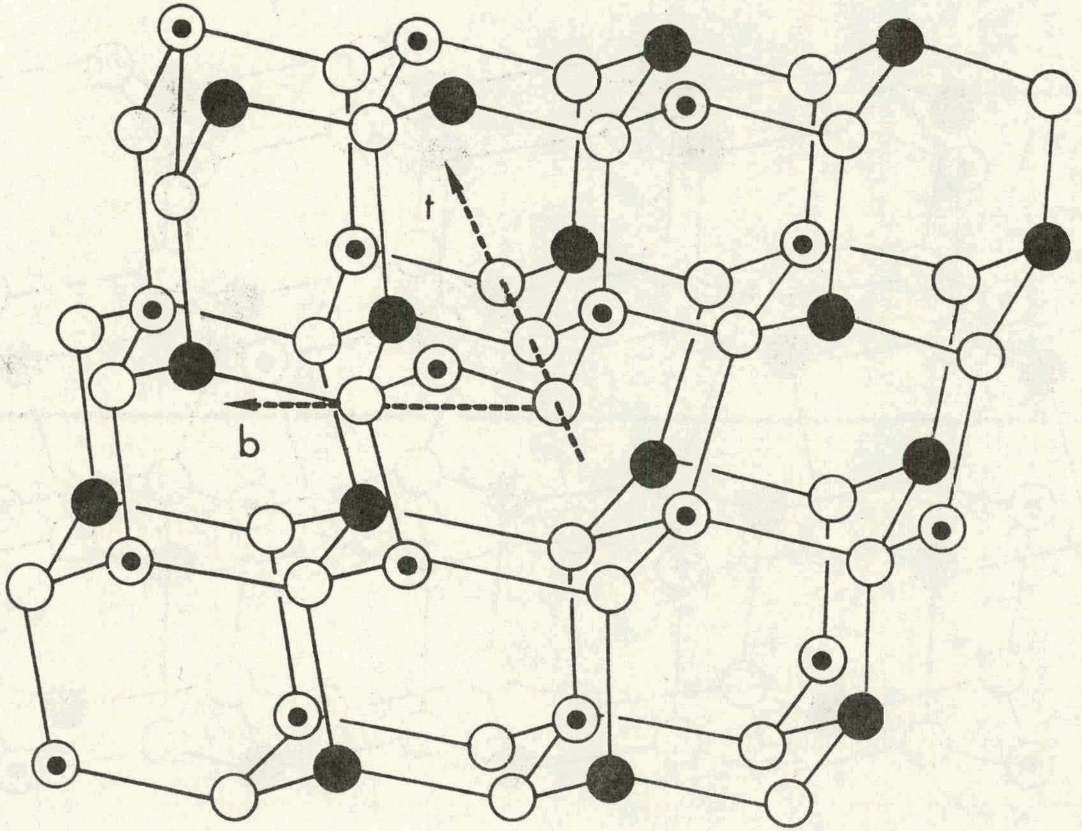


Fig. 4 Edge Dislocation in Chalcopyrite Lattice, β form.

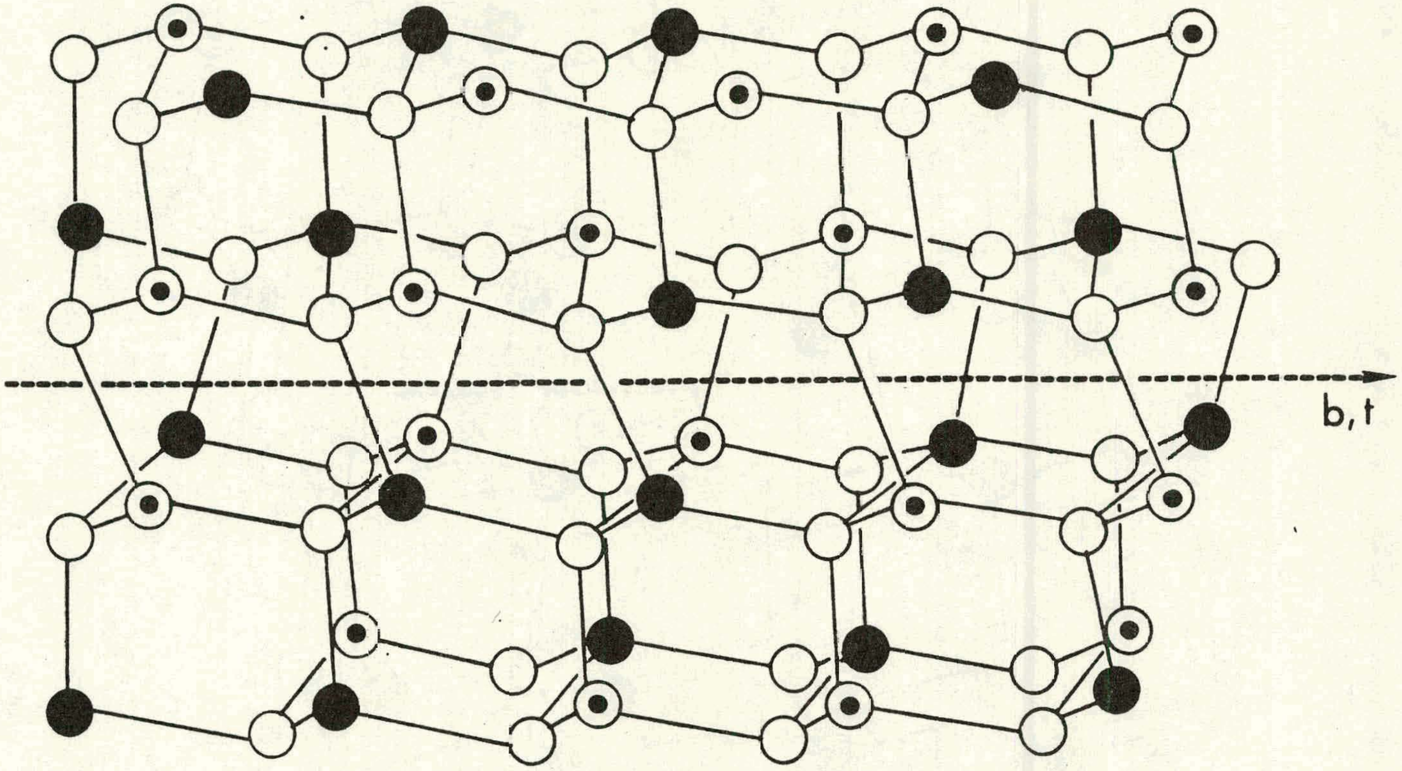


Fig. 5 Screw Dislocation in Chalcopyrite Lattice (Right-Handed).

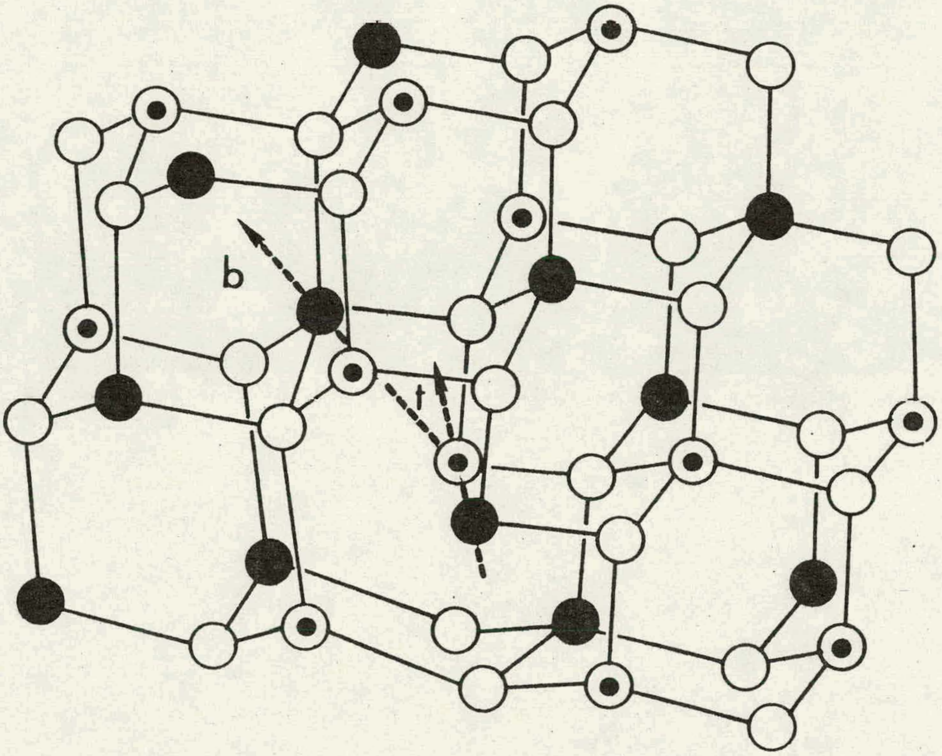


Fig. 6 60° Dislocation in Chalcopyrite Lattice.

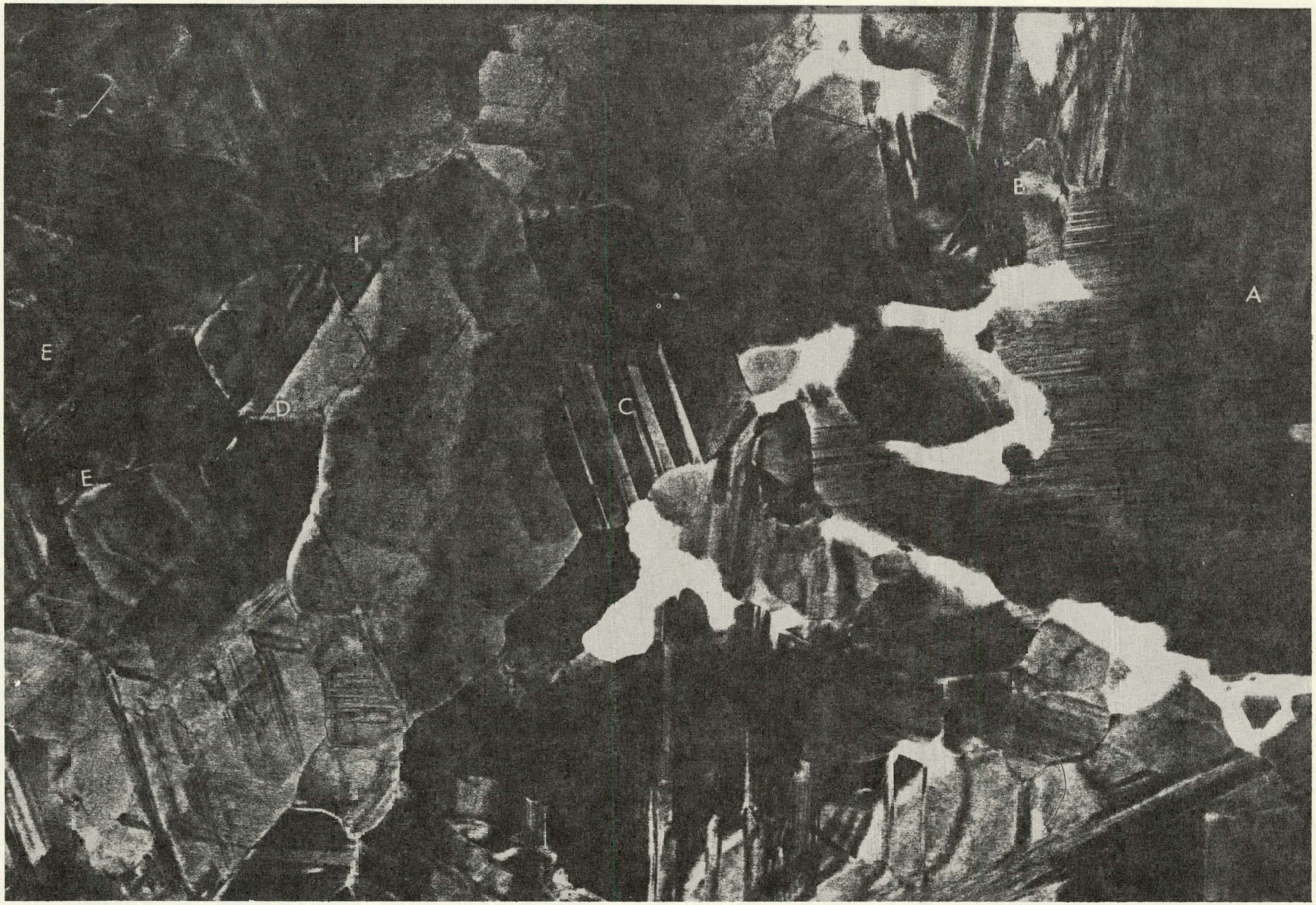
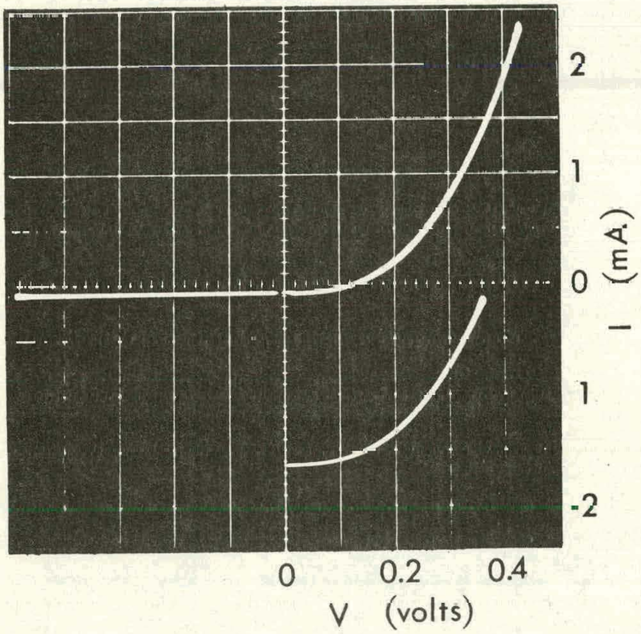


Fig. 5a. CuInS$_2$ Sample, Illustrating Several Defects.

Table II. Summary of Dislocation Types and Associated Dislocation Parameters for the Chalcopyrite Lattice. The Burger's Vectors for These are b = $\frac{1}{2}$ ⟨20⟩⟨ 1⟩ and b = $\frac{1}{2}$ ⟨11 ⟩⟨0⟩.

TYPE		ANGLE: $\bar{b}$ & $\bar{t}$	$\bar{t}$	SLIP PLANE	COMMENTS	NOTATION:
EDGE	(a)	90°	⟨11 ⟩⟨ 0⟩ ⟨20 ⟩ 1⟩	{100 }	2 forms each of α & β forms	⟨ab ⟩⟨c⟩ indicates the following directions: $[abc]$, $[\bar{a}bc]$ $[\bar{a}\bar{b}c]$, $[a\bar{b}c]$, $[ab\bar{c}]$, $[\bar{a}b\bar{c}]$, $[\bar{a}\bar{b}\bar{c}]$, $[a\bar{b}\bar{c}]$, {ab} {c} indicates the following plane (abc), $(\bar{a}bc)$ $(\bar{a}\bar{b}c)$, $(a\bar{b}c)$ $(ab\bar{c})$, $(\bar{a}b\bar{c})$ $(\bar{a}\bar{b}\bar{c})$, $(a\bar{b}\bar{c})$
	(b)	90°	⟨111⟩ ; ⟨42 ⟩⟨ 1⟩	{11} { 2 }	α , β forms exist	
	(c)	90°	⟨100⟩	{11} {0}; {10} { 2 }	2 forms, but no α , β forms exist	
SCREW		0°	⟨11 ⟩⟨ 0 ⟩ ; ⟨20⟩⟨ 1⟩	No definite slip plane	4 geometrically distinct distinct forms exist	
MIXED		60° dislocation	⟨11 ⟩⟨ 0⟩ ; ⟨20⟩⟨ 1⟩	{11} { 2}	2 forms each of α and β forms exist	
		45° dislocation	⟨100⟩	{100}	2 geometrically distinct structures exist. Each has an α , β form	
		30° dislocation	⟨111⟩ ; ⟨42 ⟩⟨ 1⟩	{11 }{ 2 }	3 geometrically different forms exist	
		73° 13' dislocation	⟨111⟩ ; ⟨42⟩⟨ 1⟩	{31}{ 2 } ; {11 } { 6 }	α , β forms exist	
		54° 44' dislocation	⟨111⟩ ; ⟨42 ⟩⟨ 1⟩	{11 }{ 0 } ; {10 }{ 2 }	α , β forms exist	



n,p CuInS$_2$ THIN FILM HOMO-JUNCTION

V_{oc} = 0.34 v

I_{sc} = 1.39 mA

FF = 0.29

A = 0.124 cm^2

η = 1.07 %

Fig. 7 Thin Film CuInS$_2$ Homojunction. Illumination if Tungsten - Halogen, 100 mW/cm^2.

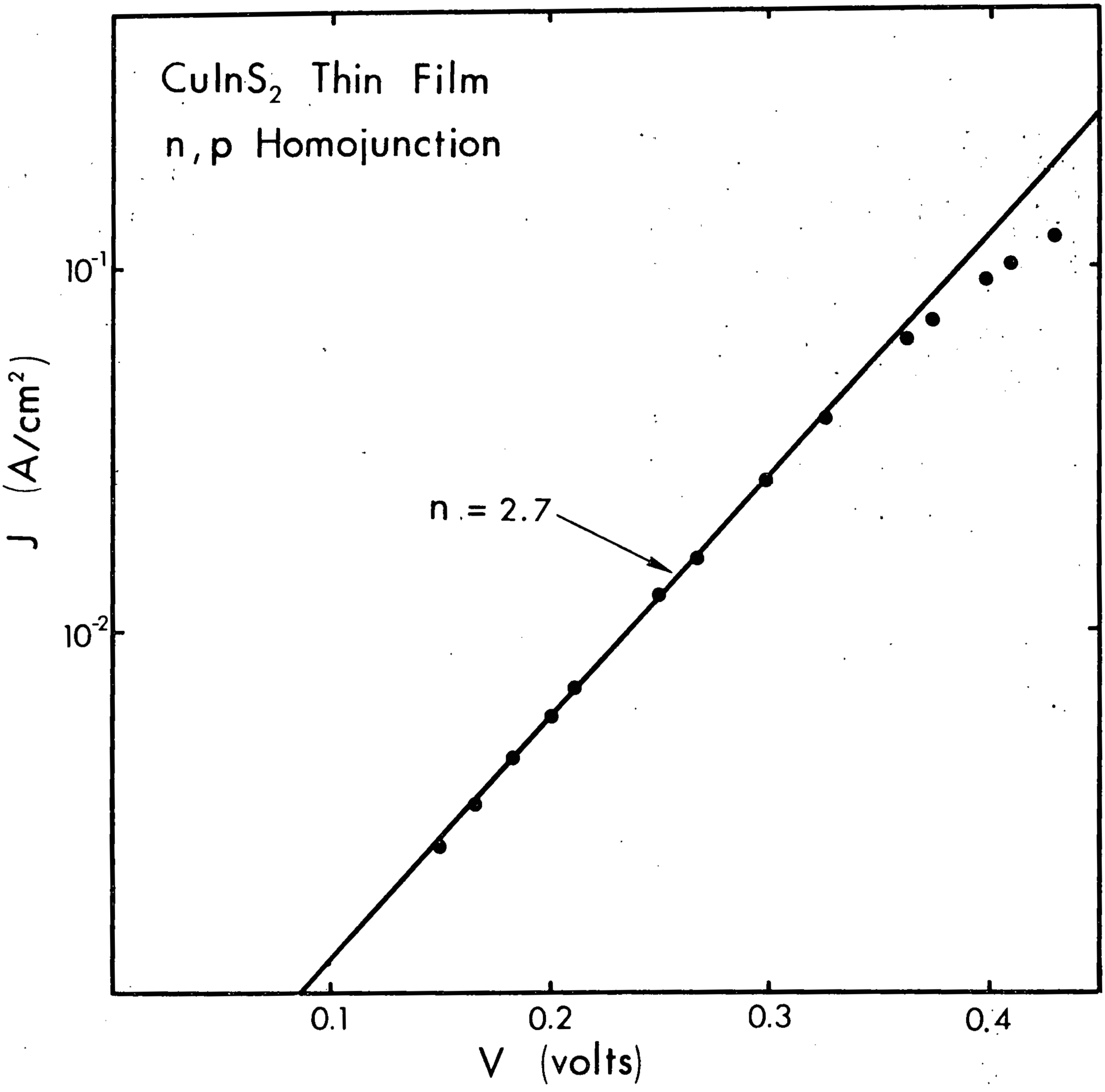

CuInS$_2$ Thin Film
n, p Homojunction
n = 2.7
10^{-1}
10^{-2}
J (A/cm^2)
0.1
0.2
0.3
0.4
V (volts)

Fig. 7a

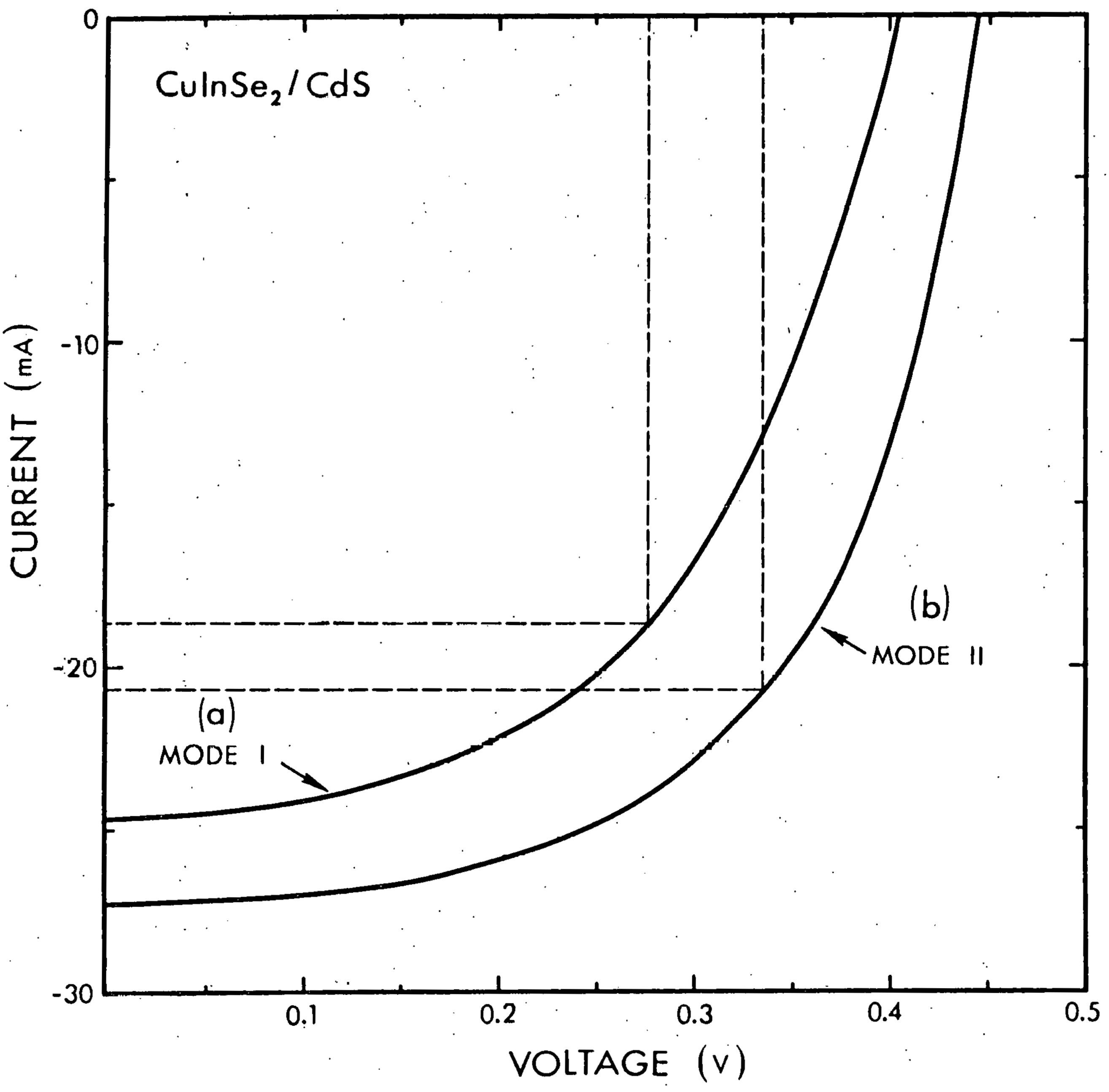


Fig. 8 Comparison of Devices in: (a) Mode I, and (b) Mode II Opera s.

