1993

Report Issued:
January 8, 1993

GEO only

Research and Development

Summary of New Generation Technologies and Resources

Advanced Energy Systems
Report 007.6-92.3

Program Manager: George A. Hay III

Technology Assessment, Monitoring, and Scanning (TAMS)

Final Report, December 1992

Project Managers: David W. Behrens
Donna S. Lindquist
Ronnie A. Holland

Project Team: John F. Doyle
James M. Eyer
Franjee Hay
Ralph H. Hollenbacher
Jennifer A. Martin
Susan K. Moxley

Prepared for:

**Pacific Gas and Electric Company
Department of Research and Development
3400 Crow Canyon Road
San Ramon, California 94583**

© 1993 by PG&E

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Report Issued:

January 8, 1993

Research and Development

Summary of New Generation Technologies and Resources

Advanced Energy Systems

Report 007.6-92.3

Program Manager: George A. Hay III

Technology Assessment, Monitoring, and Scanning (TAMS)

Final Report, December 1992

Project Managers: David W. Behrens
Donna S. Lindquist
Ronnie A. Holland

Project Team: John F. Doyle
James M. Eyer
Franjee Hay
Ralph H. Hollenbacher
Jennifer A. Martin
Susan K. Moxley

Prepared for:

**Pacific Gas and Electric Company
Department of Research and Development
3400 Crow Canyon Road
San Ramon, California 94583**

© 1993 by PG&E

LEGAL NOTICE

Pacific Gas and Electric Company (PG&E) makes no warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe upon privately owned rights. Nor does PG&E assume any liability with respect to use of, or damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

© 1993 by PG&E
All Rights Reserved

CONTENTS

	Page
Program Perspective	xi
Acknowledgments	xvii
Glossary	xix
COST AND PERFORMANCE DATABASE	
COST AND PERFORMANCE DATABASE (1992)	3
RENEWABLES	
PHOTOVOLTAICS (1992)	13
SOLAR THERMAL (1991)	27
WIND (1992)	45
GEOTHERMAL ENERGY (1992)	57
BIOMASS (1992)	71
MUNICIPAL SOLID WASTE (1991)	93
LANDFILL GAS (1991)	99
OCEAN ENERGY (1991)	109
ADVANCED HYDRO (1992)	121
ENERGY STORAGE	
ENERGY STORAGE (1992)	125
ADVANCED FOSSIL CONVERSION	
LARGE ADVANCED THERMAL CYCLES (1992)	147
SMALL ADVANCED CYCLES (1992)	165
FUEL CELLS (1991)	183
ADVANCED COAL (1992)	197
INDUSTRIAL WASTE FUELS AND BY-PRODUCTS (1991)	221
ADVANCED NUCLEAR POWER	
FISSION (1992)	225
FUSION (1991)	245
BIBLIOGRAPHY	251

FIGURES

Page

PHOTOVOLTAICS

1	PV module costs and sales (historic and forecast)	21
2	Diffusion model of PV utility applications	24
3	The PV utility market gap	24

SOLAR THERMAL

4	System layouts	30
5	Existing and planned deployment capacities	33
6	Comparison of solar central receiver and combined cycle generation costs	40

WIND

7	Worldwide wind energy resource distribution estimates	48
8	Wind turbine configurations	49
9	Five areas of extensive wind development in California	51

BIOMASS

10	Schematic of atmospheric fluidized bed combustor	76
11	Schematic of spreader stoker fired steam generator	77
12	Schematic of standard dutch oven boiler	78
13	California biomass fuels demand: new capacity/total demand during the 1980s	83
14	Environmental considerations associated with biomass use	86

LANDFILL GAS

15	Schematic of gas recovery system	102
16a	High-Btu process-adsorption-compression membrane separation diagram	105
16b	Electrical generation block diagram	105

OCEAN ENERGY

17	Projected capital investment for a 27-MWe heaving buoy wave energy plant	111
18	Sensitivity analysis of capital investment for a 27-MWe heaving buoy wave energy plant....	112
19	Wave energy conversion processes	113
20	Resource supply curve for northern California	117

FIGURES (Cont.)

	Page
ENERGY STORAGE	
21 Battery energy storage	128
22 Schematic of a CAES plant using a depleted gas field	129
23 Superconducting magnetic energy storage	130
24 Helms 1,000-MW pumped hydroelectric energy storage	131
 LARGE ADVANCED THERMAL CYCLES	
25 Projected performance improvements in advanced natural gas conversion technologies	149
26 Gas turbine technology transfer	151
27 Gas turbine configurations	154
28 Carbon dioxide emissions for natural-gas-fueled technologies	161
 SMALL ADVANCED CYCLES	
29a Advanced rotary engine	168
29b Advanced gas turbine (steam-injected cycle)	168
29c Stirling engines	169
 FUEL CELLS	
30 Schematic representation of a typical fuel cell	186
31 Economic comparison: mature MCFC vs. combined cycle alternative	194
 ADVANCED COAL	
32 Advanced pulverized coal	200
33 Atmospheric fluidized bed combustion	200
34 Pressurized fluidized bed combustion	201
35 Coal gasification combined cycle	201
36 Traditional utility view of year 2005 electric generating resources	214
37 A multi-attribute view of year 2005 electric generating resources	218
38 Year 2015 repowering scenarios	219

FIGURES (Cont.)

	Page
FISSION	
39 Advanced fission design concepts	229
40 Traditional utility view of year 2005 electric generating resources	240
41 A multi-attribute view of year 2005 electric generating resources	242

MEMORANDUM

TO : Mr. Tolson
FROM : Mr. [Name]
SUBJECT: [Subject]

TABLES

	Page
COST AND PERFORMANCE DATABASE	
1 Advanced Gas/Oil Baseload Generation Options	4
2 Advanced Gas Intermediate Load Generation Options	5
3 Advanced Gas Distributed Generation Options	6
4 Peak Load Generation and Storage Options	7
5 Renewable Technologies, Baseload Generation Options	8
6 Renewable and Storage Technologies, Intermediate Load Generation Options	9
7 Advanced Coal and Nuclear, Baseload Central Station Options	10
PHOTOVOLTAICS	
8 Photovoltaic Plant Characteristics and Costs	14
9 PV Power Systems and Applications	17
10 Photovoltaic Cell Technologies	20
SOLAR THERMAL	
11 Solar Thermal Plant Characteristics	28
WIND	
12 Wind Power Plant Characteristics	46
GEO THERMAL ENERGY	
13 Capital Costs for Recently Constructed Geothermal Plants	58
14 Hydrothermal Resources Within PG&E's Service Area	62
15 Hydrothermal Resources in the Salton Trough, California	63
16 Hydrothermal Resources in the Basin and Range, Oregon Plateaus, Snake River Plain and Northern Rockies Provinces	64
17 Hydrothermal Resources in the Cascades	65

TABLES (Cont.)

	Page
BIOMASS	
18 Conversion of Biomass into Electricity in 1990	74
19 Comparison of Current Biomass Combustion Technology Emissions Guarantees	79
20 Biomass Plants Currently Serving PG&E's Grid	80
21 Available Waste and Residue Fuels for the California Biomass Energy Industry	84
22 Comparison of Wood Burning Technologies	89
OCEAN ENERGY	
23 Cost and Performance Data for Planned or Hypothetical Wave Power Plants	110
24 Wave Energy Facilities	116
ENERGY STORAGE	
25 Energy Storage Characteristics	132
26 Advanced Energy Storage Projects (Current and Planned)	133
27 Cost and Performance of Battery Energy Storage Technologies	135
28 Cost and Performance of CAES, SMES, and Pumped Hydro Energy Storage Technologies	136
29 Cost and Performance of Flywheel Technology	137
LARGE ADVANCED THERMAL CYCLES	
30 Projected Improvements in Large Advanced Thermal Cycle Technologies	148
31 Emerging Aeroderivative Gas Turbine Engines for Power Generation Applications	152
SMALL ADVANCED CYCLES	
32 Typical Applications for Small Advanced Cycles	171
33 Summary of Small Advanced Reciprocating and Rotary Engines	172
34 Summary of Small Advanced Gas Turbines	175
35 Summary of Stirling Engines	177
36 Fuels for Small Advanced Cycles	178

TABLES (Cont.)