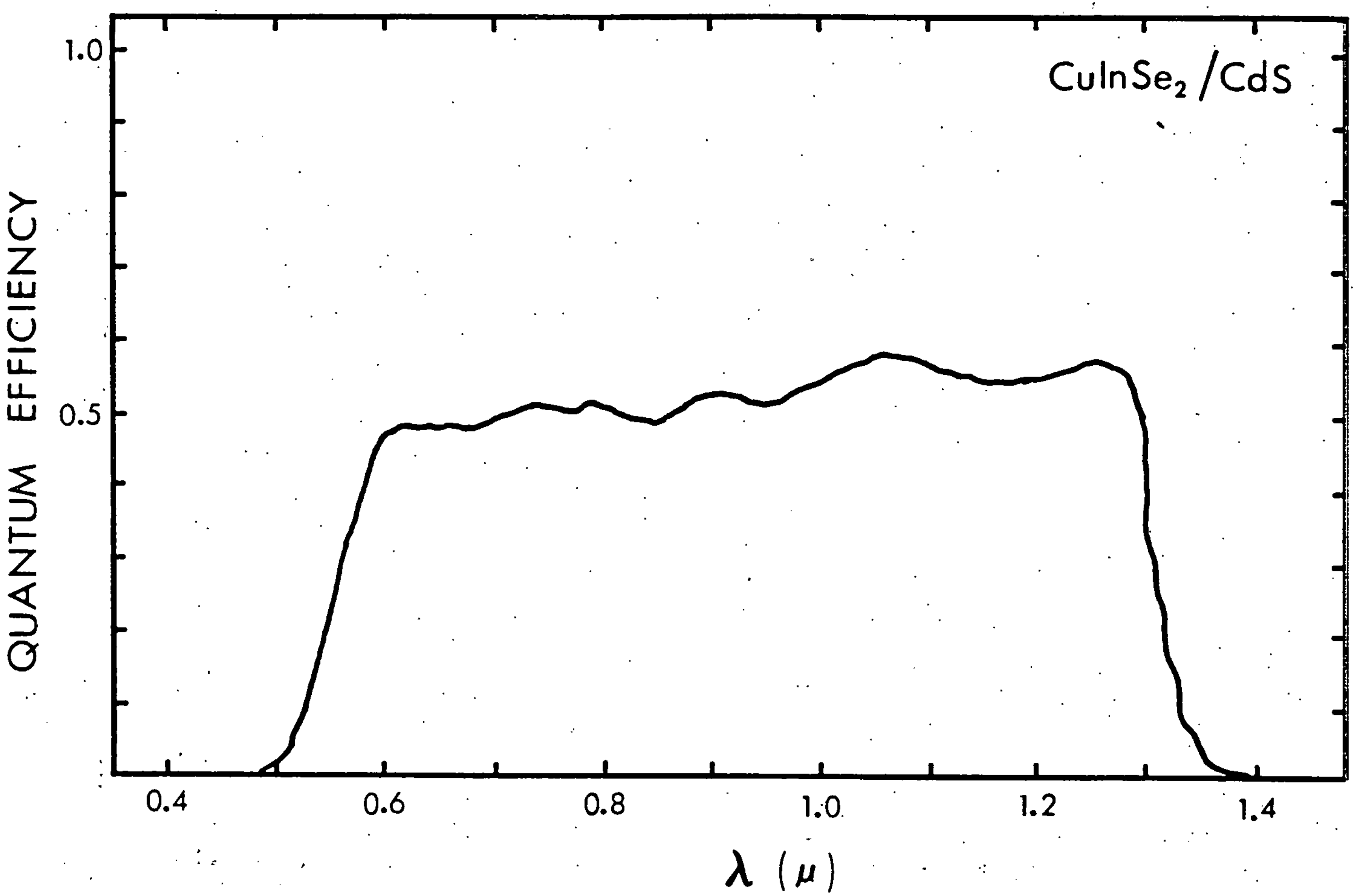


Fig. 9 Spectral Response Characteristics for CuInSe$_2$/CdS Heterojunction.

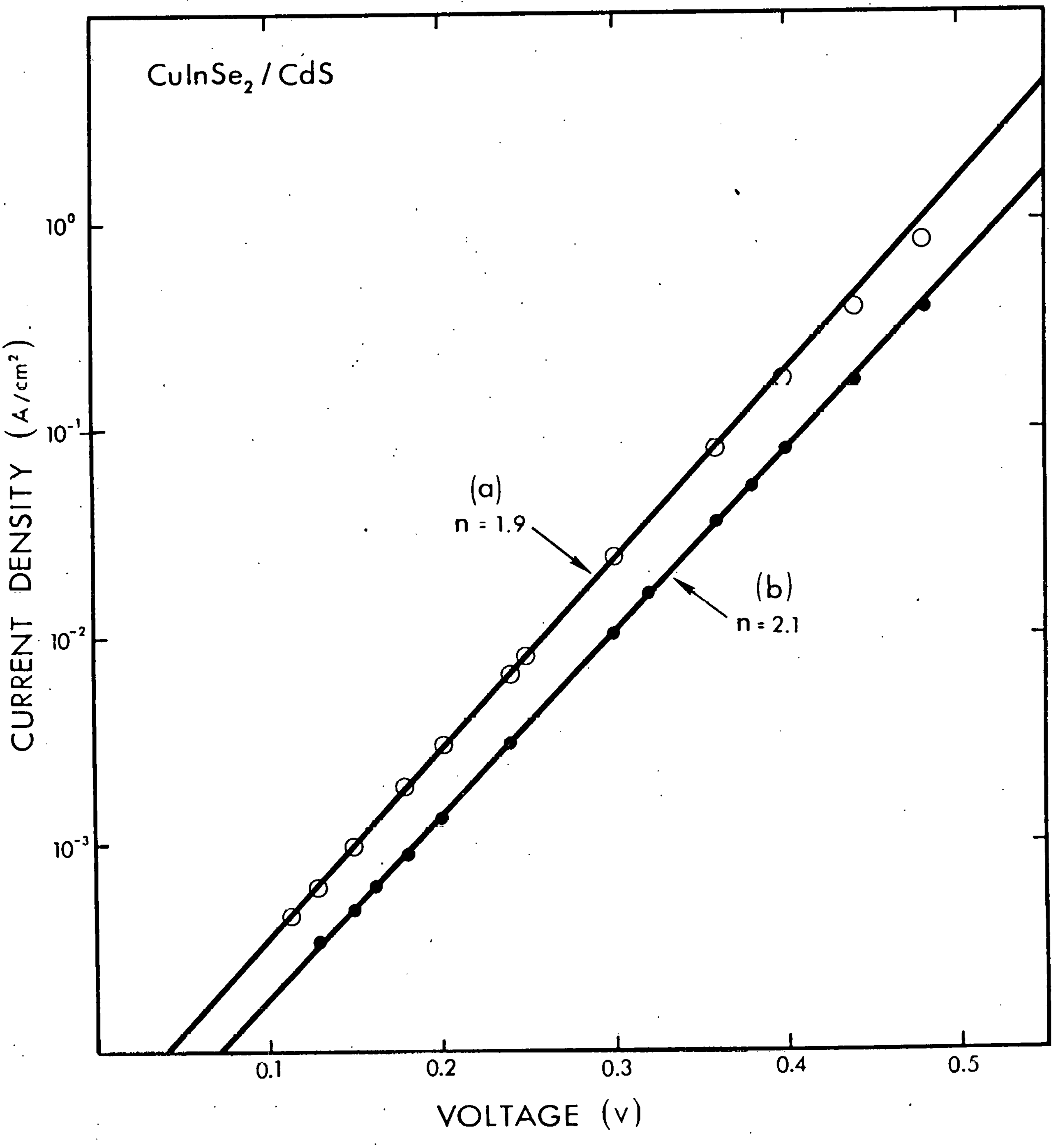


Fig. 10 Forward Characteristics of CuInSe$_2$ Diodes. (a) Etched and (b) In-Sit Junctions.

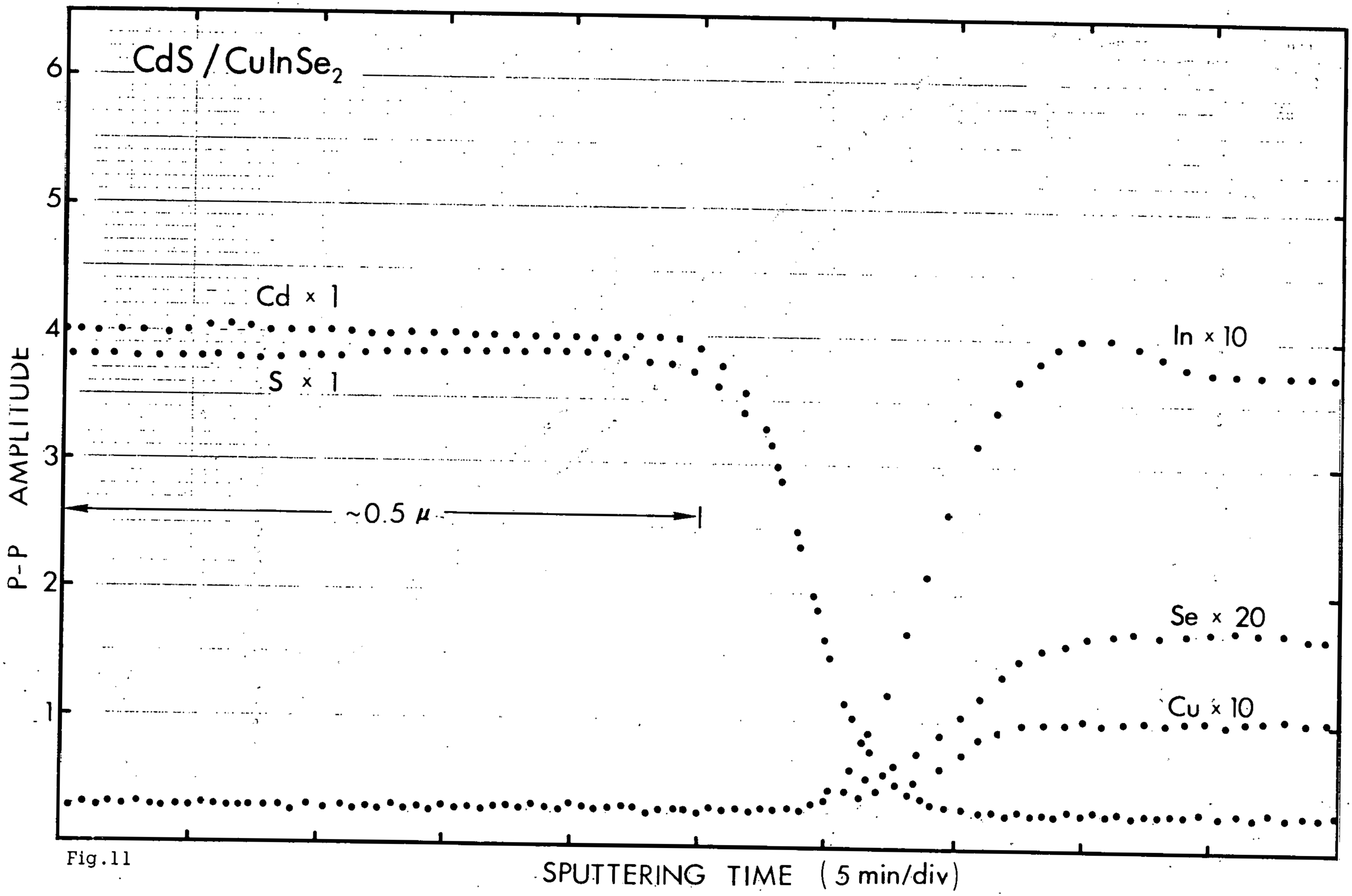

CdS / CuInSe$_2$
Cd × 1
S × 1
In × 10
Se × 20
Cu × 10
~0.5 μ
P-P AMPLITUDE
6
5
4
3
2
1
SPUTTERING TIME (5 min/div)

Fig.11

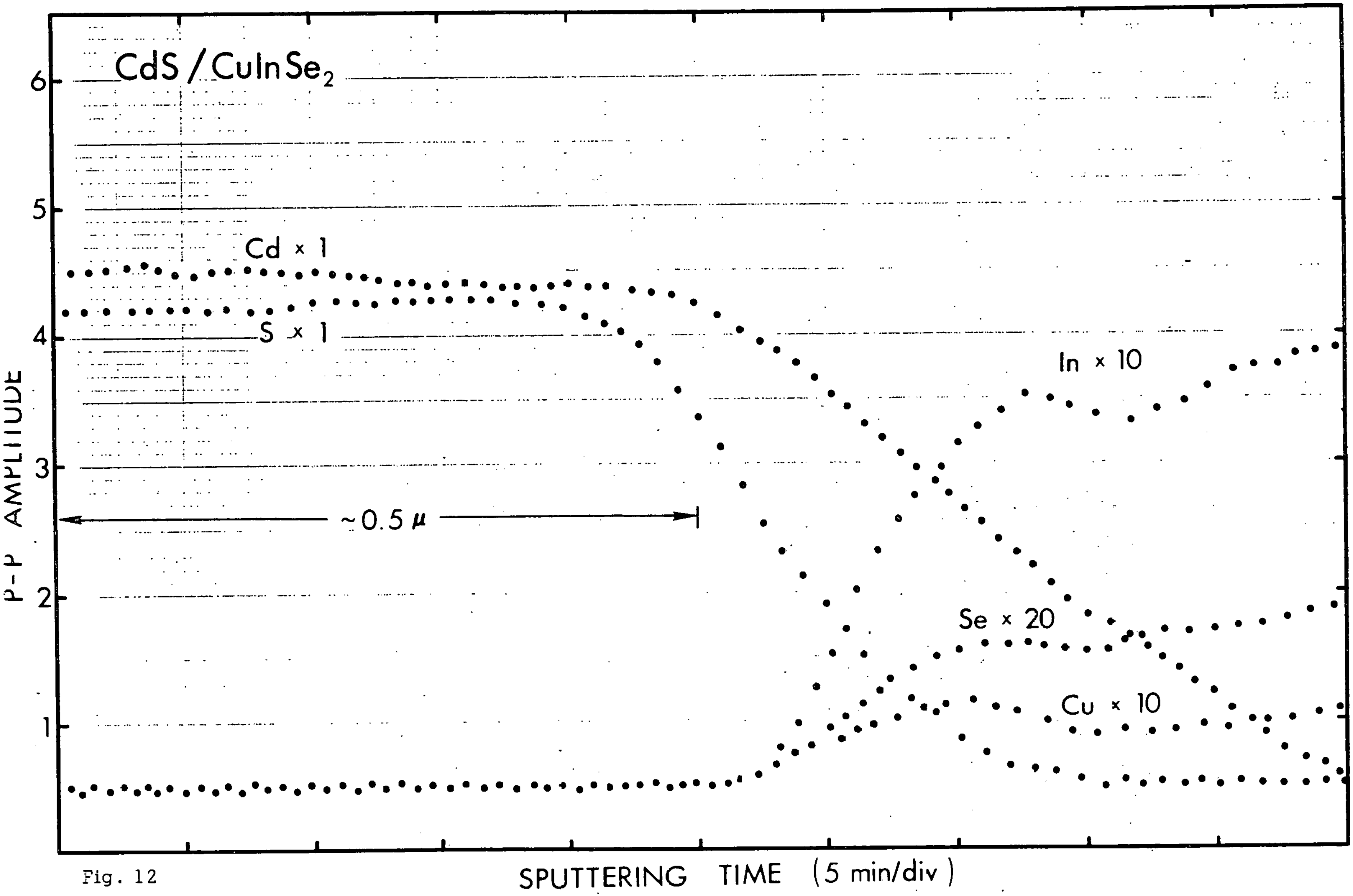
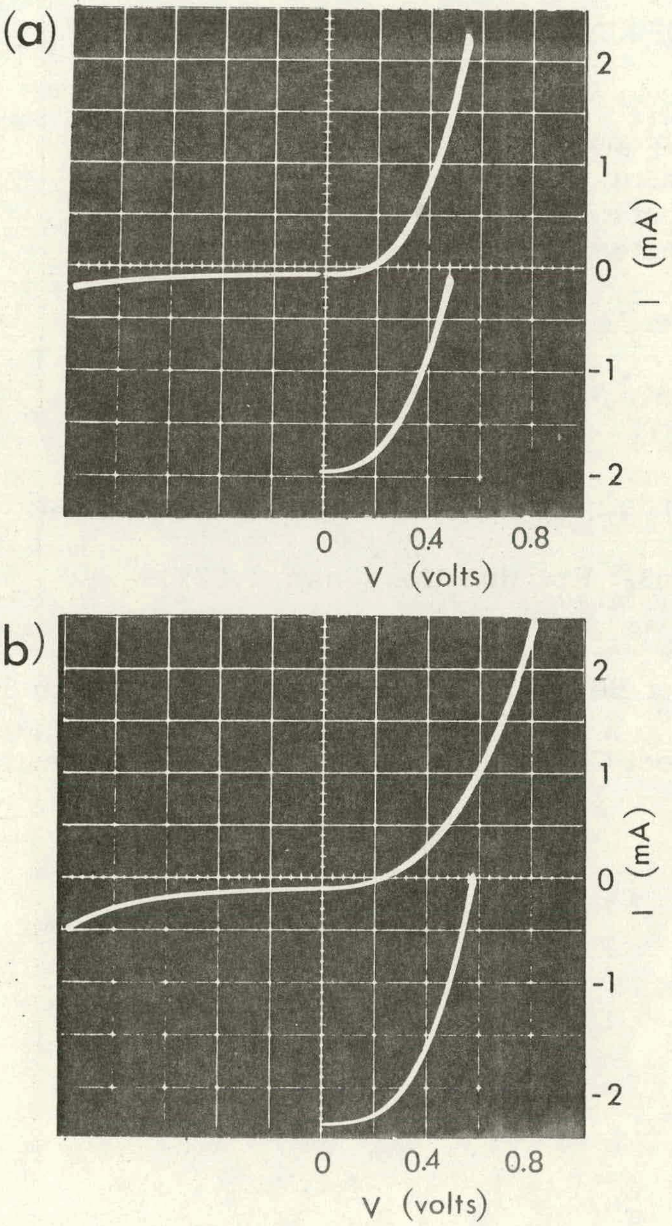

CdS / CuInSe$_2$
P-P AMPLITUDE
6
5
4
3
2
1
Cd × 1
S × 1
In × 10
Se × 20
Cu × 10
~0.5 μ
SPUTTERING TIME (5 min/div)

Fig. 12



(a) n-$CuInS_2$ (FILM)/p-Si (CRYSTAL)

V_{oc} = 0.48 v

I_{sc} = 1.96 mA

FF = 0.38

A = 0.124 cm^2

η = 2.88 %

(b) n-$CuInS_2$ (FILM)/p-Si (CRYSTAL)

V_{oc} = 0.57 v

I_{sc} = 2.34 mA

FF = 0.46

A = 0.124 cm^2

η = 4.95 %

Fig. 13 $CuInS_2$/Si Heterojunctions. (a) As-Grown Device, (b) Annealed Device.

SUMMARY OF KEY RESULTS

1. Thin Films:
    - a. Photoconductivity Measurements
        - Energy Gap Dependences on Temperature
        - Spectral Response
        - Photoconductive Decay
    - b. Auger Analyses
    - c. $CuInTe_2$ Film Growth, Characterization
2. Devices:
    - a. $CuInSe_2$/CdS Thin Film Heterojunction (Best: 5.7%)
    - b. $CuInS_2$ Homojunction (Best: 1.07%)
3. Other:
    - a. Other Heterojunctions (e.g. ternary films on Si)
    - b. Defect Categorization for Ternary Chalcopyrite System

MAJOR PROBLEMS

1. Ternary Film Growth:
    - Stoichiometry Control (Growth Mechanisms)
    - Contact Stability
2. Devices:
    - Pinholes (shorting)
    - Failure Mechanisms (e.g. Cd diffusion into $CuInSe_2$)
    - Standard Testing
    - Stability Determination

PLANNED ACTIVITY

1. Continued Investigation of Growth and Characteristics of I - III - VI_2 Thin Films.
    - MBE
    - Optical Properties
    - Determination of Evaporation Mechanisms

2. Heterojunction: Continued Emphasis of $CuInSe_2$/CdS Development
    - Standardize Device Fabrication Procedures
    - Contact Improvement
    - Investigation of Failure Mechanisms, Stability

3. Homojunction: Priority on $CuInS_2$ Device

4. Preparation of Standard Cell for NASA/Lewis ($CuInSe_2$/CdS)

5. Auger Electron Spectroscopy Analyses of Films, Devices

6. Investigation of Ternary Heterojunctions

IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC SOLAR CELLS

U.S. Energy Research and Development Administration

Contract No. E(49-18)-2457

Period of Grant: June 15, 1976 - July 15, 1977

Value: $129,655

by

Robert L. Rod, Principal Investigator
Monosolar, Inc., a subsidiary of
Monogram Industries, Inc. (Prime Contractor)
Suite 600
100 Wilshire Boulevard
Santa Monica, CA. 90401

and

Ferdinand A. Kroger, Co-Principal USC Investigator
Materials Sciences Department
School of Engineering
University of Southern California (Subcontractor)
Los Angeles, CA. 90007

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

I. OBJECTIVES

It is planned to develop solar cells of the types

n CdTe/p CdTe

n CdS or n CdSe/p CdTe

n (Cd,Zn)Te or n (Cd,Mg)Te/p CdTe

n CdS or n CdSe/p(Cd,Zn)Te or (Cd,Mg)Te

n CdTe/p Cu_xTe

all with the left side substance on a light-transparent base of glass covered with antimony doped tin oxide.

The work includes manufacture of cells on an experimental basis and measuring their basic properties. Initial work is being concentrated on optimization of an electrochemical method for forming the semiconductor layers. This leads to layer formation on either the anode or the cathode of a cell with a liquid electrolyte.

Subsequent work will involve measurement of the properties of various cells to include conductivity, life times of the minority carrier, band edge, and other pertinent parameters.

II. PREVIOUS ACTIVITIES

Activities during the first month of the Contract were as follows:

A. Several dozen glass substrates were produced by Monosolar in different electrode configurations. All were first coated with antimony doped tin oxide by a chemical vapor deposition technique. Several of these then were provided with an overlay grid of conductive gold ink to lower resistance to values of about 2-3 ohms measured point-to-point from one side of one grid to the other grid opposite, or across a span of 1.9 inches.

B. At USC, work during the period started July 1, 1976, the date of Monosolar's award of a subcontract to that institution. Endeavors included formation of layers of Cd, Te, and CdTe both on metal and conductive glass substrates by cathodic deposition from an aqueous solution of $CdSO_4$ ($\longrightarrow$ Cd), a solution of TeO_2 in H_2SO_4 ($\longrightarrow$ Te), and a solution of $CdSO_4$ + H_2SO_4 in water using two anodes, one inert and the other of Te.

III. CURRENT EFFORTS

Present work is an extension of the previous activities with increasing attention now being directed to the efforts of Dr. F.A. Kroger, one of the two co-principal investigators at USC. Dr. Kroger is presently investigating the effect of the pH on the deposition of Cd, Te, and CdTe.

IV. SUMMARY OF KEY RESULTS

A. In the area of producing electrically conductive, light transparent glass substrates on which the semiconductor layers are to be electrochemically formed, present techniques yield light transmission of 90-95% and resistances of 10 ohms per square. Application of a gold ink grid lowers resistance by almost one order of magnitude. Light transparency in the visible range is about 75-80% for gridded cells having resistances of several ohms across a span of almost 2 inches.

B. USC has shown the feasibility of making layers of Te, Cd, and CdTe by a cathodic process, depositing the latter from a solution of $CdSO_4$ in H_2SO_4 with the aid of two anodes, one inert, the other consisting of pure Te.

We intend to determine the dependence of the properties of the layers that are formed on the experimental conditions, such as the Cd concentration, the pH of the solution, and the ratio of the currents through the two anodes. The properties to be investigated include microstructure, X-ray diffraction pattern, electrical resistance conductivity type, and minority carrier life times. Doping will be achieved by adding donors such as In and Ga as sulfates to the $CdSO_4$ solution or acceptors such as P, As, or Sb to the Te anode.

○ IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC SOLAR CELLS

○ PRIME CONTRACTOR: MONOSOLAR, INC., SUBSIDIARY OF
MONOGRAM INDUSTRIES, INC.
SANTA MONICA, CA. 90401

○ SUBCONTRACTOR: UNIVERSITY OF SOUTHERN CALIFORNIA
LOS ANGELES, CA. 90007

○ PERIOD OF CONTRACT: JUNE 15, 1976 – JULY 15, 1977

○ AMOUNT OF AWARD: $129,655

○ PRINCIPAL INVESTIGATORS: MONOSOLAR – ROBERT L. ROD
USC – FERDINAND A. KROGER
– KURT LEHOVEC

DEFINITION OF OVERALL PROJECT OBJECTIVES

- IT IS PLANNED TO DEVELOP SOLAR CELLS OF THE TYPES
  - n CdTe/p CdTe
  - n CdS or n CdSe/p CdTe
  - n (Cd,Zn)Te or n (Cd,Mg)Te/p CdTe
  - n CdS or n CdSe/p (Cd,Zn)Te or (Cd,Mg)Te
  - n CdTe/p Cu_xTe

........ALL WITH THE LEFT SIDE SUBSTANCE ON A TRANSPARENT, ELECTRICALLY CONDUCTIVE GLASS SUBSTRATE

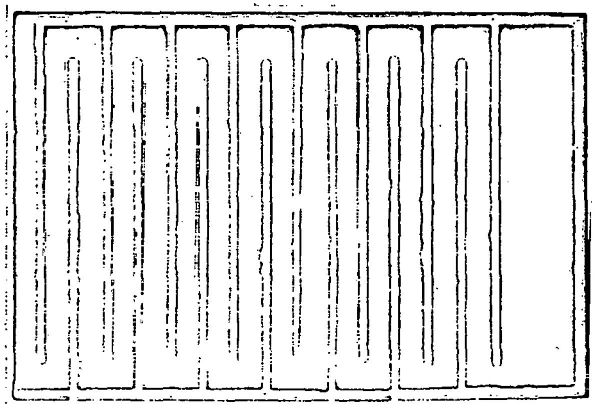
- INITIAL EFFORTS
  - MANUFACTURE OF CELLS ON AN EXPERIMENTAL BASIS
  - OPTIMIZATION OF THE ANTIMONY-DOPED TIN OXIDE CONDUCTIVE FILM ON A GLASS SUBSTRATE
  - OPTIMIZATION OF AN ELECTROCHEMICAL DEPOSITION METHOD FOR FORMING THE SEMICONDUCTOR LAYERS
- SUBSEQUENT EFFORTS
  - MEASUREMENTS
    - CONDUCTIVITY
    - LIFE TIMES OF THE MINORITY CARRIERS
    - BAND EDGE
    - EFFICIENCY

PLANNED ACTIVITY TO DATE

FOR THE FIRST MONTH OF THE CONTRACT TO DATE . . . .

1. BY MONOSOLAR
   - o SEVERAL DOZEN Sb-DOPED SnO_2 COATED GLASS SUBSTRATES WERE MADE MEASURING 2 X 3 X 0.125 INCHES
   - o GOLD INK GRIDS WERE OVERLAYED OVER SEVERAL OF THE ELECTRICALLY CONDUCTIVE, LIGHT-TRANSPARENT SUBSTRATES TO LOWER POINT-TO-POINT RESISTANCES
   - o TYPICAL CHARACTERISTICS:

     A. APPEARANCE

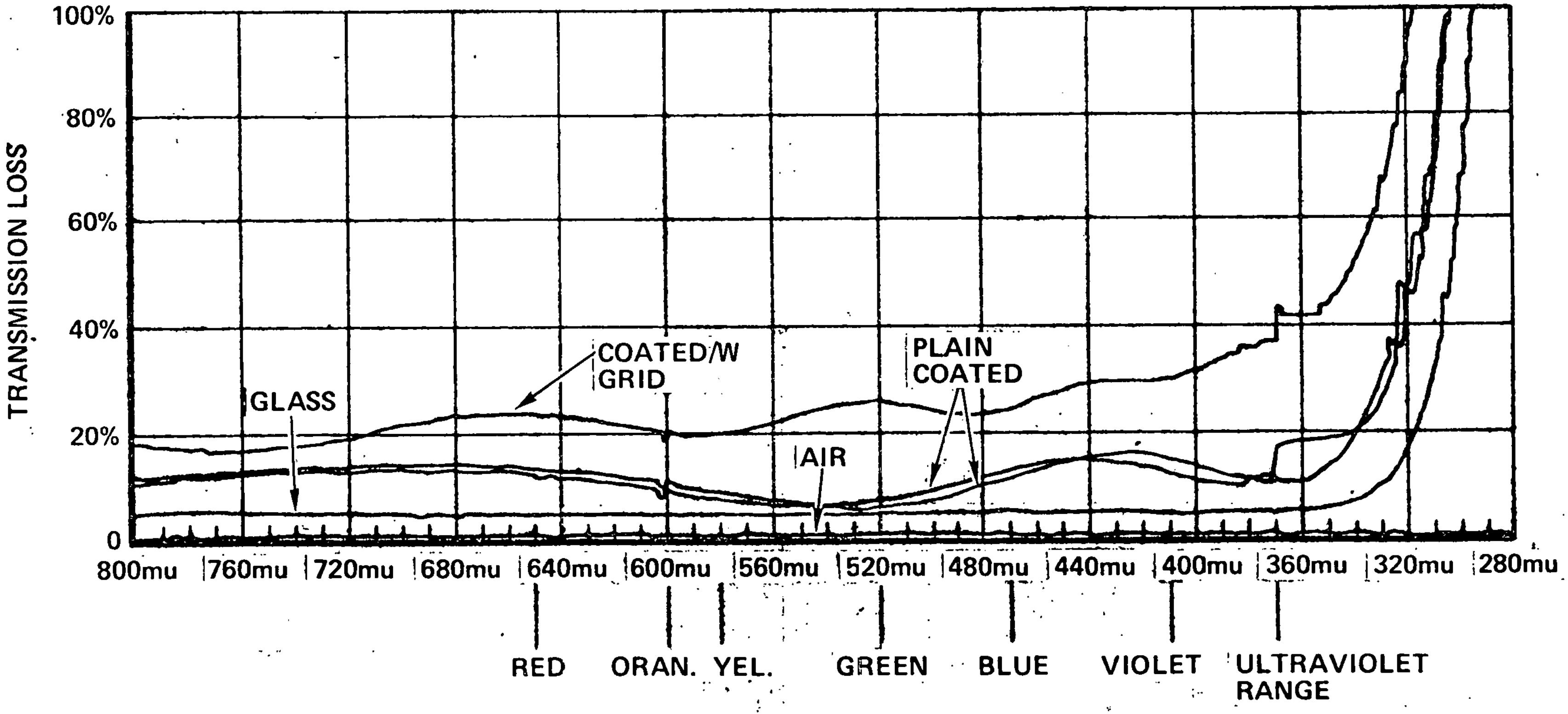


     B. FILM THICKNESS – 6,000 ANGSTROMS (TYPICAL)

     C. RESISTANCES – 10 OHMS/SQUARE WITHOUT GRID
     2-3 OHMS POINT-TO-POINT ACROSS THE CELL WITH GOLD INK GRID

     D. LIGHT TRANSMISSION – FOLLOWING VIEWGRAPH

LIGHT TRANSMISSION THROUGH CONDUCTIVE GLASS SUBSTRATES



PERKIN-ELMER DOUBLE BEAM SPECTROPHOTOMETER 124
MONOSOLAR, INC., SUBSIDIARY OF MONOGRAM INDUSTRIES, INC.
JULY 28, 1978

PLANNED ACTIVITY TO DATE

(Continued)

2. BY USC –

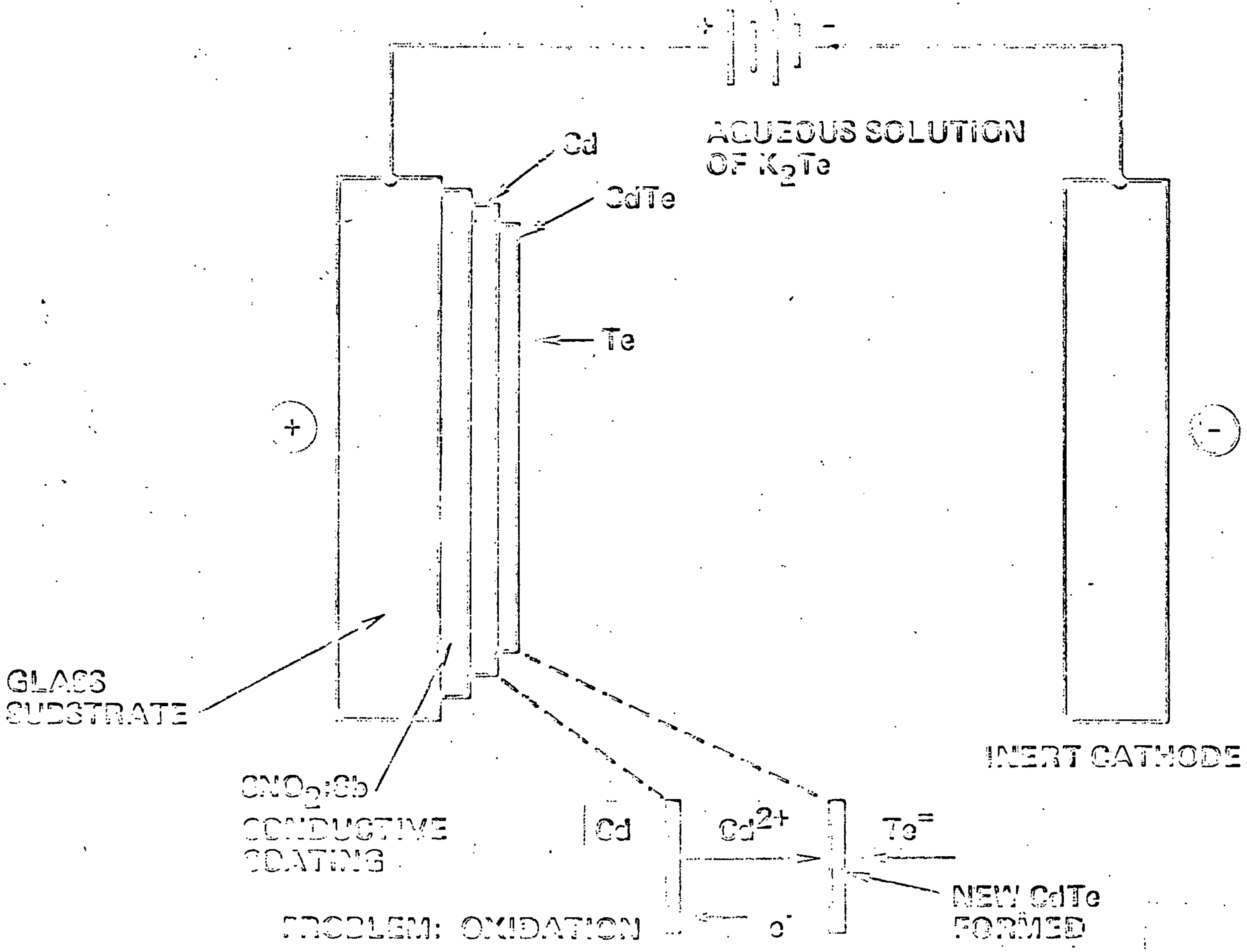
- ○ LAYERS OF Cd, Te, AND Cd + Te WERE ELECTROCHEMICALLY DEPOSITED ON METAL AND CONDUCTIVE GLASS SUBSTRATES
- ○ THE EFFECTS OF CHANGES IN THE CONDITIONS OF DEPOSITION ON THE QUALITY OF THE LAYERS WERE INVESTIGATED

DESCRIPTION OF PROGRESS MADE

TWO TYPES OF ELECTROCHEMICAL DEPOSITION OF INTEREST

- ANODIC
- CATHODIC (PREFERRED)

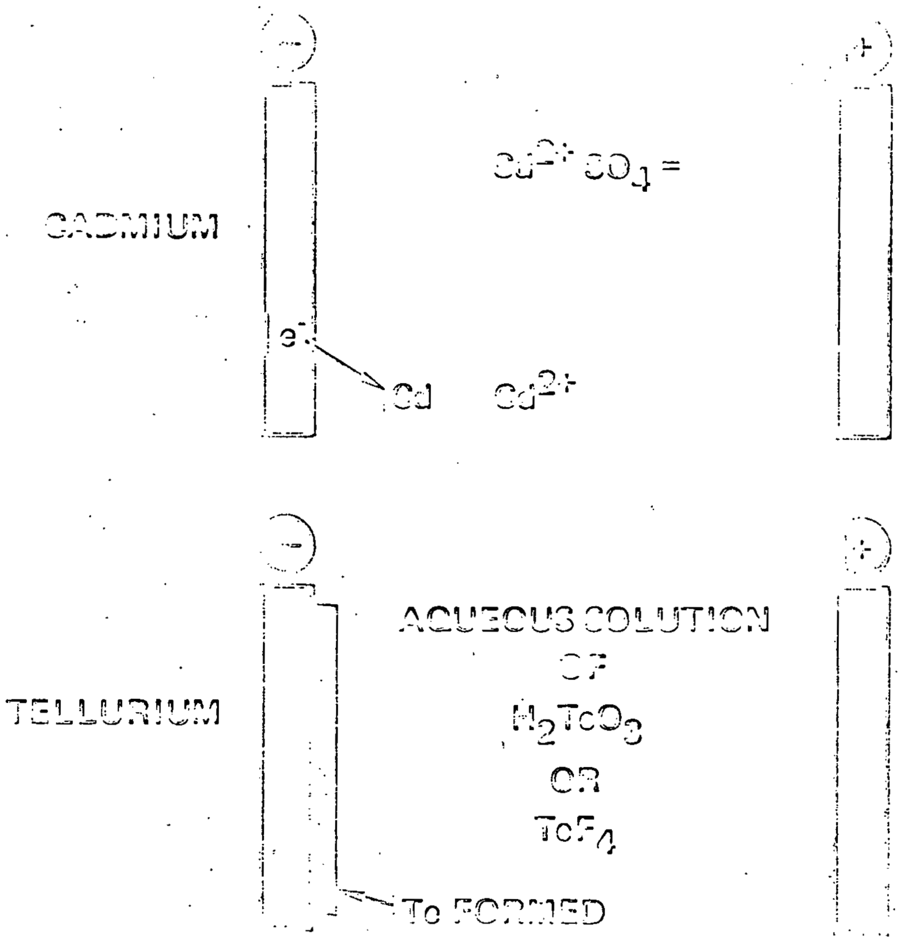
ANODIC DEPOSITION



PROBLEM: OXIDATION

$$3/2\ O_2 + K_2Te + H_2O \longrightarrow TeO_2 + 2\ KOH$$

CATHODE DEPOSITION

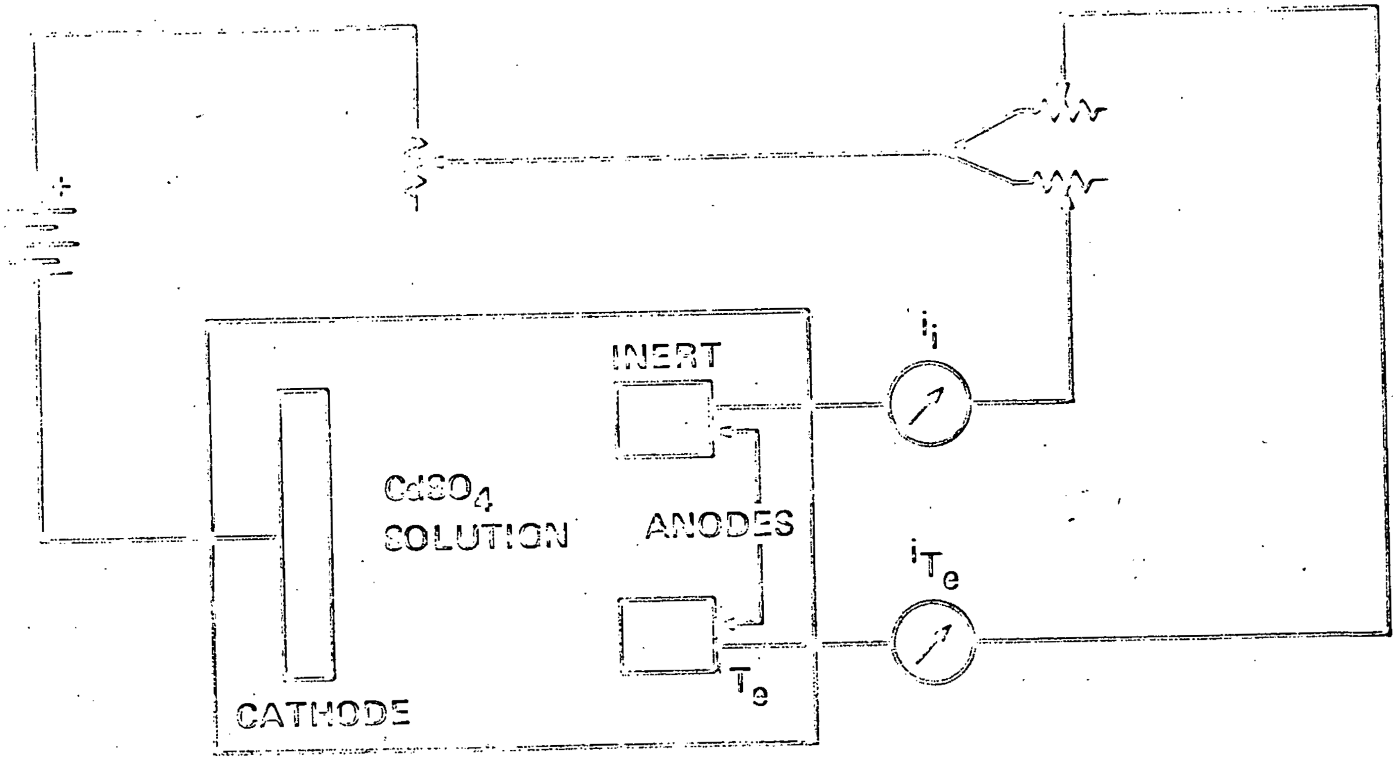


SIMULTANEOUS DEPOSITION OF BOTH Cd AND Te
HINDERED BY DIFFERENT DEPOSITION POTENTIALS

(Te MORE NOBLE THAN Cd)

$\downarrow$ −0.2V (Te) $\downarrow$ −1.4V (Cd)

DUAL CATHODIC DEPOSITION



ONLY Cd^{2+} IN SOLUTION;
Te INJECTED WITH Te ANODE;
DEPOSITION RATIO: $Cd/T_e = i_i/i_{T_e}$

SOME EQUALIZATION OF DEPOSITION
POTENTIALS BY REACTION $Cd + T_e \rightarrow CdTe$

$\Delta E = \Delta G/nF \approx 0.5V$

KEY RESULTS

- ○ Cd DEPOSITED FROM $CdSO_4$ SOLUTION: DEPOSITION INDEPENDENT OF pH
- ○ Te DEPOSITED FROM H_2TeO_3 SOLUTION IN H_2SO_4 (INERT ANODE); No pH DEPENDENCE IN THE CATHODIC PROCESS
- ○ Te DEPOSITED FROM H_2SO_4 (Te ANODE); STRONG pH DEPENDENCE IN THE ANODIC PROCESS
- ○ Cd + Te DEPOSITED FROM A CELL WITH TWO ANODES; STRONG DEPENDENCE OF THE TOTAL CELL VOLTAGE ON pH DUE TO THE ANODIC PROCESS AT THE Te ANODE (NO DEPENDENCE IN THE CATHODIC PROCESS)
- ○ THE CdTe LAYER IS DENSE, WITHOUT PINHOLES, AND IS A FEW MICRONS THICK
- ○ LIGHT TRANSPARENT, ELECTRICALLY CONDUCTIVE FILMS HAVE BEEN SUCCESSFULLY APPLIED TO GLASS-SUBSTRATES WITH RESISTANCES POINT-TO-POINT OF 2-3 OHMS WITH GOLD GRIDS AND LIGHT TRANSMISSION BETTER THAN 75%

MAJOR PROBLEMS

TECHNICAL

- IDENTIFICATION OF PRODUCT LAYER BY X-RAY DIFFRACTION, ELECTRON MICROPROBE, AND OPTICAL ABSORPTION IS REQUIRED
- MEASUREMENT OF CONDUCTIVITY AND CONDUCTIVITY TYPE (n OR p) DIFFICULT BECAUSE OF CONDUCTIVE BASE LAYER

SCHEDULE

- ON TARGET

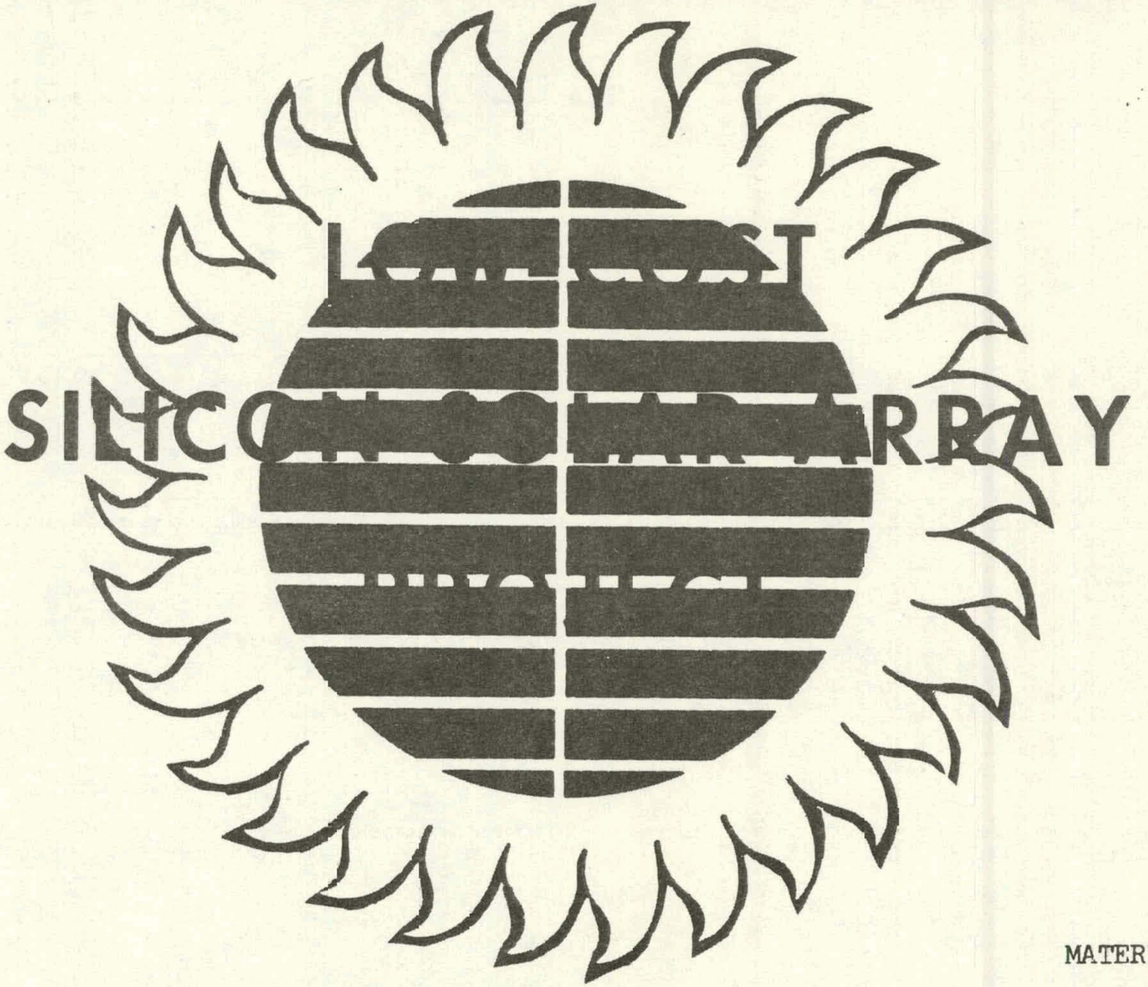
COSTS

- ON TARGET

PLANNED ACTIVITY
FOR NEXT 6 MONTHS

- MAKING LARGER CONDUCTIVE COATED GLASS SUBSTRATES
- MAKING n- AND p-TYPES LAYERS OF CdTe BY VARIATION OF STOICHIOMETRY AND/OR USE OF DOPANTS
- MEASUREMENTS OF THIN LAYER CHARACTERISTICS
- MAKING CELLS BY SUCCESSIVELY DEPOSITING
    - AN n-LAYER,
    - A p-LAYER,
    - AND A METALLIC LAYER OF Ag OR Ni
- MEASUREMENTS OF CELL CHARACTERISTICS

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION



JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

MATERIAL PRESENTED AT

ERDA SEMIANNUAL NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

University of Maine
4 August 1976

LOW-COST SILICON SOLAR ARRAY PROJECT

Abstract

It is the objective of the ERDA Low-cost Silicon Solar Array Project to develop by the FY 85-86 solar array technology so that arrays will sell for less than $500/kW (peak) and have a national production capability of greater than 500 MW/Yr. The arrays will have a lifetime of greater than 20 years and will have an overall array electrical conversion efficiency of greater than 10%.

The achievement of this objective requires that the best ideas and talents of the U.S. industry and universities be identified and brought into this effort. We are striving to identify, assess, incorporate, and integrate these ideas into low-cost solar arrays which are compatible with the requirements and applications being developed within the elements of the ERDA Photovoltaic Conversion Program.

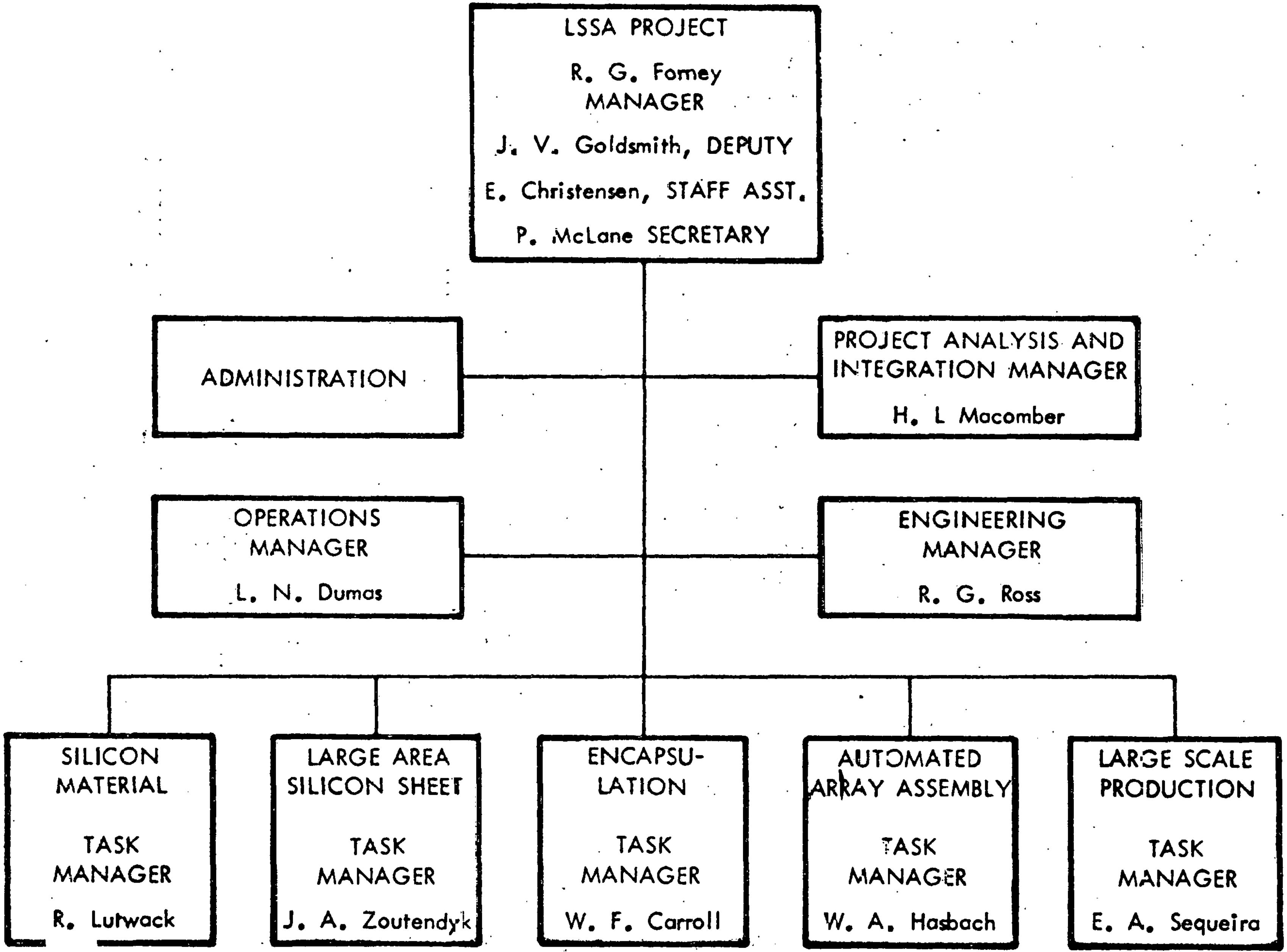
This Project was initiated in 1975 and is presently in what may be described as the technology assessment or process identification phase involving forty-three contracts with industries and universities. This effort is divided into several interrelated technical areas:

- The reduction of basic silicon material price from the present price level of approx. $65/Kg to levels like $10/Kg;
- The development of techniques for the growth of large-area sheets of the silicon in a form that can result in high efficiency solar cells;
- The development of encapsulation techniques which will provide required performance and allow lifetimes of greater than twenty years, and
- A cost-effective manufacturing process that will integrate all these technologies, materials, and processes and will meet the production levels and cost goals of the Project.

It is planned that the process development and scale-up phases of the Project will be initiated in the near future.

JPL is chartered by ERDA to insure that technology which is being developed is efficiently transferred to the solar array manufacturing industry and to procure the quantities of solar cells that will be employed in the ERDA Photovoltaic Test and Demonstration Program. It is anticipated that these latter two functions are effectively combined as a fifth major JPL task area termed Large-Scale Production Task.

The presentation will describe the status of the technical work, an assessment of the progress that is being experienced. Generally, on the basis of the work so far accomplished, it is felt that goals presently defined can be realized within the time and resource constraints that have been identified.


LSSA PROJECT
R. G. Forney
MANAGER
J. V. Goldsmith, DEPUTY
E. Christensen, STAFF ASST.
P. McLane SECRETARY
ADMINISTRATION
PROJECT ANALYSIS AND INTEGRATION MANAGER
H. L Macomber
OPERATIONS MANAGER
L. N. Dumas
ENGINEERING MANAGER
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SILICON MATERIAL
TASK MANAGER
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LARGE AREA SILICON SHEET
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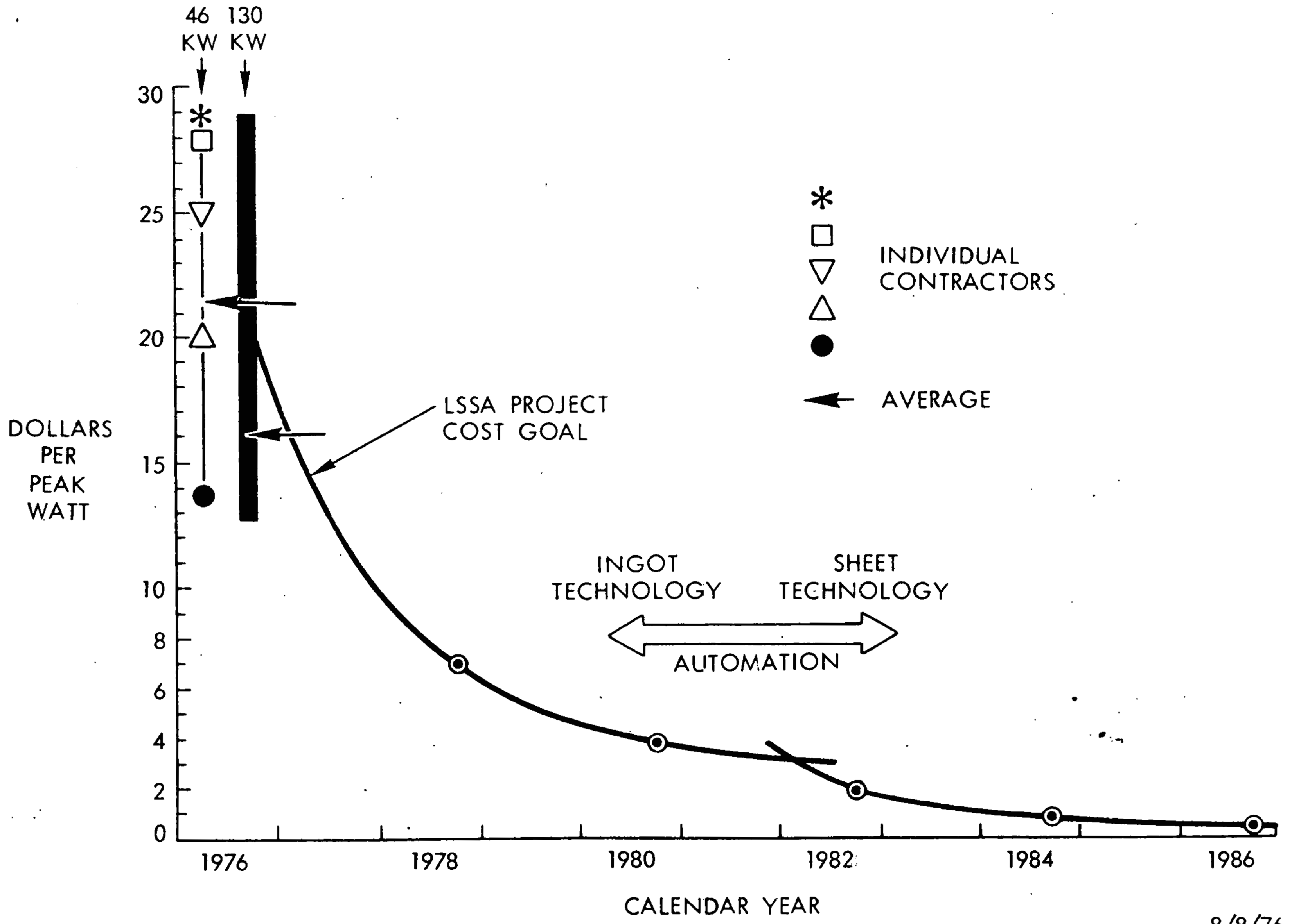
TASK MANAGER
W. A. Hasbach
LARGE SCALE PRODUCTION
TASK MANAGER
E. A. Sequeira

LOW-COST SILICON SOLAR ARRAY PROJECT

TERRESTRIAL SOLAR ARRAY PRICE HISTORY/GOALS



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LOW-COST SILICON SOLAR ARRAY PROJECT
NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW

SILICON MATERIAL TASK

Dr. RALPH LUTWACK
TASK MANAGER

AUGUST 1976

Summary
Silicon Material Task

The objective of the Silicon Material Task is to establish the capability of producing Si, suitable for solar cells for terrestrial applications, at a market price of less than $10/Kgm and at a volume equivalent to at least 500 peak MW/year. The first phase of this Task is comprised of three efforts: (1) the development of the practicality of processes for semiconductor grade Si; (2) the determination of the effects of impurities in Si on the properties of Si material and the performance of solar cells; and (3) the development of the practicality of processes for solar cell grade Si, a material which is defined as being suitable for terrestrial solar arrays.

The first phase is being accomplished primarily with the use of contracts. There are three contracts underway in the first element. One is with Battelle for investigations of reactions involving $SiCl_4$ reduction by Zn and SiI_4 reduction by H_2 (or thermal dissociation). The second is with Union Carbide for the low cost, high volume production of SiH_4, to be used in a following Si deposition step. The third, with Motorola, is for the development of the SiF_4/SiF_2 transport process.

There are two contracts in the second element. These programs with Monsanto and Westinghouse are parallel in several features. The differences are cited below in the descriptions of contract progress.

In the third element the development contracts are with (1) Texas Instruments for the use of a plasma reactor to reduce SiO_2 with C; (2) Stanford Research Institute for a duplex process involving the reduction of SiF_4 (from Na_2SiF_6) by Na and the use of the SiF_4/SiF_2 transport reaction; (3) Dow Corning for the use of purer C and SiO_2 in the submerged arc furnace followed by unidirectional freezing and vacuum evaporation; (4) Westinghouse for the use of a plasma arc heater for the reduction of $SiCl_4$ with Na, Mg, or H_2; and (5) AeroChem for the investigation of the non-equilibrium plasma jet for the preparation of SiH_4 and Si using $SiCl_4$.

In support of these contracts, process analyses and economic evaluations are being performed under contract by Lamar University. JPL is conducting a complementary program, which is partially in-house, to support the efforts dealing with various measurements and the development of aspects of fluidized bed reactor technology.

The progress and status of this Task program are presented in the following discussions.

Following a period for obtaining descriptions of the two processes with thermodynamic calculations, Battelle has performed analyses for estimating the plant construction and product costs. The factors taken into consideration were major items of equipment, material and energy, utilities, fixed charges, overhead, general expenses, manpower, and fixed capital investment. The fluidized bed reactor was sized for an output of 24 Kgm/hr, and thus a production of 1000 MT/year would require six of these reactors with an 80% on-stream operation. The conclusions were that, using a conservative set of assumptions and estimating procedures, the product costs were: \$9.12 for the $SiCl_4$ process and \$20.65 for the SiF_4 process. (The calculations used a cost base as of January 1975, and the data were either actual or extrapolated from prior year's costs.) The energy-use for the $SiCl_4$ process was estimated to be 46 Kwh/Kgm Si. Battelle also concluded that although these product costs could be reduced by optimization methods, the $SiCl_4$ would remain economically superior to that for SiI_4.

Battelle has also performed an analysis using reasonable assumptions for the dependence of equipment and labor on process-condition variations, to de mine the economic effects of non-stoichiometric ratios for the $Zn/SiCl_4$ reaction.

The conclusion was that there are no appreciable disadvantages which are caused by varying the ratio within 43% of the 2/1 stoichiometry; the cost penalty at the extremes is $.10/Kgm. This result, which obviates the need for strict stoichiometric control of the reaction composition, will be subjected to further study by taking into account the influence of kinetics as well as the requirements for the purity and form of the product.

Battelle has designed and installed a miniplant to demonstrate the capability for producing greater than 200 gm/hr of Si for a 4 to 6 hr run, to verify product purity, to determine process operating conditions, and to secure data for the design specifications of a large plant. The material balances calculated for the first runs were reasonable. Although operating problems have occurred, particularly in the performance of the fluidized bed reactor, some promising data have been obtained. For example, in one run the yield of Si on the bed was 67% at a rate of 68.5 gm/hr; this run was conducted at a reactant ratio which would theoretically cause an economic penalty of $0.04/Kgm when compared with the calculated optimum. This experimental effort is dealing principally with the problems involved in the Si deposition on the fluidized bed reactor.

In the section of the Union Carbide contract for the establishment of the economic practicality of a process for producing semiconductor grade SiH_4 the program consists of investigations of the disproportionation of chlorosilane mixtures, the hydrogenation of $SiCl_4$ to produce $SiHCl_3$, and the direct synthesis of SiH_2Cl_2. A subsequent section will deal with procedures for the economic deposition of Si from a SiH_4 feed. The disproportionation is accomplished utilizing a tertiaryamine ion exchange resin, Robin and Haas Amberlyst 21. The process model involves a series of 3 disproportionation reactors, the feed for the last two being the effluent from disillation columns. The bottoms from the distillation columns are recycled, and the $SiCl_4$, which is a by-product of the first disproportionation reactor, is recycled after hydrogenation. The preliminary product-cost estimates based upon this process range between \$2.97 and \$4.42/Kgm, depending upon particular assumptions for recycling by-products.

In a series of experimental studies of the disproportionation reaction the effects of temperature (40 to 80°C) and SiH_2Cl_2 flow rates (residence time of up to 9 sec.) on the conversion yields of SiH_4 were obtained. The conclusions from these data are that the mole % for each of the chlorinated silanes and SiH_4 is still changing at 9 sec. at 40°C, although the $SiCl_4$ is barely measurable and the values of SiH Cl and SiH_4 seem to be rapidly approaching constantancy. The composition dependence on residence time varies with temperature until at 80°C the system, with exception of $SiCl_4$, seems to have reached a steady state condition within a 2 sec residence time; the $SiCl_4$ concentration increases with temperature at each residence time and a continuing production is evident at 7 sec at 80°C. The data show that a constant 14 mole % yield of SiH_4 is obtained between 2 and 3 sec in the range between 60 to 80°C; consequently, a preliminary conclusion is that the operating temperature will be in this range.

The dependence of the production rate of SiH_4 on the feed rate of SiH_2Cl_2 was determined within the temperature range of 60 to 80°C. The data show, in general, that the SiH_4 production rate increases with temperature and SiH_2Cl_2 feed rate. The effect of recycling SiH_3Cl and SiH_2Cl_2 was calculated, forcing lower residence times and indicating substantial increases in the SiH_4 rate. A further calculation, based on extrapolations from experimental data, results in a projection that a 1000 MT/year plant, which is equivalent to 227 Kgm/hour at a 60% service factor, would require a resin column 1 ft in diameter and 10 ft. in length.

A separate investigation of the reaction is underway for the hydrogenera of $SiCl_4$ to $SiHCl_3$. The objective of this work is to improve the economics of the overall process by converting the end by-product $SiCl_3$ into a component of the feed for the disproportionation reaction. Although 15 to 20% yields of $SiHCl_3$ have been obtained per pass, the preliminary experiments have revealed that the operating conditions of the fluidized bed reactor must be improved to obtain better temperature control and satisfactory bed performance.

The objective of the miniplant for SiH_4 production are to demonstrate the production capability of 4.6 Kgm/day, to verify product purity, to determine operating characteristics, and to secure data for design criteria for a 1000 MT/year plant. The design of this miniplant and the flow chart for the process have been completed. The equipment is being installed, and the instrumentation is being checked-out. An investigation of the means for storing SiH_4 is also underway with studies of storage methods, of SiH_4 characteristics for various conditions of temperature and pressure, and of the design of safety devices. The next phase entails the check-out and then the operation of the plant to determine the behavior of the process under a set of conditions described by the conclusions of the preliminary experiments.

Westinghouse and Monsanto are conducting investigations of the effects of impurities on material properties and solar cell performance. The principal differences between these contracts are that the Westinghouse contract includes work with dendritic web crystals and Monsanto also deals with float zone crystals. Both programs involve doping crystals with impurities and measuring impurity concentrations, resistivities, minority carrier recombination lifetimes, microstructural effects, and solar cell efficiencies and short circuit currents.

A summary of the results obtained by Westinghouse is as follows:

(1) Solar cell efficiency is severely degraded by the presence of V or Ti. For example, the relative cell efficiencies (compared to cells fabricated using baseline Si) for different concentrations are: (1) for V: at 1×10^{13} atoms/cc -

76% and at 3.1 x 10^{14} atoms/cc - 39% and (2) for Ti: at 1 x 10^{13} atoms/cc - 83% and at 3.6 x 10^{14} atoms/cc - 15%.

(2) The results for cells doubly doped with combinations of Mn., Cu, and Cr show that these impurities set independently. Thus, Cu, which has no effect alone, neither enhances nor ameliorates the effects of Cr and Mn., whereas the action of Cr and Mn is additive.

(3) A comparison of the values for the effective segregation coefficients determined in this work with literature values revealed several differences. The coefficients calculated for Ti, V, and Zr were significantly smaller and that for Mg was 2 orders of magnitude smaller than those given in the literature.

(4) Preliminary results in a study of the effects of high temperature annealing (at 550°C and 825°C) and diffusion (at 825°C) on minority carrier recombination lifetimes in wafers using photoconductive decay measurements indicate that the values change even at 550°C. The deduction is that the mechanisms of gettering, precipitation and dissolution, and complexing need to be considered in explanations of the data. The mechanism characterization of the consequences of processing-steps could form an information base for predicting the effects of the presence of impurities during the steps of cell fabrication.

(5) Although, in general, the electrically active concentration of an impurity will be less than the actual concentration due to such effects as precipitation and complexing, the predicted inverse linear relationship between lifetime and actual concentration was shown to hold over the range from 10^{13} to about 10^{15} atoms/cc for Cr; this indicates the apparent 100% electrical activity of added Cr. It was also shown that this relationship does not hold for a diffused wafer. In this case the data indicate that Cr recombination centers are decreased by gettering and precipitation.

A summary of the results obtained by Monsanto is as follows:

(1) A conclusion derived from the data is that Ti and Zn can be gettered from Si using N_2 and O_2.

(2) Although Mn does not seem to affect cell performance, the presence of Mn should be avoided since it forms a slag.

(3) The literature values for the segregation coefficients are generally valid except for Zr and Mg.

(4) The results from multiply doped cells indicate that impurities seem to act independently.

(5) Al is about 20% electrically active.

(6) In all cases cells fabricated from float zone ingots were superior to cells from Czochralski ingots. Some comparative data, given as % of baseline cells, for ingots with nearly the same impurity concentrations are: for V - 61%/66%, Ti - 29%/43%, and Al - 32%/100%.

(7) From comparisons of the data for each impurity for float zone and Czochralski cells it was concluded that O_2 at concentrations of about 250×10^{16} atoms/cc in the Czochralski material causes distinct reductions in cell performance.

The contract for process feasibility studies at Lamar University is comprised of three principal sections: Analyses of proces-system properties, chemical engineering analyses, and economic analyses. A great deal of data have been gathered for the properties of the materials involved in the process developments of the Silicon Material Task. In the chemical engineering area the preliminary design for a 1000 MT/year plant using the process for the Zn reduction of $SiCl_4$, being developed by Battelle, is nearing completion. Estimations of capital investment and of total product cost have been made; they are $10,026,000 and $9.42/Kgm, respectively. These analyses are continuing in support of the JPL program to assess the practical economic potential of each of the processes being developed.

It is anticipated that the next ERDA Review Meeting will also include reports on the progress achieved in the process development contracts, which are now at a relatively immature stage and were not described in this summary.

LOW-COST SILICON SOLAR ARRAY PROJECT

OBJECTIVES

- ESTABLISH PRACTICALITY OF PROCESSES FOR HIGH VOLUME PRODUCTION OF SILICON, SUITABLE FOR SOLAR CELLS
  - FY85 OBJECTIVE
    - VOLUME - EQUIVALENT TO 500 PEAK mW/yr
    - PRICE - <$10.0/Kgm
  - FY80 OUTPUT AND PRICE
    - VOLUME - EQUIVALENT TO 5 PEAK mW/yr
    - PRICE - <$35/Kgm

LOW-COST SILICON SOLAR ARRAY PROJECT
PHASE I PROGRAM

- PART I: TECHNICAL FEASIBILITY OF PROCESSES FOR SEMICONDUCTOR GRADE Si
- PART II: EFFECTS OF IMPURITIES
- PART III: TECHNICAL FEASIBILITY OF PROCESSES FOR SOLAR CELL GRADE Si

LOW-COST SILICON SOLAR ARRAY PROJECT
PHASE II PROGRAM

- EFFECTS OF IMPURITIES - PROCESSING
- ENGINEERING-ECONOMIC SCALE-UP STUDIES

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROGRESS

PHASE I

- PART I: SEMICONDUCTOR GRADE Si PROCESSES
    - BATTELLE MEMORIAL INSTITUTE
    - UNION CARBIDE
    - MOTOROLA
- PART II: EFFECTS OF IMPURITIES
    - MONSANTO
    - WESTINGHOUSE
- PART III: SOLAR CELL GRADE Si PROCESSES
    - TEXAS INSTRUMENTS
    - STANFORD RESEARCH INSTITUTE
    - AEROCHEM
    - WESTINGHOUSE
    - DOW CORNING
- PART IV: ECONOMIC ANALYSES
    - LAMAR UNIVERSITY

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROGRESS

BATTELLE MEMORIAL INSTITUTE

- ECONOMIC ANALYSES
  - PROCESSES
    - Zn REDUCTION OF $SiCl_4$
    - THERMAL DECOMPOSITION OF SiI_4
    - H_2 REDUCTION OF SiI_4

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
BATTELLE MEMORIAL INSTITUTE (contd)

- ASSUMPTIONS
  - THERMODYNAMIC DESCRIPTIONS
  - FLUIDIZED BED REACTORS SCALED FROM 15 in. D FOR 24 Kgm/hr OUTPUT CONDITIONS
  - Zn RECOVERY - MOLTEN SALT ELECTROLYSIS
  - ELECTRICAL HEATING
  - 50% HEAT RECOVERY AT T > 800 K

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROCESS

BATTELLE MEMORIAL INSTITUTE (contd)

- ECONOMIC ANALYSES
  - RESULTS
    - Zn REDUCTION OF $SiCl_4$

• MASS AND ENERGY FLOW SHEET	
• EQUIPMENT	$322, 000
• MATERIAL AND ENERGY COSTS	
• Zn AND $SiCl_4$	$2.59/Kgm Si
• ENERGY (11.17 KWh/Kgm)	$0.335/Kgm
• MANPOWER	$893, 100/yr
• FIXED CAPITAL INVESTMENT	$1, 437, 400
• PRODUCT COST FOR 1000 MT/yr	
• DIRECT PRODUCTION COST	$5, 442, 100
• FIXED CHARGES	$1, 638, 630
• PLANT OVERHEAD	$1, 133, 490
• GENERAL EXPENSES	$902, 220
• TOTAL PRODUCT COST	$9, 116, 440

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROCESS

BATTELLE MEMORIAL INSTITUTE (contd)

- ECONOMIC ANALYSES
  - RESULTS
    - SiI_4 - HYDROGEN OR THERMAL REDUCTION
      - TOTAL PRODUCT COST >\$20/Kgm
      - OPTIMIZATION RESULTS
        - COST <\$20/Kgm
        - COST >Zn REDUCTION OF $SiCl_4$

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROCESS
BATTELLE MEMORIAL INSTITUTE (contd)

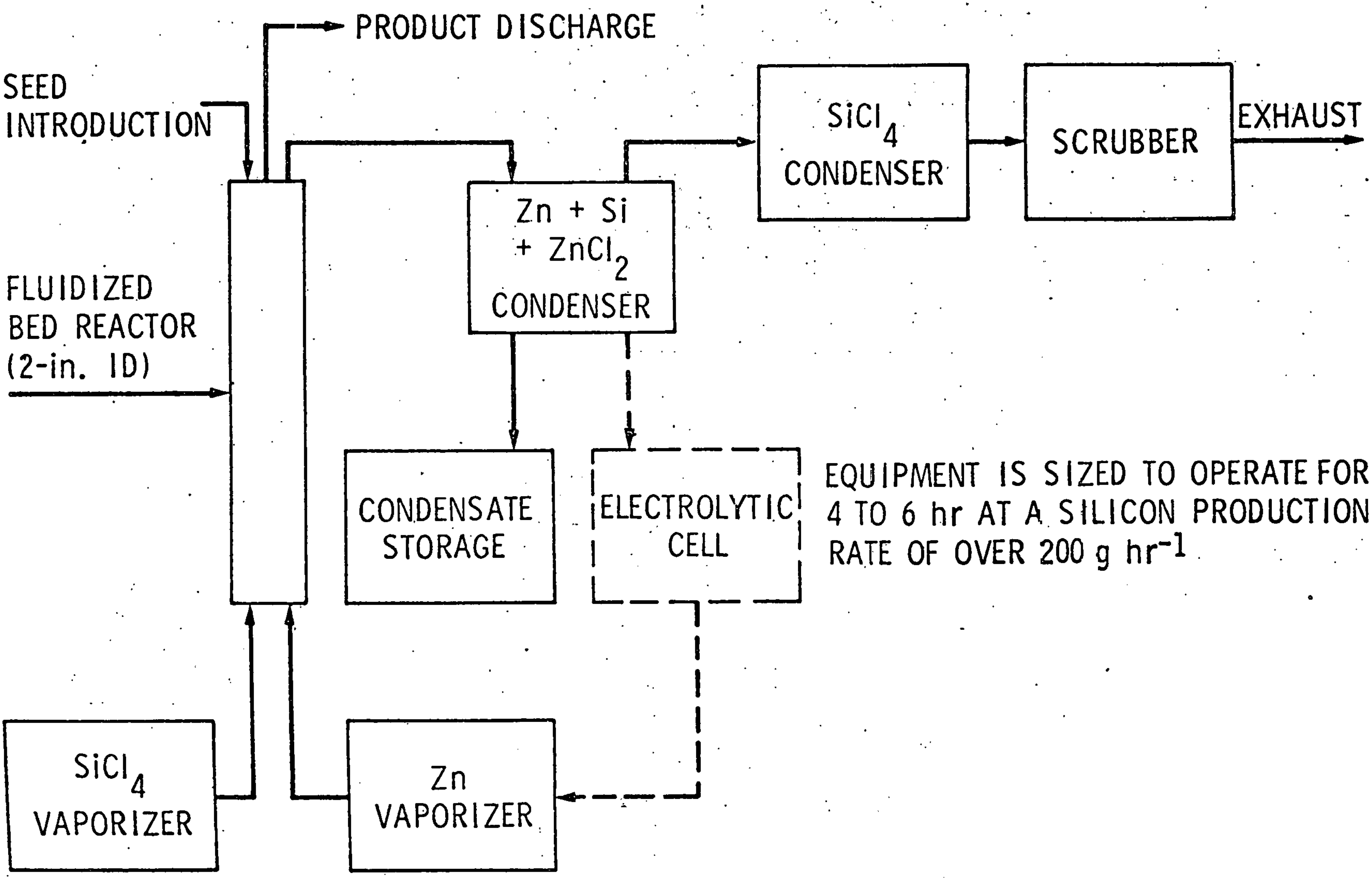
- ECONOMIES OF NON-STOICHIOMETRIC RATIOS
  - ASSUMPTIONS
    - REACTOR SIZE ~ TOTAL MOLES TO PRODUCE 1 mole Si
    - CONSTANT $ZnCl_2$ ELECTROLYSIS COST
    - CONSTANT LABOR COSTS
  - RESULTS
    - NO ECONOMIC ADVANTAGE $Zn/SiCl_4 \neq 2/1$
    - ADDED COST BETWEEN 1.4 AND 2.86 <\$0.10/Kgm
  - CONCLUSIONS
    - STRICT STOICHIOMETRY CONTROL NOT REQUIRED
  - OTHER CONSIDERATIONS
    - KINETICS
    - PURITY
    - FORM

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROCESS
BATTELLE MEMORIAL INSTITUTE (contd)

- MINIPLANT
  - OBJECTIVES
    - DEMONSTRATE >200 gm/hr FOR 4 TO 6 hr
    - VERIFY PRODUCT PURITY
    - DETERMINE OPERATING CHARACTERISTICS
    - SECURE DATA FOR DESIGN CRITERIA
  - STATUS
    - MAJOR EQUIPMENT CONSTRUCTED AND BEING EVALUATED
    - AUXILIARY EQUIPMENT CONSTRUCTED AND OPERATIONAL
    - ELECTROLYTIC CELL BEING MODIFIED
    - EXPERIMENTAL RESULTS
      - MATERIAL BALANCES REASONABLE
      - SINGLE RUN RESULTS
        - OVERALL CONVERSION ON BED = 67%
        - ECONOMIC PENALTY = $0.04/Kgm
        - MODERATE RATE 65.5 gm/hr
      - PROBLEMS
        - BAD BED PERFORMANCE
        - Si DEPOSITION ON REACTOR WALLS
        - T - OPTIMIZATION

LOW-COST SILICON SOLAR ARRAY PROJECT

SCHEMATIC DIAGRAM OF MAJOR "MINIPLANT" COMPONENTS



PRODUCT DISCHARGE

SEED INTRODUCTION

FLUIDIZED BED REACTOR (2-in. ID)

Zn + Si + $ZnCl_2$ CONDENSER

$SiCl_4$ CONDENSER

SCRUBBER

EXHAUST

CONDENSATE STORAGE

ELECTROLYTIC CELL

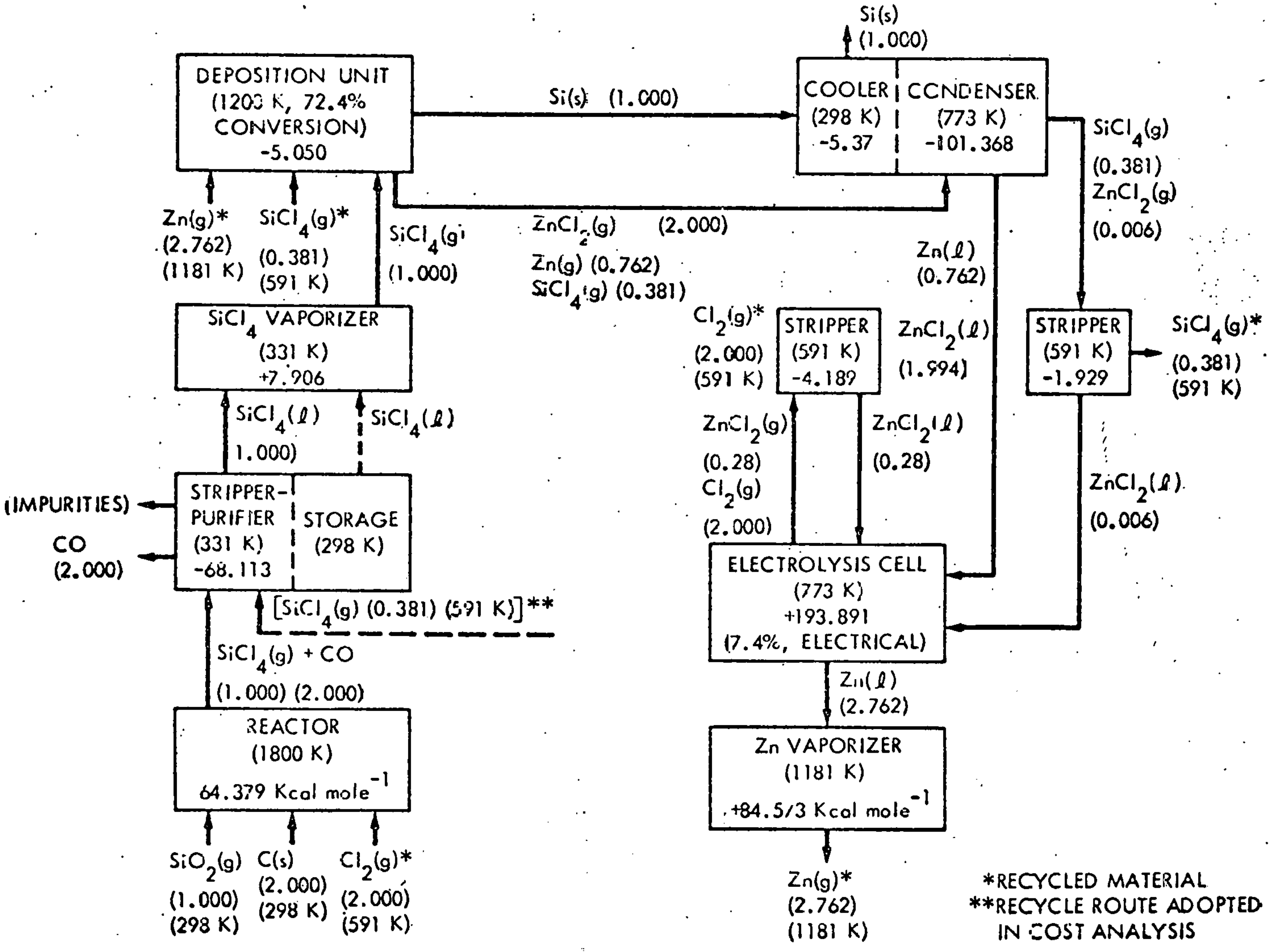
$SiCl_4$ VAPORIZER

Zn VAPORIZER

EQUIPMENT IS SIZED TO OPERATE FOR 4 TO 6 hr AT A SILICON PRODUCTION RATE OF OVER 200 g hr^{-1}

LOW-COST SILICON SOLAR ARRAY PROJECT

PROCESS A FLOW SHEET ZINC REDUCTION OF SILICON TETRACHLORIDE



DEPOSITION UNIT
(1200 K, 72.4% CONVERSION)
-5.050

Si(s) (1.000)

COOLER
(298 K)
-5.37

CONDENSER
(773 K)
-101.368

Si(s)
(1.000)

$SiCl_4(g)$
(0.381)
$ZnCl_2(g)$
(0.006)

Zn(g)*
(2.762)
(1181 K)

$SiCl_4(g)$*
(0.381)
(591 K)

$SiCl_4(g)$
(1.000)

$ZnCl_2(g)$ (2.000)
Zn(g) (0.762)
$SiCl_4(g)$ (0.381)

Zn(ℓ)
(0.762)

$SiCl_4$ VAPORIZER
(331 K)
+7.906

$Cl_2(g)$*
(2.000)
(591 K)

STRIPPER
(591 K)
-4.189

$ZnCl_2(ℓ)$
(1.994)

STRIPPER
(591 K)
-1.929

$SiCl_4(g)$*
(0.381)
(591 K)

$SiCl_4(ℓ)$
1.000)

$SiCl_4(ℓ)$

$ZnCl_2(g)$
(0.28)
$Cl_2(g)$
(2.000)

$ZnCl_2(ℓ)$
(0.28)

$ZnCl_2(ℓ)$
(0.006)

(IMPURITIES)

CO
(2.000)

STRIPPER-PURIFIER
(331 K)
-68.113

STORAGE
(298 K)

[$SiCl_4(g)$ (0.381) (591 K)]**

ELECTROLYSIS CELL
(773 K)
+193.891
(7.4%, ELECTRICAL)

$SiCl_4(g)$ + CO
(1.000) (2.000)

Zn(ℓ)
(2.762)

REACTOR
(1800 K)
64.379 Kcal $mole^{-1}$

Zn VAPORIZER
(1181 K)
+84.5/3 Kcal $mole^{-1}$

$SiO_2(g)$
(1.000)
(298 K)

C(s)
(2.000)
(298 K)

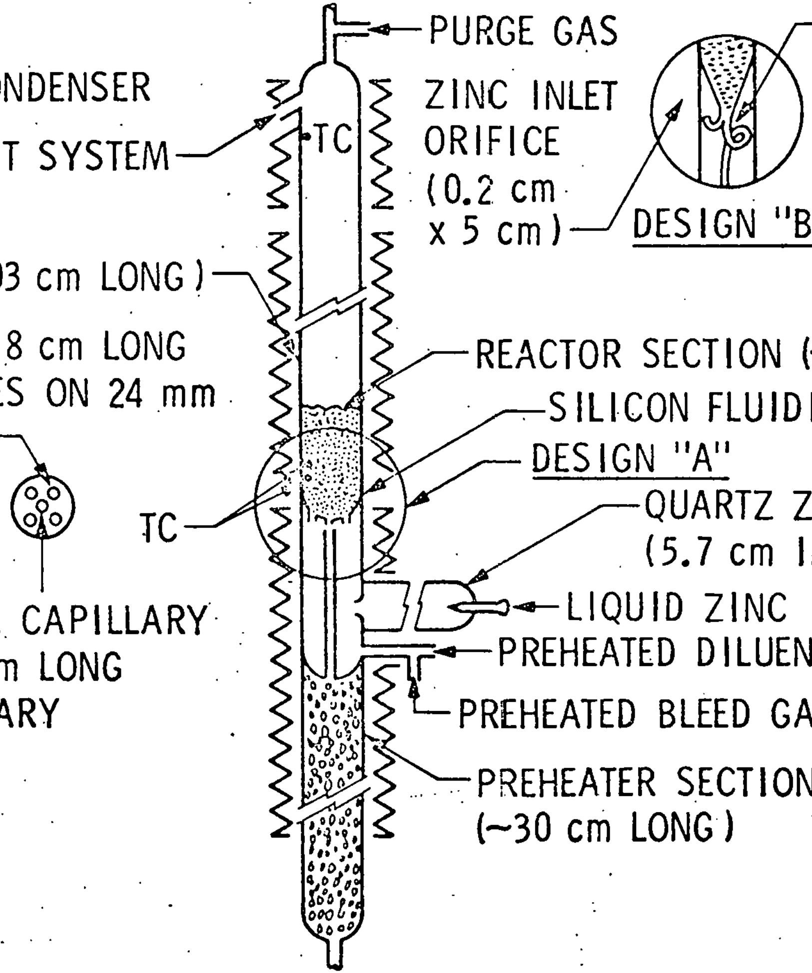
$Cl_2(g)$*
(2.000)
(591 K)

Zn(g)*
(2.762)
(1181 K)

*RECYCLED MATERIAL
**RECYCLE ROUTE ADOPTED IN COST ANALYSIS

LOW-COST SILICON SOLAR ARRAY PROJECT

SCHEMATIC DIAGRAM OF FLUIDIZED-BED REACTOR FOR THE PREPARATION OF SILICON BY THE ZINC (VAPOR FEED) REDUCTION OF $SiCl_4$



FEED CHARGING AND BED REMOVAL POINT

PURGE GAS

TO $ZnCl_2$ CONDENSER AND EXHAUST SYSTEM

TC

ZINC INLET ORIFICE (0.2 cm x 5 cm)

$SiCl_4$ INLET ORIFICE (0.2 cm x 15 cm)

DESIGN "B"

QUARTZ TUBE (≈5 cm ID x 103 cm LONG)

0.1 cm x 3.8 cm LONG CAPILLARIES ON 24 mm DIAMETER

REACTOR SECTION (~53 cm LONG)

SILICON FLUIDIZED BED

DESIGN "A"

TC

QUARTZ ZINC VAPORIZER CHAMBER (5.7 cm ID x 20 cm)

LIQUID ZINC

0.15 cm CAPILLARY x 3.8 cm LONG CAPILLARY

PREHEATED DILUENT GAS WHEN USED

PREHEATED BLEED GAS (PRESSURE EQUALIZER)

PREHEATER SECTION, QUARTZ PACKING (~30 cm LONG)

$SiCl_4$ AND DILUENT GAS WHEN USED

LOW-COST SILICON SOLAR ARRAY PROJECT

PHASE I PART I

CONTRACT WITH UNION CARBIDE CORP.

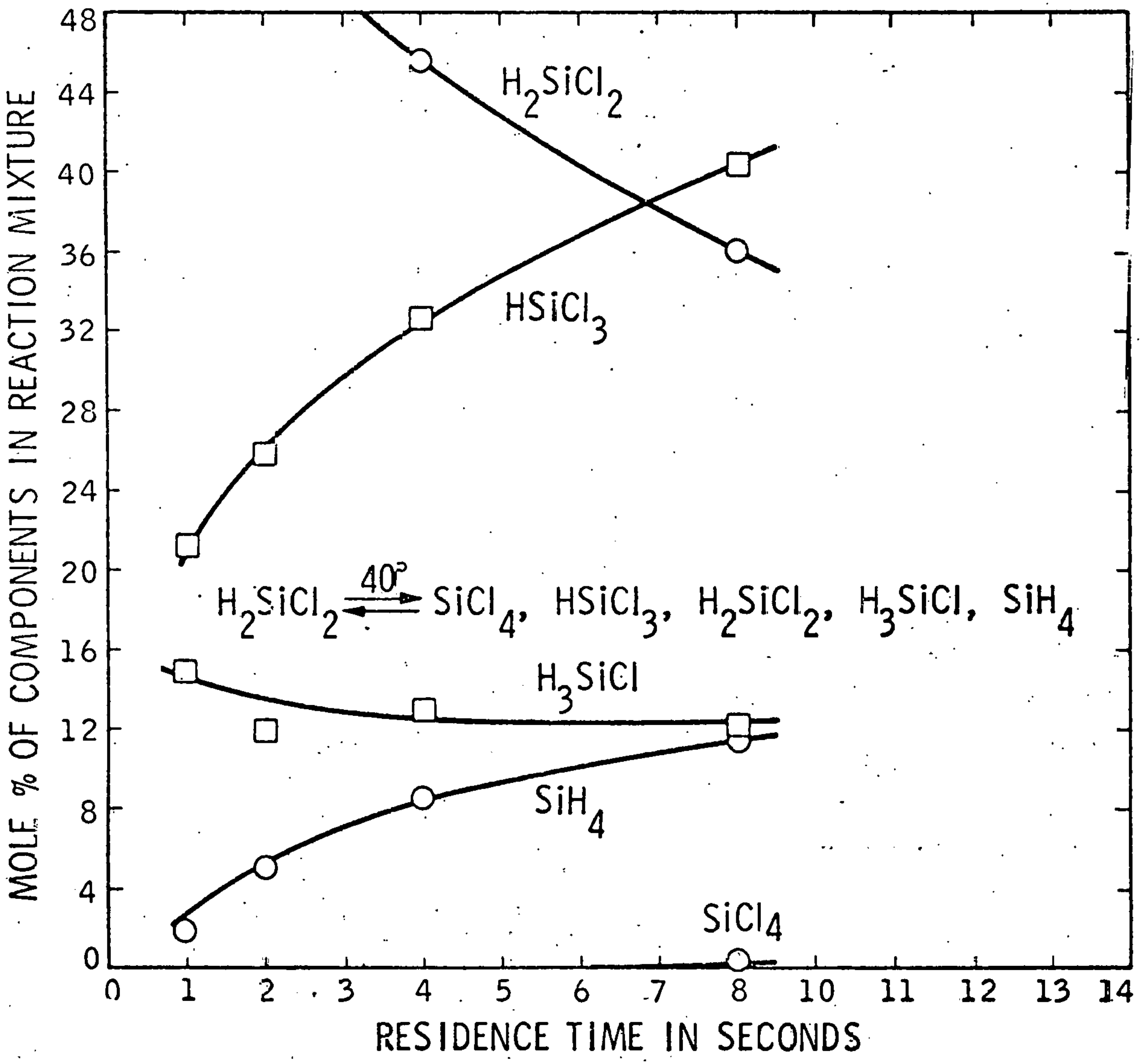
- OBJECTIVES
  - ESTABLISH ECONOMIC PRACTICALITY SiH_4 PROCESS
  - ESTABLISH ECONOMIC PRACTICALITY Si PRODUCTION USING SiH_4
- APPROACH FOR SiH_4 PRODUCTION
  - DISPROPORTIONATION OF CHLOROSILANE MIXTURES
  - HYDROGENATION OF $SiCl_4$ FOLLOWED BY DISPROPORTIONATION
  - SYNTHESIS SiH_2Cl_2 FOLLOWED BY DISPROPORTIONATION
- APPROACH FOR Si PRODUCTION
  - FREE FLOW GAS REACTOR
  - FLUIDIZED BED REACTOR

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
UNION CARBIDE CORP.

- DISPROPORTIONATION REACTION
  - KINETIC STUDIES OF CONVERSION SiH_2Cl_2 TO SiH_4
    - T-RANGE (40°C TO 80°C) AND SiH_2Cl_2 FLOW RATES (125 TO 1000 cc/min
    - RESIDENCE TIME
    - YIELD SiH_4 DEPENDENCE ON RESIDENCE TIME AND T
    - PRODUCTION RATE DEPENDENCE ON SiH_2Cl_2 FEED
  - HEAVIES
  - EFFECT OF RECYCLING
  - ESTIMATES BASED ON 1000 MT/yr PRODUCTION
    - EXPERIMENTAL DETERMINATIONS

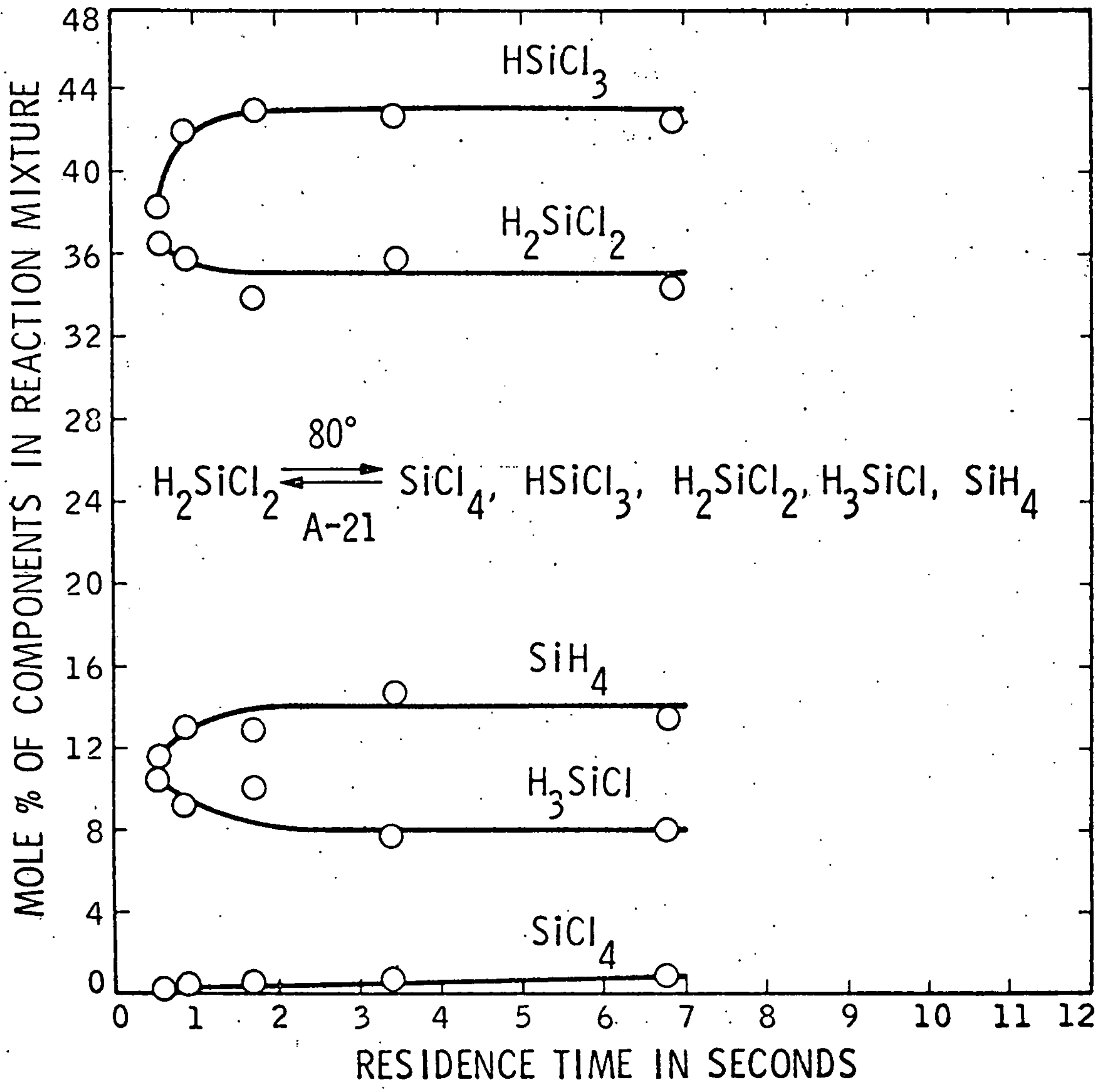
LOW-COST SILICON SOLAR ARRAY PROJECT

DISPROPORTIONATION OF H_2SiCl_2 OVER A-21 RESIN AT 40°



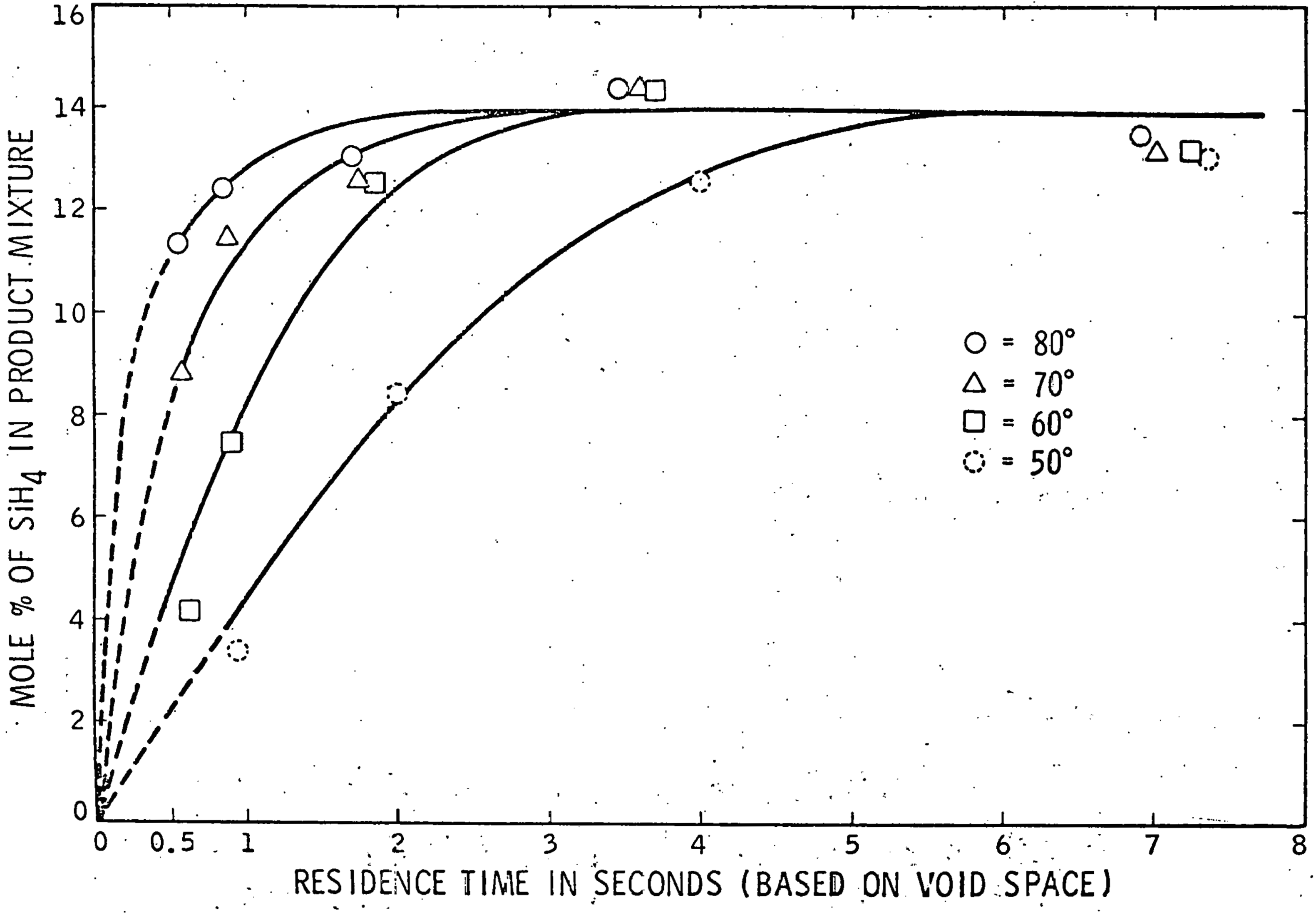
LOW-COST SILICON SOLAR ARRAY PROJECT

DISPROPORTIONATION OF H_2SiCl_2 OVER A-21 RESIN AT 80°



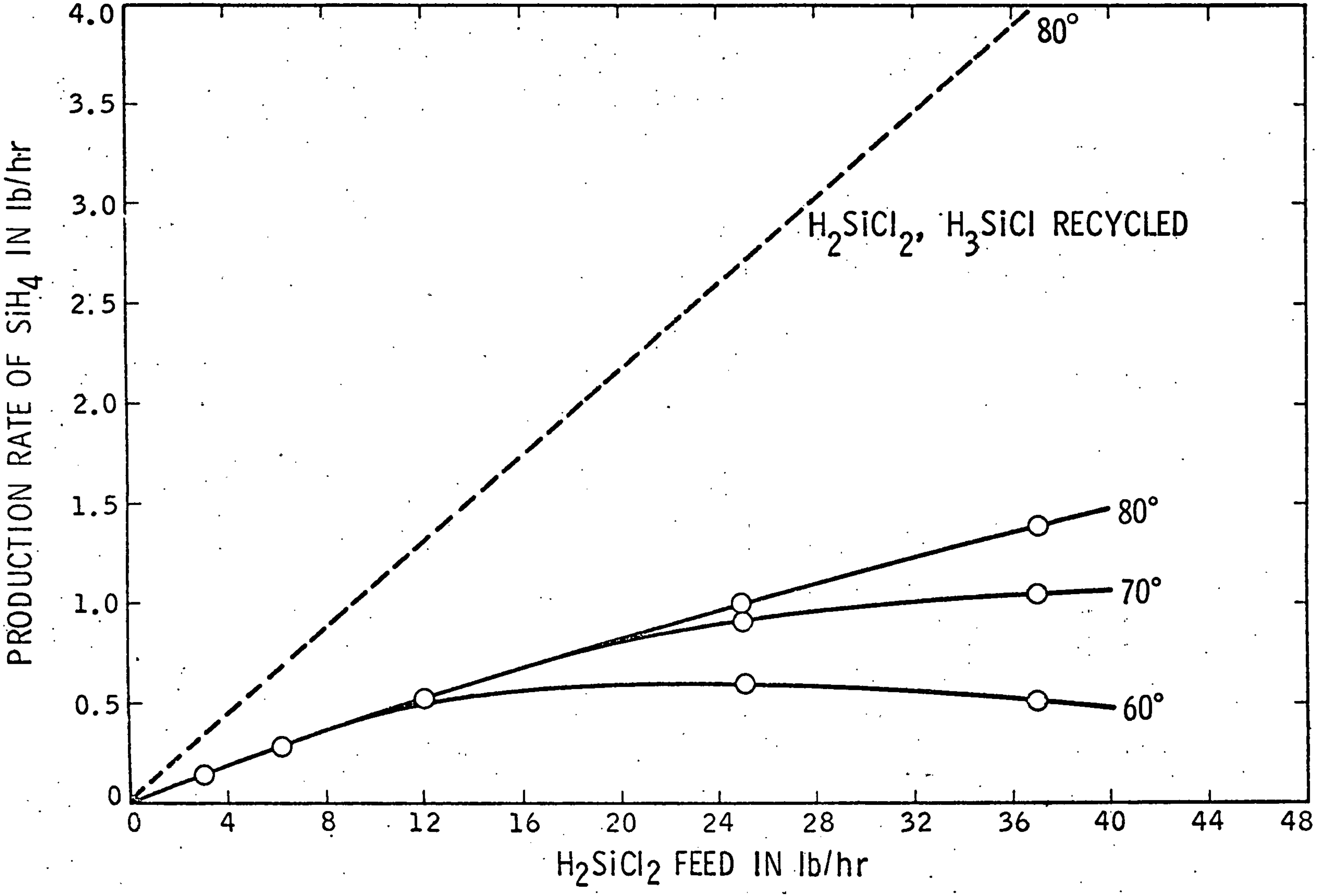
LOW-COST SILICON SOLAR ARRAY PROJECT

SiH_4 YIELD IN THE DISPROPORTIONATION OF H_2SiCl_2 OVER A-21 RESIN AT VARIOUS TEMPERATURES



LOW-COST SILICON SOLAR ARRAY PROJECT

RATE OF DISPROPORTIONATION OF H_2SiCl_2 TO SiH_4 BASED ON ONE POUND A-21



LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROGRESS

UNION CARBIDE CORP. (contd)

- HYDROGENATION OF $SiCl_4$ TO $SiHCl_3$
  - $3SiCl_4 + 2H_2 + Si \xrightarrow[550°C]{Cu} 4\ SiHCl_3$
  - PRELIMINARY RESULTS
  - RE-DESIGNED FLUIDIZED BED REACTOR
  - EXPERIMENTAL RESULTS
    - 15 TO 20% $SiHCl_3$ PER PASS

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROGRESS

UNION CARBIDE CORP. (contd)

- DIRECT SYNTHESIS OF SiH_2Cl_2
  - $Si + 2HCl \xrightarrow[H_2]{Cu} SiH_2Cl_2$
  - EXPERIMENTAL RESULTS
    - EFFECTS OF EXPERIMENTAL CONDITIONS
    - SiH_2Cl_2 INSTABILITY

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
UNION CARBIDE CORP. (contd)

- MINIPLANT FOR SiH_4
  - OBJECTIVES
    - DEMONSTRATE PRODUCTION 4.6 Kgm/day
    - VERIFY PRODUCT PURITY
    - DETERMINE OPERATING CHARACTERISTICS
    - SECURE DATA FOR DESIGN CRITERIA
  - STATUS
    - DESIGN AND FLOW CHART COMPLETED
    - INSTALLATION OF EQUIPMENT IN PROGRESS
    - INSTRUMENTATION BEING CHECKED AND INSTALLED
    - STORAGE OF SiH_4
  - NEXT PHASE
    - CALIBRATION OF INSTRUMENTS
    - PRESSURE TESTING
    - OPERATION CHARACTERISTICS

LOW-COST SILICON SOLAR ARRAY PROJECT

CONTRACT PROGRESS

WESTINGHOUSE ELECTRIC CORP.

- OBJECTIVE
  - DETERMINE EFFECTS OF IMPURITIES ON MATERIAL PROPERTIES AND SOLAR CELL PERFORMANCE
- APPROACH
  - DOUBLY AND MULTIPLY DOPED CZOCHRALSKI AND WEB CRYSTALS
  - INGOT EVALUATION
  - MEASUREMENTS ON WAFERS
  - MEASUREMENTS ON CELLS
  - ANALYSES OF MEASUREMENTS

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
WESTINGHOUSE ELECTRIC CORP. (Contd)

- STATUS
  - INGOT PREPARATIONS AND MEASUREMENTS:
    - FIRST AND SECOND GENERATIONS COMPLETED
    - THIRD GENERATION NEARLY COMPLETED
    - MULTIPLY-DOPED AND DENDRITIC WEB GROWN
    - CHEMICAL ANALYSES
    - RESISTIVITY

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
WESTINGHOUSE ELECTRIC CORP. (Contd)

- WAFER EVALUATIONS
  - MICROSTRUCTURAL EVALUATION
  - SPREADING RESISTANCE
  - MINORITY CARRIER RECOMBINATION LIFETIME
    - EFFECTS AT 550°C SINTERING
    - EFFECTS AT 825°C DIFFUSION
    - SURFACE RECOMBINATION VELOCITY MEASUREMENTS
    - IMPURITY EFFECTS
- GETTERING AND PRECIPITATION

LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
WESTINGHOUSE ELECTRIC CORP. (Contd)

- SOLAR CELL CHARACTERIZATION
  - DOUBLY DOPED
    - LARGE EFFECTS OF Ti AND V
    - MODERATE EFFECTS OF Cr, Mn, Fe, AND Al
    - SMALL EFFECTS OF Cu, Ni, AND Zr
- MULTIPLY DOPED
  - INDEPENDENT EFFECTS OF Cu + Cr AND Cu + Mn
  - COMBINED EFFECTS OF Mn + Cr

LOW-COST SILICON SOLAR ARRAY PROJECT

STATUS OF THE METAL-DOPED INGOTS WHICH FORM THE IMPURITY MATRIX FOR THIS PROGRESS

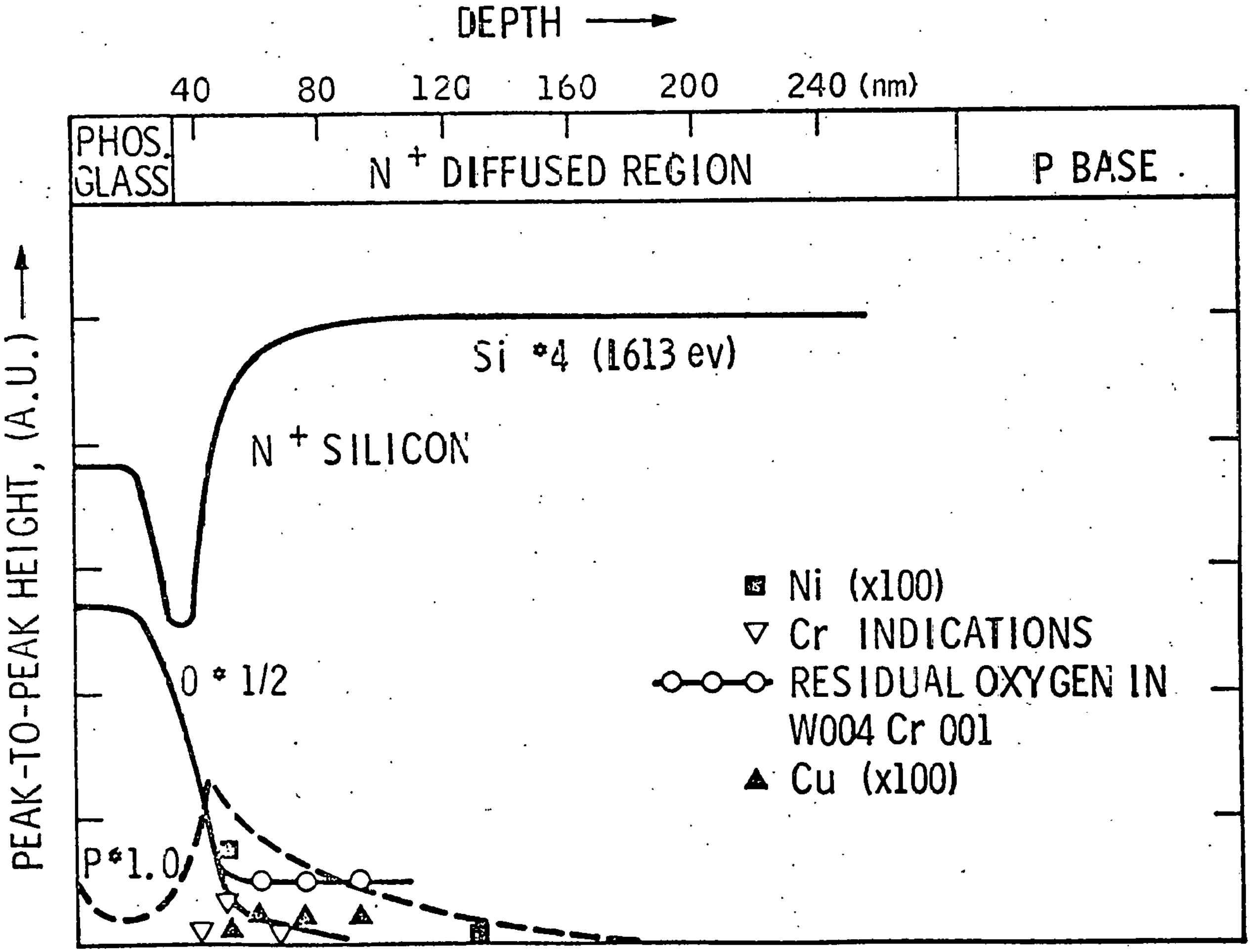
INGOT STATUS / CONCENTRATION RANGE

G-GROWN
F-CELL FABRICATED
T-CELL TESTED

IMPURITY ELEMENT	$<10^{14}$	5×10^{14} TO 1×10^{15}	1×10^{15} TO 5×10^{15}	5×10^{15} TO 1×10^{16}	$>10^{16}$
Cr	G, F	G, F, T	G, F, T		
Mn	G, F, T	G, F, T	G, F, T		
Cu		G, F, T	G, F, T	G, F, T	
Ni		G, F, T	G, F, T		
Fe			G, F, T		
Ti	G, F, T	G, F, T			
V	G, F, T	G, F, T			
Mg	G, F, T	G, F, T			
Zn	G, F, T				
Zr		G, F, T			
Al					G, F, T

LOW-COST SILICON SOLAR ARRAY PROJECT

AUGER DEPTH PROFILES OF PHOSPHORUS DIFFUSED WAFERS SHOWING PILE-UP OF IMPURITIES IN THE N+ REGION



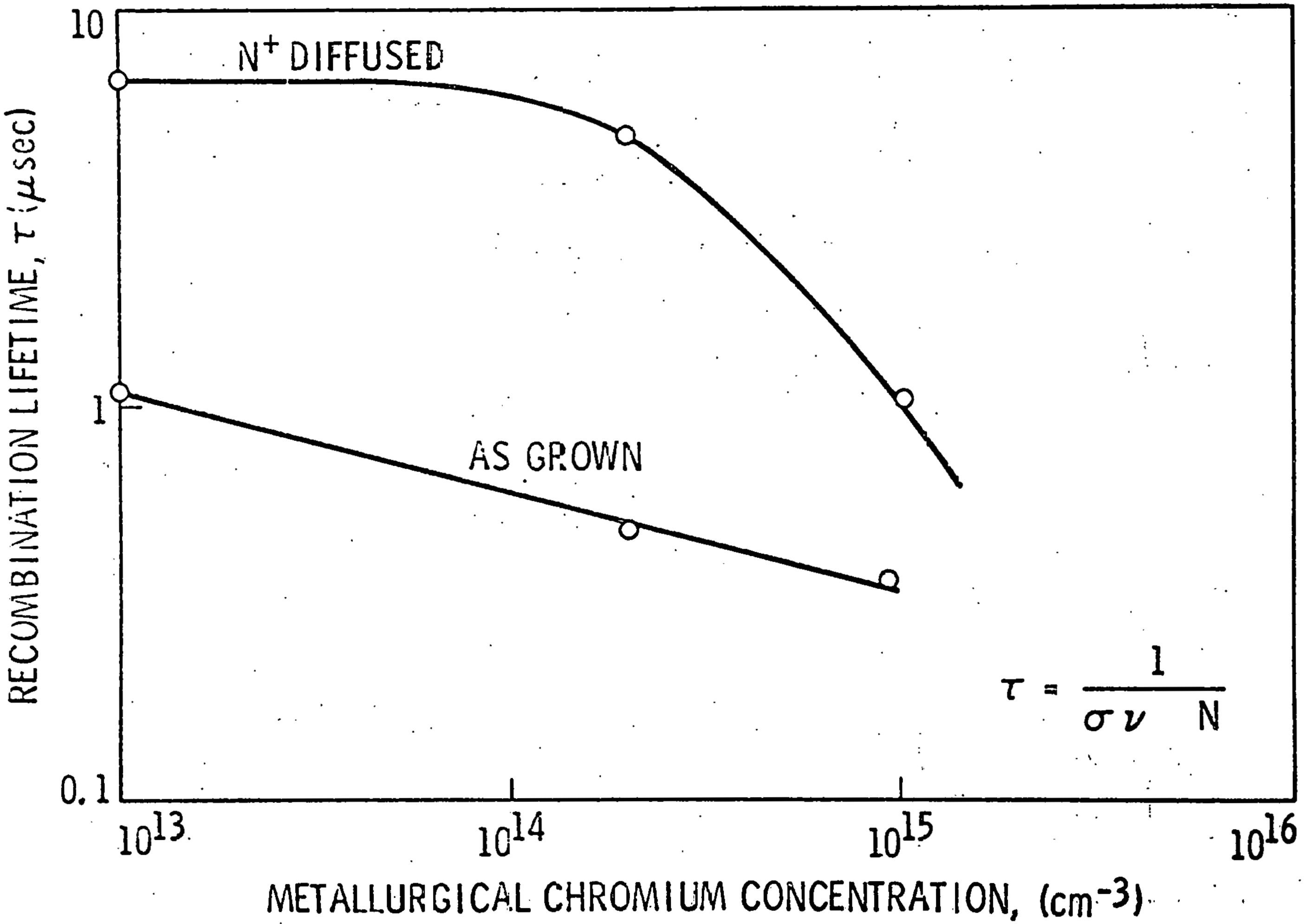
LOW-COST SILICON SOLAR ARRAY PROJECT

EFFECT OF HEAT TREATMENT ON RECOMBINATION LIFETIME τ_r (μsec)

SPECIMEN IDENTIFICATION	AS-GROWN	ANNEALED 5 Hrs @ 550 °C	ANNEALED 50 Min @ 825°C	PHOSPHORUS DIFFUSED 50 Min @ 825°C
W001 BASELINE	5.0	5.3	5.7	7.2
W004-CR001	0.4	1.0	0.7	1.1
W021-CR002	0.5	—	3.2	4.5
W010-NI002	4.1	7.4	4.5	9.4
W013-MN002	< 0.3	2.1	4.1	10.5
W009-V001	< 0.3	< 0.3	< 0.3	< 0.3
W007-CU001	5.4	8.5	3.6	4.4
W008-TI001	2.0	1.8	0.3	0.5

LOW-COST SILICON SOLAR ARRAY PROJECT

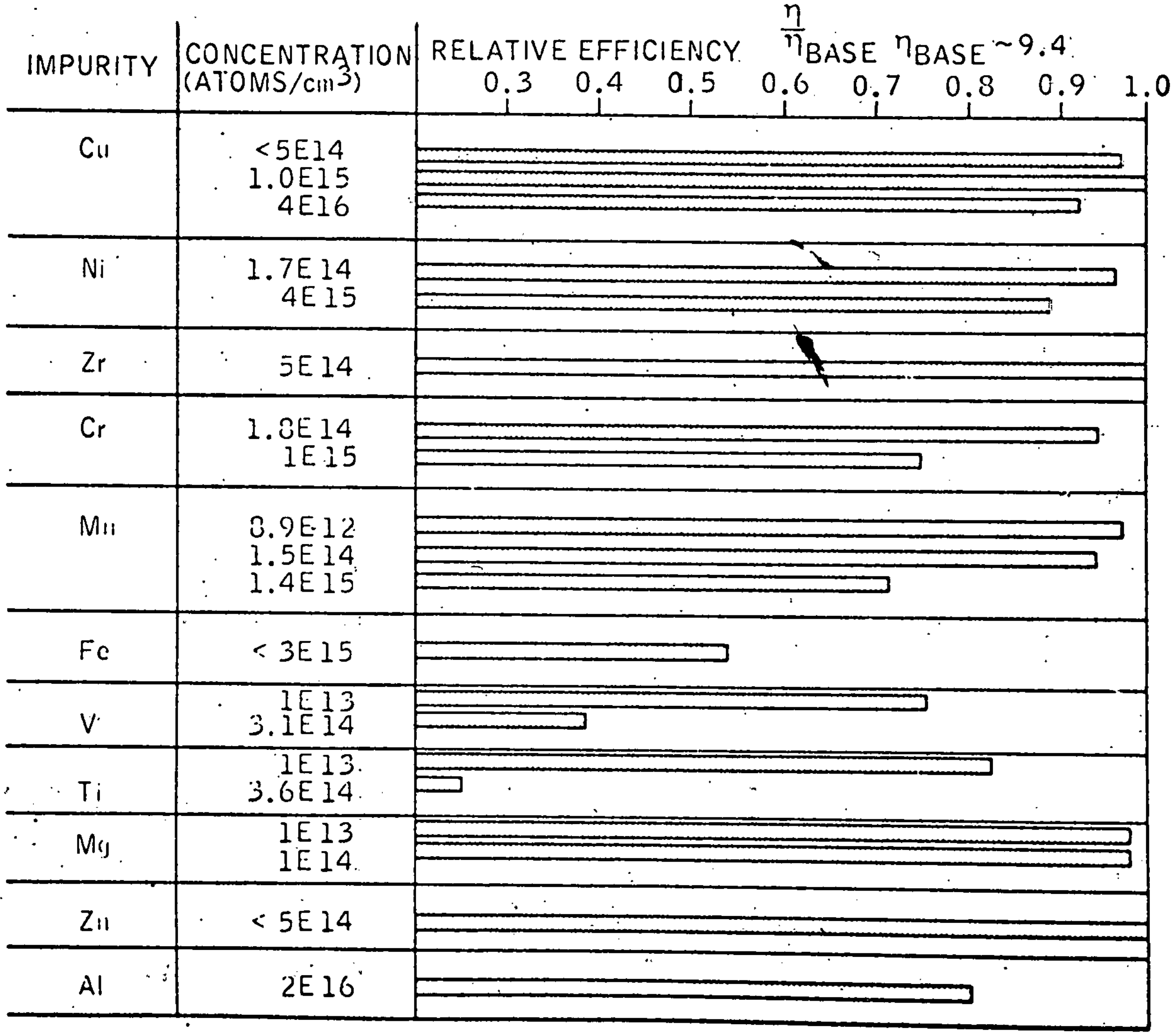
CORRELATION BETWEEN RECOMBINATION LIFETIME AND METALLURGICAL CONCENTRATION OF CHROMIUM IMPURITY



LOW-COST SILICON SOLAR ARRAY PROJECT

VARIATION IN SOLAR CELL PERFORMANCE WITH METAL DOPING NO AR COATING, AM1 QUARTZ-IODINE ILLUMINATION

EFFECT OF METAL DOPING
ON SOLAR CELL EFFICIENCY (UNCOATED)



LOW-COST SILICON SOLAR ARRAY PROJECT
CONTRACT PROGRESS
LAMAR UNIVERSITY

- OBJECTIVE
  - CHEMICAL ENGINEERING ANALYSES OF PROCESSES
  - ECONOMIC EVALUATIONS OF PROCESSES
- STATUS
  - PROCESS SYSTEM PROPERTIES ANALYSES
  - CHEMICAL ENGINEERING ANALYSES
    - KEY GUIDELINE ITEMS FOR PRELIMINARY PROCESS DESIGN
    - INFORMATION EXCHANGES
    - CONDITIONS
    - 1000 MT/YEAR - GRADE Si - JANUARY 1975 COST INDEX
    - PROCESS FOR Zn REDUCTION OF $SiCl_4$
- ECONOMIC ANALYSES
  - REVIEW OF APPLICABILITY OF ESTIMATION METHODS

LOW-COST SILICON SOLAR ARRAY PROJECT
NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW

LARGE AREA SILICON SHEET TASK

Dr. J. ZOUTENDYK
TASK MANAGER

AUGUST 1976

LABORATORY	R&D AREA
RIBBON GROWTH	
MOBIL-TYCO	EFG
IBM	CAST
U. SO. CAR.	WEB-DENDRITE
RCA	IST
MOTOROLA	RTR
SHEET GROWTH	
HONEYWELL	DIP-COATING
ROCKWELL	CVD
GE	FLOATING SUBSTRATE
U. PENN.	HOT-FORMING
INGOT GROWTH/CUTTING	
CRYSTAL SYSTEMS	HEM/MULTIPLE WIRE SAW
INGOT CUTTING	
VARIAN	MULTIPLE BLADE SAW

MOBIL-TYCO

EFG

START: OCTOBER, 1975 END: APRIL, 1977

PROGRESS

- NON-EQUILIBRIUM RIBBON GROWTH AT 7 cm/minute
- MODIFICATION OF FAST-THIN GROWTH MACHINE (25 mm wide) WITH AFTER HEATERS (ACTIVE THERMAL CONTROL)
- DESIGN OF 75 mm WIDE RIBBON GROWTH MACHINE WITH AFTER HEATERS (ACTIVE THERMAL CONTROL)
- THERMAL ANALYSIS FOR FAST, LOW- STRESS RIBBON GROWTH
- MATERIAL CHARACTERIZATION (SPREADING RESISTANCE, EBIC)

PROBLEMS

- UNSTABLE RIBBON GROWTH WITH INITIAL RUNS USING ACTIVE THERMAL CONTROL (NEED AFTER HEATER DESIGN ITERATIONS)

PLANS

- STABLE GROWTH OF 25 mm RIBBON AT 7.5 cm/minute (FAST-THIN MACHINE)
- COMPLETE FABRICATION OF 75 mm GROWTH MACHINE
- GROWTH OF 50 mm WIDE RIBBON
- IDENTIFICATION OF ELECTRICALLY ACTIVE DEFECTS
- SOLAR CELL CHARACTERIZATION

IBM

CAST

START: MAY, 1975 END: DECEMBER, 1976

PROGRESS

- GROWTH OF RIBBONS WITH REDUCED SURFACE CONTAMINATION (CLOSED SYSTEM)
- SUPPRESSION OF SIC INCLUSIONS (GRAPHITE DIE DESIGN)
- GROWTH OF 38mm WIDE RIBBON AT <2 cm/minute WITH PASSIVE THERMAL CONTROL ONLY
- MATERIAL CHARACTERIZATION (SPREADING RESISTANCE)
- ECONOMIC ANALYSIS OF RIBBON GROWTH (SENSITIVITY ANALYSIS)

PROBLEMS

- PASSIVE THERMAL CONTROL GIVES STABLE, LOW-STRESS GROWTH ONLY AT LOW SPEED (<3 cm/minute)

PLANS

- DESIGN, FABRICATION OF 50mm WIDE DIES
- GROWTH OF 50mm WIDE RIBBON WITH PASSIVE THERMAL CONTROL ONLY (SLOW GROWTH)
- MATERIAL CHARACTERIZATION (MOS LIFETIME, SEM, SOLAR CELLS)
- SOLAR CELL CHARACTERIZATION
- COMPARISON WITH RIBBON GROWTH

UNIV. SO. CAROLINA

WEB-DENORITE GROWTH

START: OCTOBER, 1975 END: MAY, 1977

PROGRESS

- STUDY OF TWIN NUMBER AND SPACING FOR OPTIMAL DENDRITIC GROWTH (TPREM)
- GROWTH OF 2 cm WIDE WEB (< 2 cm/minute)
- CONSTRUCTION OF SOFTWARE FOR COMPUTER THERMAL ANALYSIS OF CRUCIBLE (SUPER COOLING OF MELT) AND WEB-GROWTH REGIONS FOR ACTIVE CRUCIBLE CONTROL ONLY (NO AFTERHEATERS)

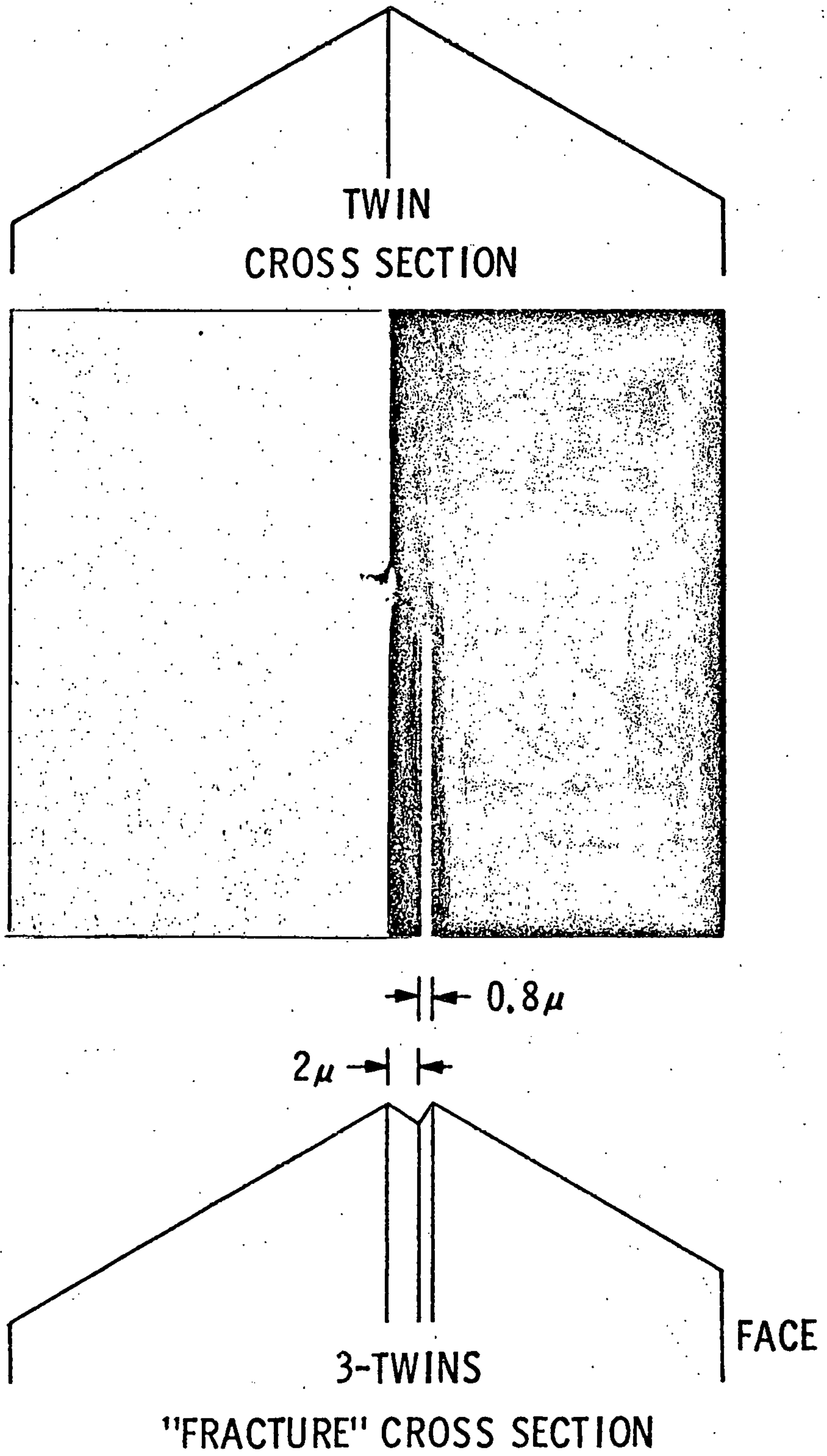
PROBLEMS

- GROWTH OF THIRD DENDRITE DUE TO IMPROPER CRUCIBLE - MELT THERMAL CONTROL

PLANS

- APPLICATION OF COMPUTER ANALYSIS TO CRUCIBLE DESIGN (DENDRITE GROWTH) AND WEB GROWTH
- GROWTH OF 5 cm WIDE WEB
- MATERIAL CHARACTERIZATION
- SOLAR CELL CHARACTERIZATION

TWIN SPACING IN SILICON DENDRITES



RCA

INVERTED STEPANOV TECHNIQUE

START: APRIL, 1976 END: JUNE, 1977

PROGRESS

- MODIFICATION OF GROWTH MACHINE WITH "V-SHAPE" VARIABLE SPACING SiO_2 DIE
- THERMAL ANALYSIS FOR IST CONFIGURATION

PROBLEMS

- THERMAL CONTROL OF LOWER PORTION OF DIE TO PREVENT FREEZING

PLANS

- GROWTH OF 375 m (15 mil) THICK RIBBON FROM "V" SiO_2 DIE (1 cm WIDE)
- DESIGN AND CONSTRUCTION OF GROWTH MACHINE WITH SUPPORTED SiO_2 DIE (FAST-THIN RIBBON GROWTH)
- MATERIAL CHARACTERIZATION
- SOLAR CELL CHARACTERIZATION

MOTOROLA

RIBBON-TO-RIBBON GROWTH

START: FEBRUARY, 1976 END: APRIL, 1977

PROGRESS

- COMPLETION OF RTR MACHINE WITH FOCUSSING OF CO_2 LASER POWER ON BOTH SIDES OF RIBBON
- SLOW GROWTH OF 10 mm WIDE RIBBON FROM POLYCRYSTALLINE AND SINGLE CRYSTAL FEED MATERIAL
- THERMAL ANALYSIS FOR RTR GROWTH (NO AFTERHEATERS)

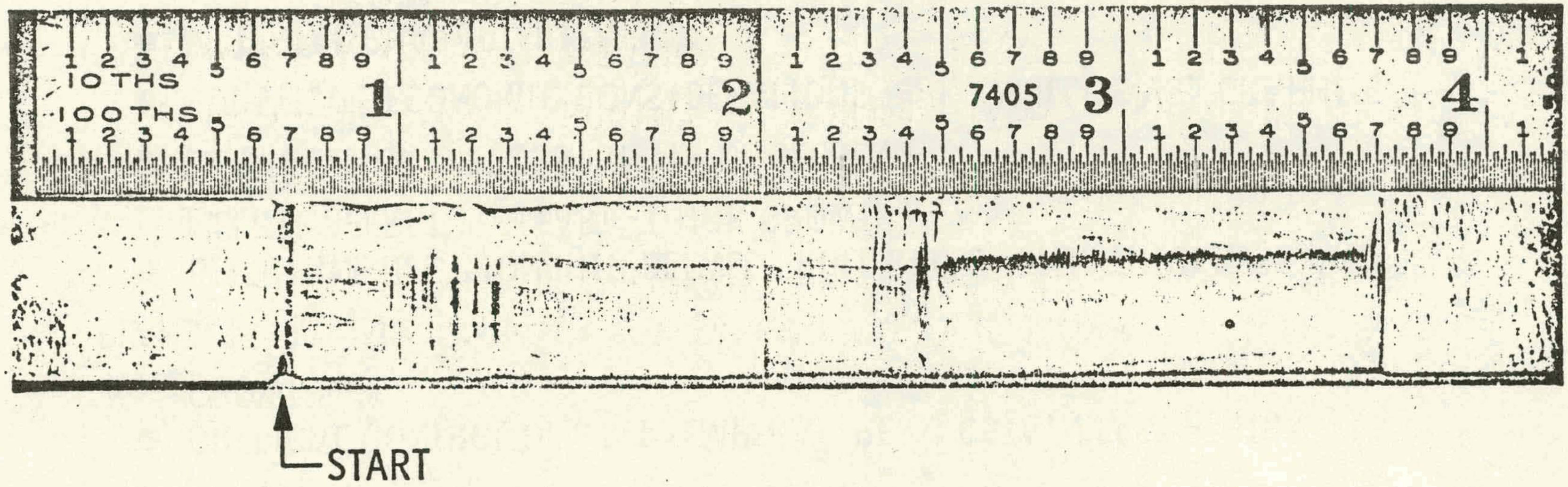
PROBLEMS

- CRITICAL OPTIMIZATION OF LASER BEAM FOCUSSING AND POWER INPUT FOR FAST-THIN RIBBON GROWTH

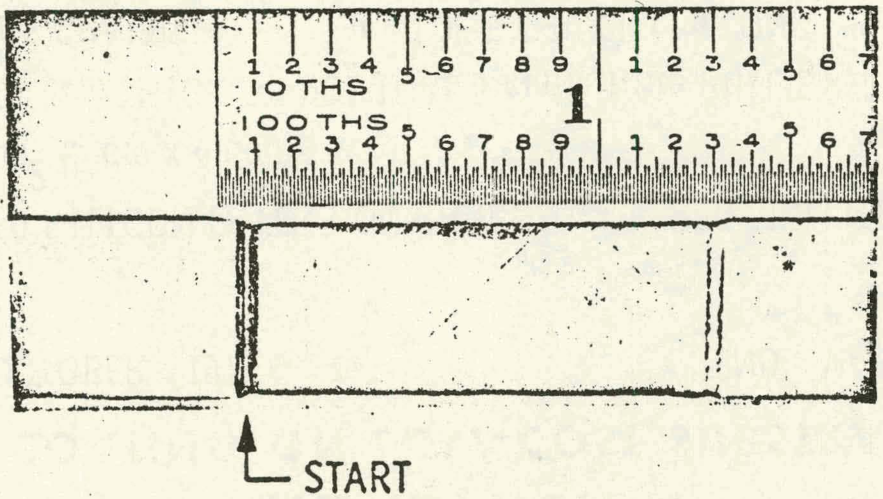
PLANS

- FAST-THIN RIBBON GROWTH (GOAL = 18 cm/minute)
- MATERIAL CHARACTERIZATION
- SOLAR CELL CHARACTERIZATION

MOTOROLA RIBBON GROWN FROM POLY-ROD SEED. AS GROWN



MOTOROLA RIBBON GROWN FROM (100) SEED. AS GROWN



HONEYWELL

DIP-COATING ON LOW-COST SUBSTRATES

START: OCTOBER, 1975 END: MARCH, 1977

PROGRESS

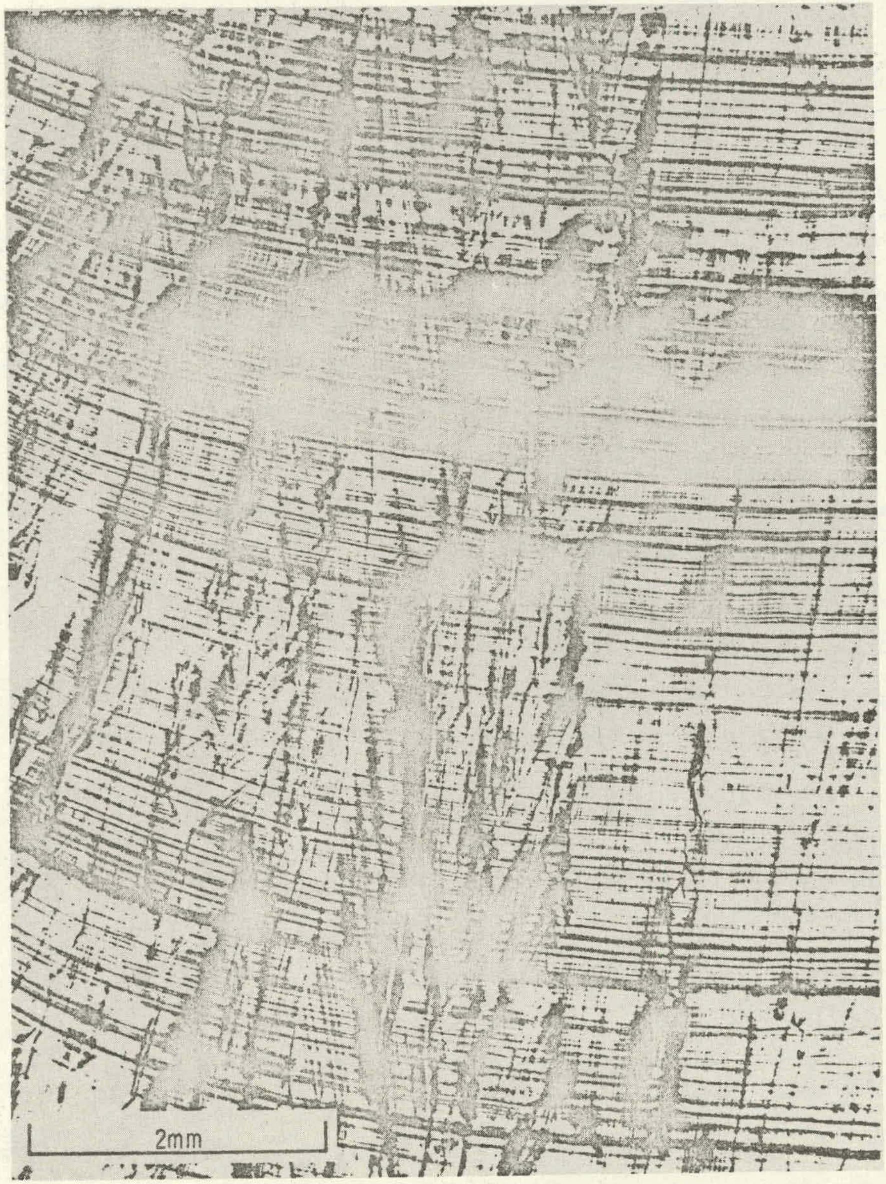
- DIP-COATED SILICON LAYERS ON CARBON-COVERED MULLITE:
    - 20 cm^2 (5 cm x 4 cm)
    - 30-50 μm THICK AT NOMINAL 5 cm/minute PULL SPEED
    - LARGE GRAINS : ~1 mm WIDE BY 10-20 mm LONG
    - NO GROSS CONTAMINATION OF Si FROM IMPURITIES IN MULLITE (EDAX -ENERGY DISPERSION)

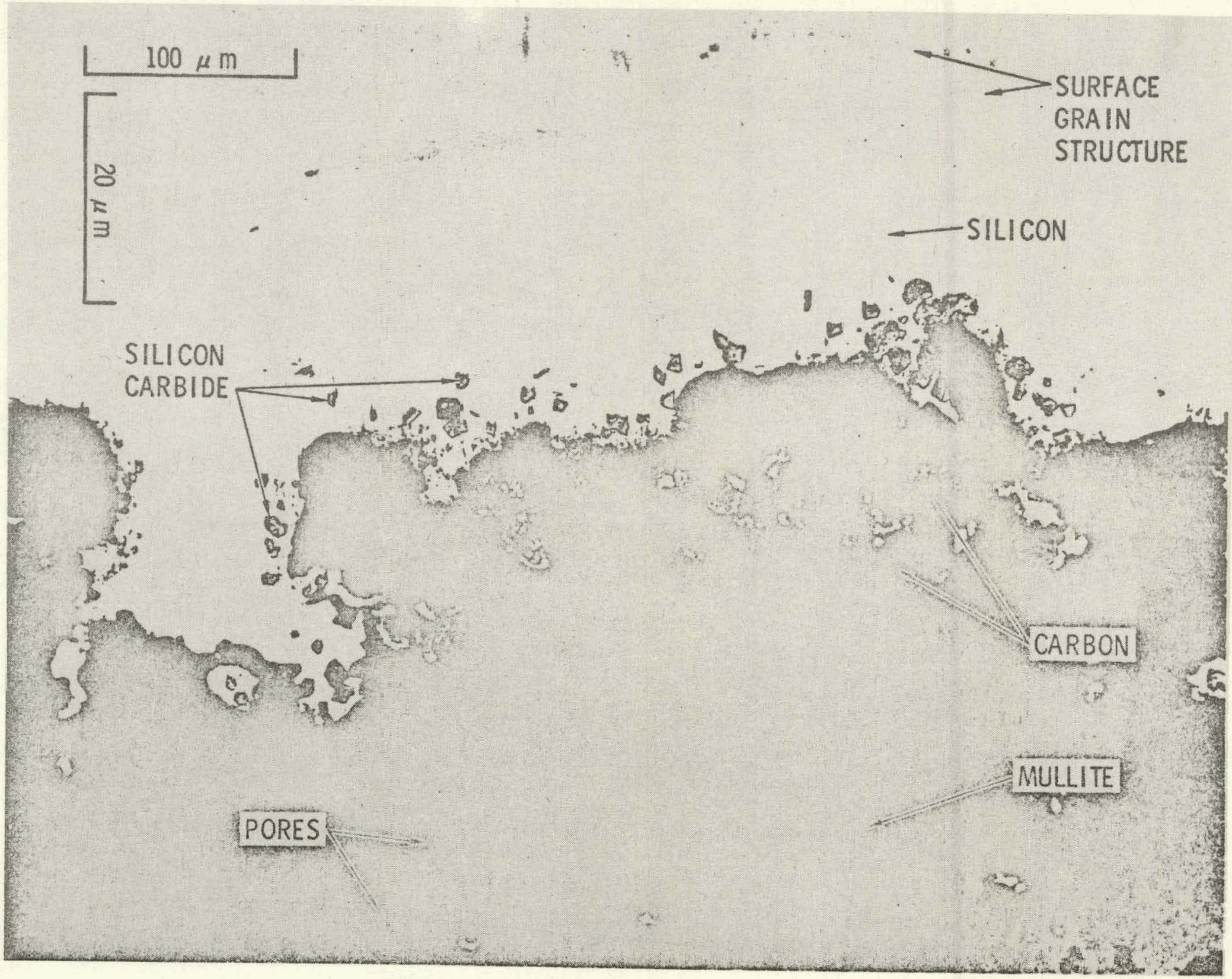
PROBLEMS

- CRITICAL CONTROL OF MELT TEMPERATURE TO OBTAIN FAST -THICK GROWTH

PLANS

- DETERMINE RELATIONSHIP BETWEEN PULL SPEED, FILM THICKNESS AND MELT TEMPERATURE (FAST -THICK GROWTH)
- EXAMINATION OF POSSIBILITY OF SEEDING
- SUBSTRATE ECONOMIC CONSIDERATIONS (e.g., MULLITE VS. GRAPHITE)
- MATERIAL CHARACTERIZATION
- SOLAR CELL CHARACTERIZATION

HONEYWELL SPECIMEN MR-8 AS GROWN SURFACE

HONEYWELL SAMPLE MR-8 ANGLE MOUNT AND POLISH WITH NO ETCH



ROCKWELL

CVD ON LOW-COST SUBSTRATES

START: JANUARY, 1976 END: JUNE, 1977

PROGRESS

- GROWTH OF ~5 μm DIAMETER WIDE ORIENTED GRAINS ON GLASS SUBSTRATES
- PARTIAL EPITAXIAL GROWTH OF UP TO 300 μm DIAMETER GRAINS ON LARGE GRAIN POLYCRYSTALLINE ALUMINA SUBSTRATES

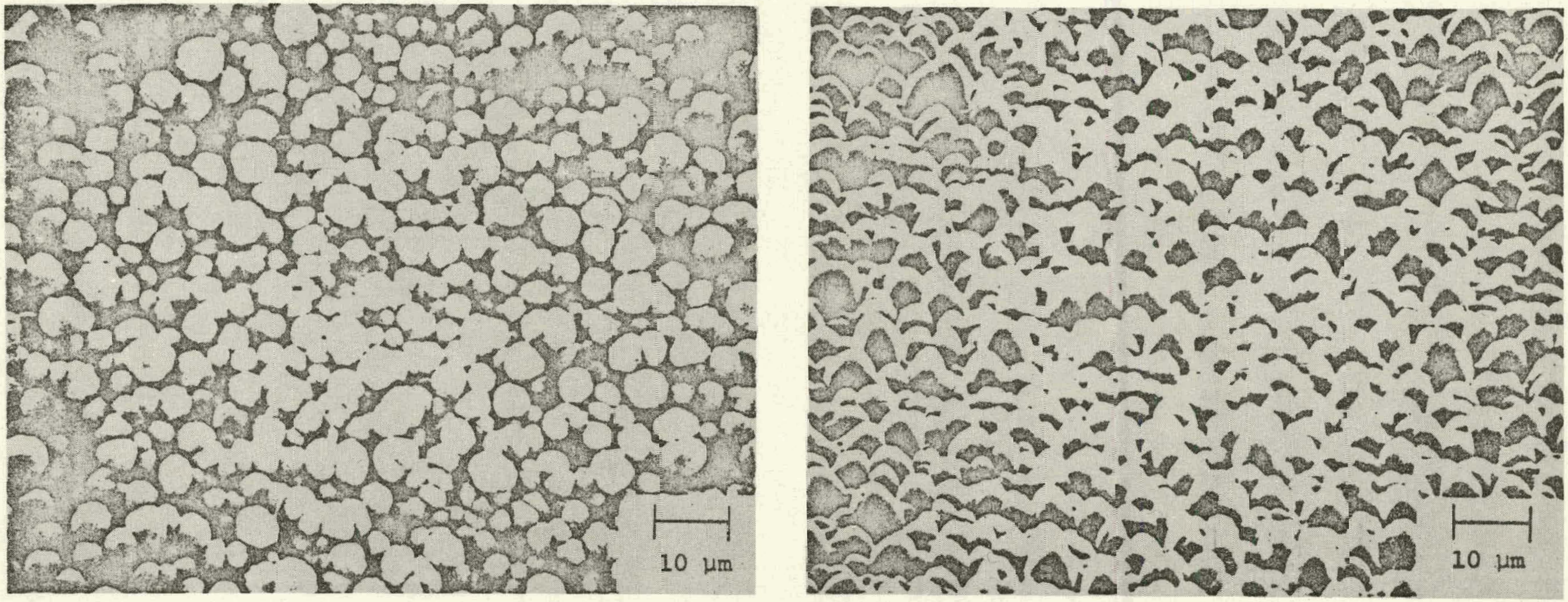
PROBLEMS

- REACTION OF GLASS SUBSTRATES WITH H_2 NECESSITATES USE OF He FOR GAS TRANSPORT (LIMITED TEMPERATURE RANGE)

PLANS

- INVESTIGATE OTHER GLASS / CERAMIC SUBSTRATE MATERIALS
- GRAIN SIZE ENHANCEMENT WITH TWO-STEP PROCESS
- MATERIAL CHARACTERIZATION
- SOLAR CELL CHARACTERIZATION

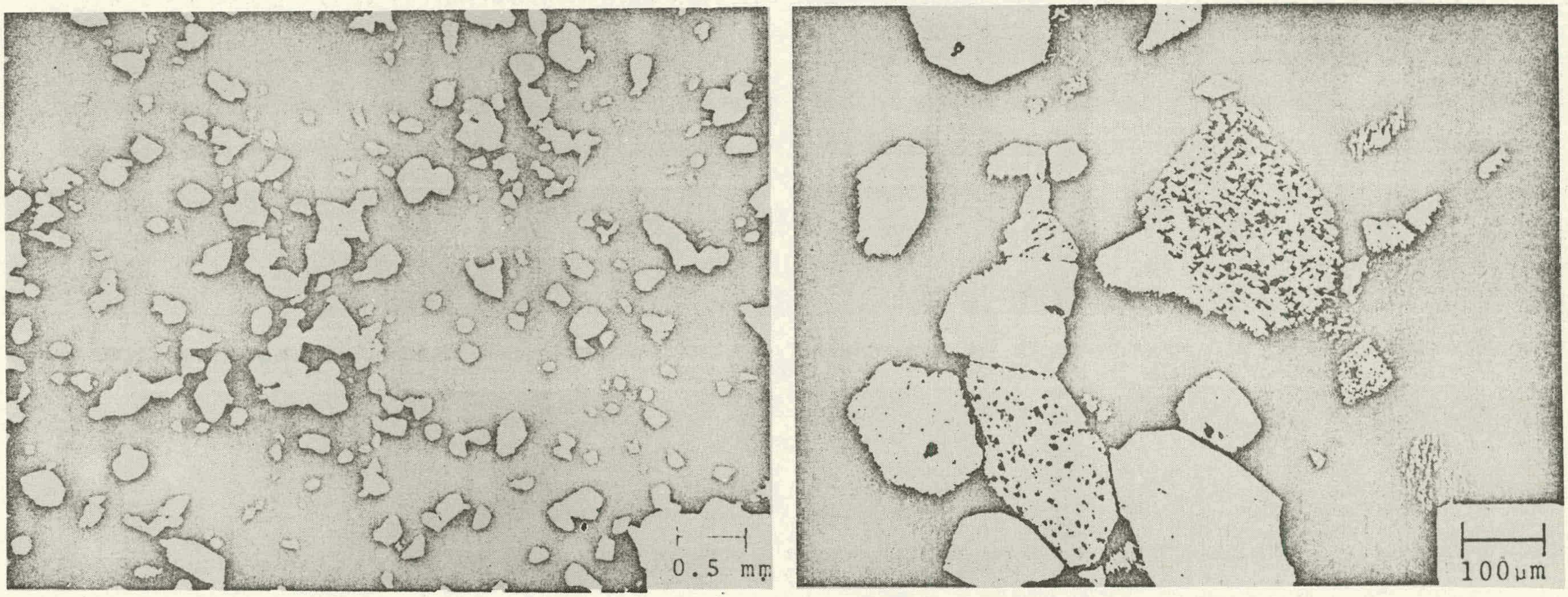
SEM PHOTOGRAPHS OF SURFACE OF CVD Si DEPOSITED ON CORNING CODE 1715 GLASS BY SiH$_4$ PYROLYSIS AT 1000°C IN He



(A) VIEW AT NORMAL INCIDENCE

(B) VIEW AT 45 DEG TO SURFACE

OPTICAL PHOTOMICROGRAPHS OF CVD Si FILM ON POLISHED VISTAL 4 POLYCRYSTALLINE ALUMINA SUBSTRATE, AT TWO DIFFERENT MAGNIFICATIONS



(A)

(B)

GE

FLOATING-SUBSTRATE GROWTH

START: FEBRUARY, 1976 END: JANUARY, 1977

PROGRESS

- SUPER-COOLING OF Si/Sn SOLUTIONS MEASURED
- SILICON UPTAKE BY MOLTEN TIN FROM SILANE REDUCTION MEASURED
- SEEDED CRYSTAL GROWTH ON Si/Sn SURFACE ACHIEVED (~0.5 mm x 0.3 mm FACETED CRYSTALS)

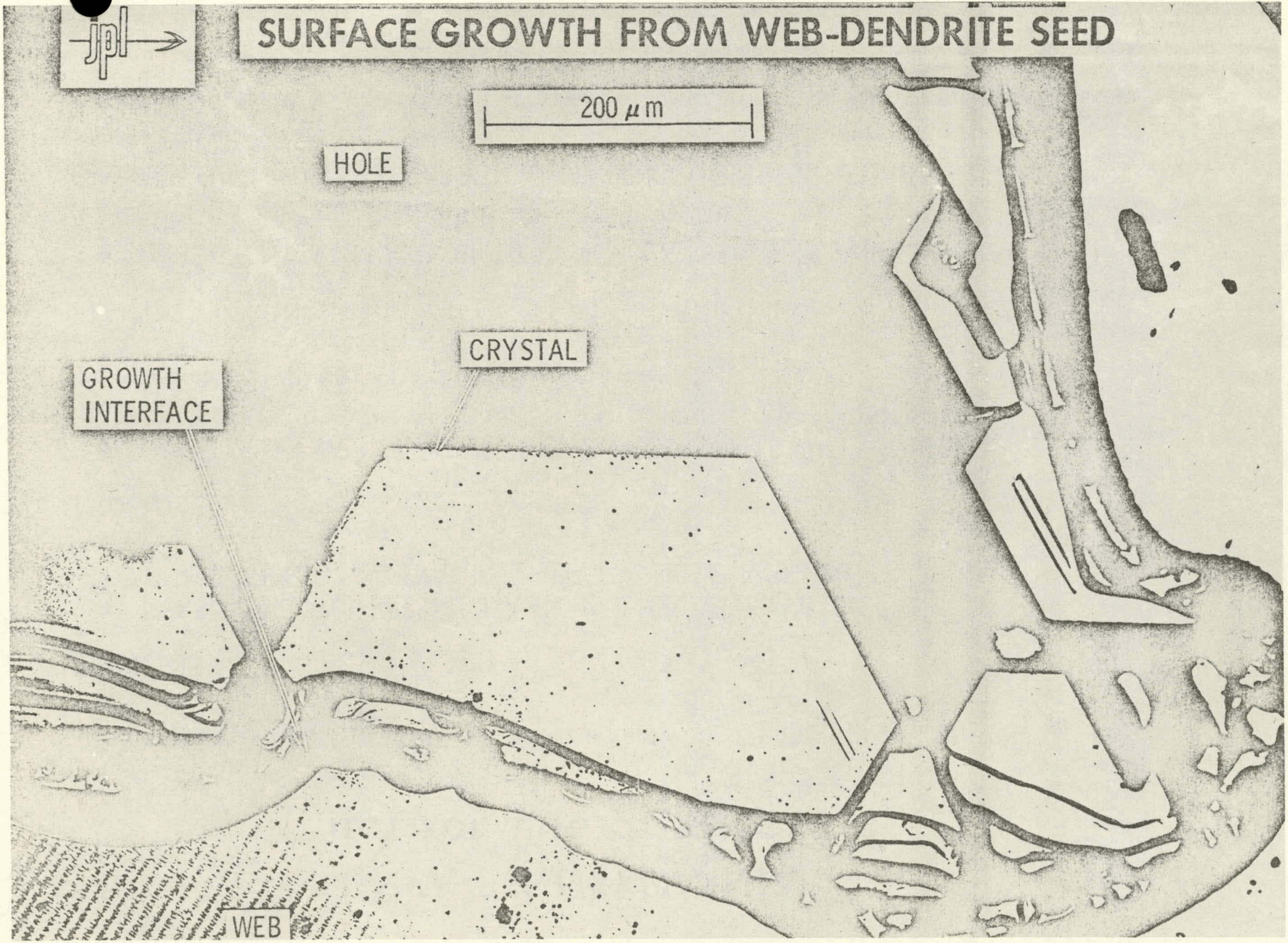
PROBLEMS

- SUSTAINING UNIFORM CRYSTAL GROWTH FRONT ON Si/Sn SURFACE

PLANS

- ACHIEVE PROPAGATION OF CRYSTAL GROWTH FRONT ON Si/Sn SURFACE (GOAL = 0.5 cm^2 CRYSTAL AREA)

SURFACE GROWTH FROM WEB-DENDRITE SEED



UNIV. PENNSYLVANIA

HOT-FORMING OF SILICON

START: MAY, 1976 END: APRIL, 1977

PROGRESS

- MEASUREMENT OF PRESSURE REQUIRED FOR DEFORMATION RATES UP 10^{-1} $\sec^{-1}$ FOR TEMPERATURES BETWEEN 1100°C AND 1380°C

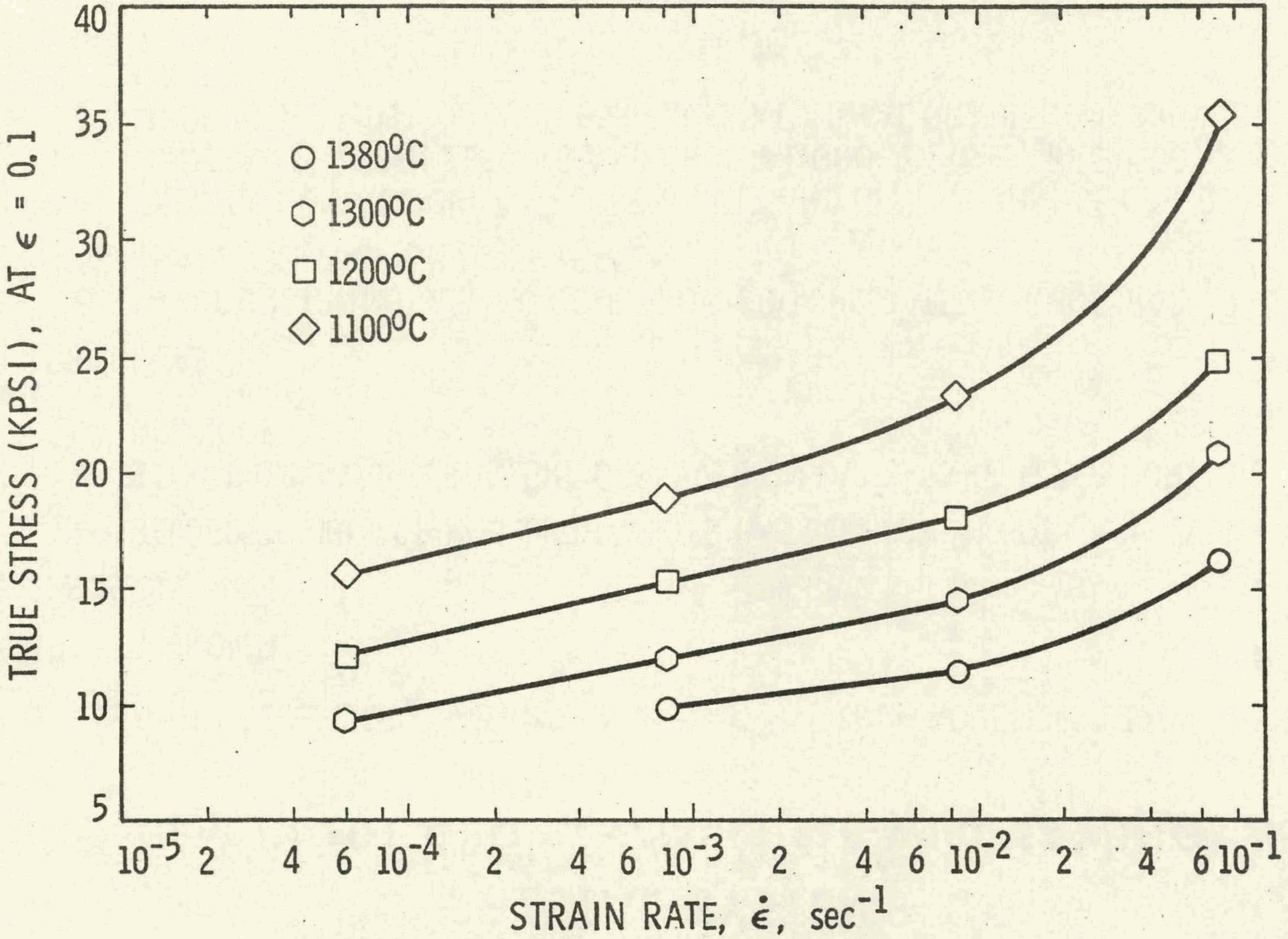
PROBLEM

- COST-EFFECTIVE HOT-ROLLING OF SILICON SHEETS WILL REQUIRE DEFORMATION RATES OF 10 $\sec^{-1}$ OR HIGHER (i.e., PRESSURES IN EXCESS OF 20 KSI AT >1300°C)

PLANS

- MEASURE STRAIN RATES UP TO 10 $\sec^{-1}$ VS. PRESSURE AND TEMPERATURE
- MEASURE CRYSTALLOGRAPHIC DEPENDENCE OF STRESS-STRAIN BEHAVIOR
- EXAMINE FORMING-LIMIT AND ANNEALING PROPERTIES OF DEFORMED SILICON

STRAIN RATE SENSITIVITY FOR SILICON



CRYSTAL SYSTEMS

HEM INGOT GROWTH/MULTIPLE-WIRE SAWING

START: DECEMBER, 1975 END: NOVEMBER, 1977

HEM INGOT GROWTH

PROCESS

- SEEDED GROWTH OF 12.5 cm DIAMETER (~5 cm HIGH) INGOTS ACHIEVED
- SINGLE CRYSTAL STRUCTURE OBSERVED ON LAST-TO-FREEZER PORTION OF INGOT

PROBLEMS

- INGOT CRACKING DURING COOL-DOWN COMPLICATES STRUCTURAL CHARACTERIZATION OF CRYSTAL
- PRECISE CONTROL OF ΔT BETWEEN MELT AND HEAT-EXCHANGER NEEDED TO OBTAIN PROPER SEEDING AND CRYSTAL GROWTH (i.e., BREAKDOWN IN CRYSTALLINITY OCCURS FOR EXCESS THERMAL GRADIENT AT GROWTH INTERFACE)

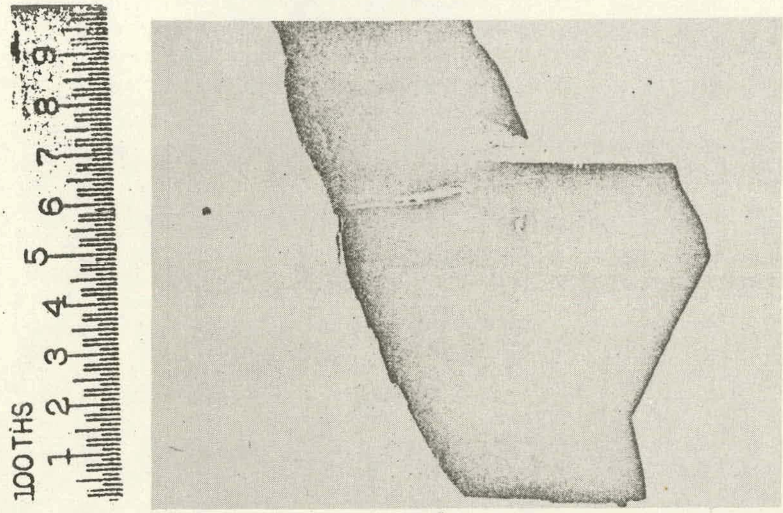
PLANS

- OPTIMIZE CONTROL OF ΔT VS. TIME FOR SINGLE CRYSTAL GROWTH
- DETERMINE OPTIMUM INGOT GROWTH RATE (KG/HOUR)

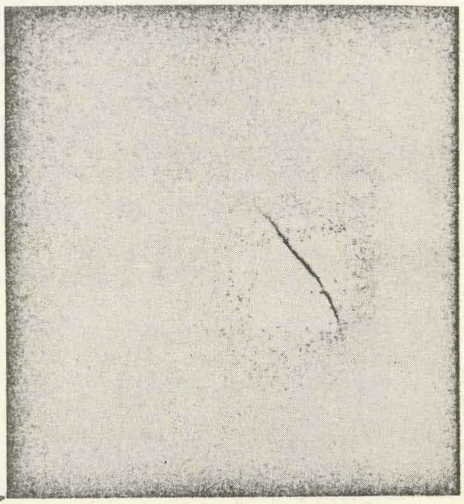
CONTROLLED CASTING OF SILICON INGOTS

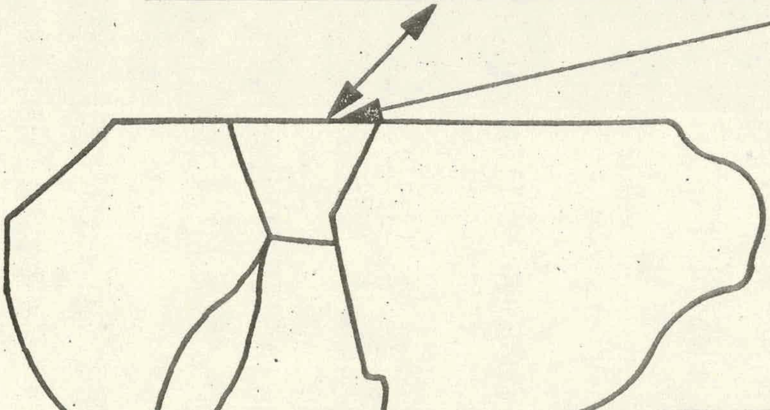
CRYSTAL SYSTEMS INGOT NO. 13A

OPTICAL MACROPHOTOGRAPH
OF SELECTED SECTION

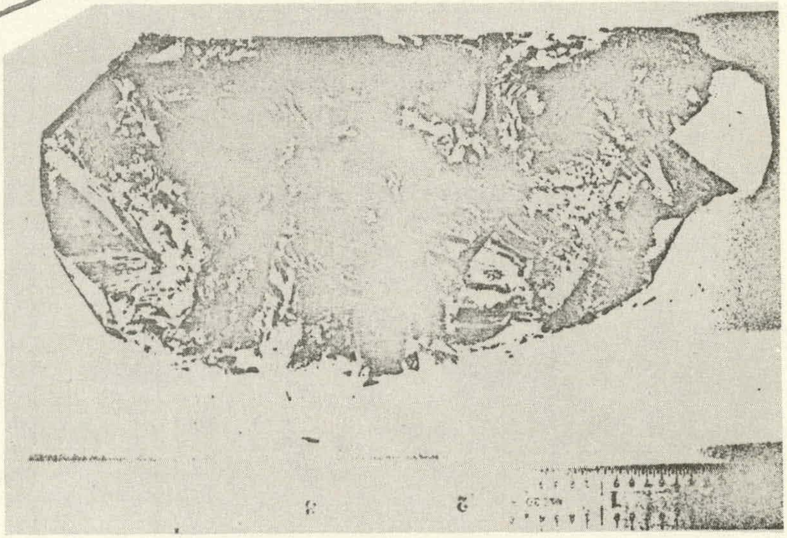


(211) BERG-BARRETT
TOPOGRAPH





SCHEMATIC VIEW OF INGOT



OPTICAL MACROPHOTOGRAPH
OF CAST INGOT

CRYSTAL SYSTEMS/VARIAN

START: JANUARY, 1976 END:

MULTIPLE WIRE/BLADE CUTTING

PROGRESS

- MODIFICATION OF VARIAN SAW(S) FOR WIRE BLADE CUTTING COMPLETE
- KEY CUTTING PARAMETERS DEFINED

PROBLEMS

- COMPLETE INVESTIGATION OR CUTTING PARAMETERS VERY TIME CONSUMING

PLANS

- CONTROL CUTTING VARIABLES TO ACHIEVE:
  - 10 MILS (250 μm) PER MINUTE CUTTING RATE IN 4 INCH LONG SILICON SLAB
  - 100 WIRE CUTTING OF 6 MIL (150 μm) WAFERS WITH 5 MIL (125 μm) KERF LOSS

MULTIBLADE SLURRY SAWING

CUTTING RATE: $\frac{dz}{dt} = \frac{L\,\bar{\varepsilon}}{\pi\, p}\left(\frac{d\ell}{dt}\right)\frac{1}{x_k\, y_k}$

$\frac{dz}{dt}$ = Vertical Cutting Rate

L = Cutting Force Per Blade

P = Work Material Hardness

$\frac{d\ell}{dt}$ = Bladehead Reciprocating Speed

x_k = Kerf Width

y_k = Kerf Length

$\bar{\varepsilon}$ = Cutting Efficiency

TYPICAL FOR SILICON/VARIAN 686

p = 1150 KG/MM^2

$\frac{d\ell}{dt}$ = 1600 IN/MIN

L = 4 oz.

x_k = .0105 INCH (.008 Blades with #600 SiC)

y_k = 3.94 INCH

$\frac{dz}{dt}$ = .0019 $\bar{\varepsilon}$ IN/MIN

RANGE OF $\bar{\varepsilon}$: 0.8 to 1.2 PREVIOUSLY

RECENTLY: $\bar{\varepsilon}$ = 1.65 TYPICAL 2.15 MAX

EFFICIENCY vs. CUTTING PRESSURE