	Page
FUEL CELLS	
37 Fuel Cell Development History and Cost Projections	184
38 Applications for Fuel Cells	187
39 Fuel Cell Emission Levels	190
40 Technical and Economic Characteristics of Competing Technologies	193
ADVANCED COAL	
41 AFBC Projects in California Fueled by Coal and Petroleum Coke	203
42 Status of Advanced Coal Technologies	207
43 Economic Comparison Between Advanced Nuclear, Coal, and Natural Gas New Generation Options	215
44 Estimated Economics for Advanced Coal Conversion Technologies for Electric Power Generation	216
FISSION	
45 U.S. Advanced Fission Power Plant Features	228
46 Economic Comparison Between Advanced Nuclear, Coal, and Natural Gas New Generation Options	241

PROGRAM PERSPECTIVE

The mission of the PG&E R&D program is to contribute to the company's competitive advantage by managing technology change and reducing technology risk. The formula for accomplishing this mission, stated very simply, is to "seek, select, try, and apply." Figure PP-1 illustrates this concept of R&D management.

In the strategic research ("seek") phase, R&D's task is to identify technologies which may be of value to the company, gather business intelligence, and provide information on emerging technologies and new applications of existing technologies. This can be approached informally or, as in the case of the technology assessments summarized here, in a more systematic way.

In 1989, the Advanced Energy Systems (AES) Technology Information Module (TIM) project began preparing a systematic compilation of information about emerging electric generation technologies, and has since published a series of 17 TIM reports, as well as a cost and performance database, which distills basic quantitative information on the various technologies of interest and presents the information in a standard format. The objective of the TIMs is to enhance and document the PG&E R&D Program's understanding of the technology status, resource potential, deployment hurdles, commercial timing, PG&E applications and impacts, and R&D issues of advanced technologies for electric utility applications in Northern California.

The project addressed two basic needs not met by technology assessments available from other sources: it evaluated each emerging option in relation to the opportunities, resources, and constraints unique to PG&E; and it provided objectivity and balance. In general, the plethora of other assessments available fall short of these needs because they are not complete, providing generic information of interest to the technology developer rather than specific information of interest to the technology user. Also, typically, for emerging options, costs are understated and performance overstated to widely varying degrees, depending on the maturity and objectivity of the evaluator.

To assure the needed degree of completeness and accuracy, a standard categorization of TIM information was established, and a review process was completed that engaged the knowledge and insight of PG&E in-house experts. Each TIM typically includes the following categories of information:

- Technology description
- PG&E applications
- Development and commercialization status
- Fuels and energy resource assessment

MISSION STATEMENT

The mission of R&D is to contribute to the company's competitive advantage by managing technology change and reducing technology risk. To accomplish this R&D will:

SEEK

Identify technologies which may be of value to the company, gather business intelligence and provide information on emerging technologies and new applications of existing technologies.

SELECT

Evaluate and select emerging technologies and new applications of existing technologies to be developed and applied by the company.

TRY & APPLY

Catalyze the rapid application and implementation of technology by the company through demonstrations, technology transfer and effective communication.

Figure PP-1. Research & Development Program.

- Environmental impacts
- Deployment considerations and hurdles
- Technology trends and forecasts
- PG&E and utility industry impacts and implications
- R&D needs and opportunities

This compendium includes a program perspective on the project, a glossary, a summary of each TIM, updated information on the status and trends of each technology, and a bibliography.

As might be expected, the goals of completeness and accuracy were attained to varying degrees, depending on the quality of contractor work products and the diligence of in-house reviewers. Further, and more importantly, none of the technologies assessed in the TIM project is standing still. Those still under development, and especially those evolving in the market as a result of experience-driven innovation, are truly moving targets. The reader is strongly encouraged to regard the information presented in the database and TIM modules as having a finite "shelf life" which may vary significantly depending on the technology and type of information. The information may be regarded as up-to-date as of 1991, since most of the report drafts were in final form prior to 1992.

The information in the TIMs is consistent with the choice of emerging options targeted ("selected") for accelerated development by the AES R&D program. Moving into the "try and apply" phase required careful selection of technologies and projects. PG&E must concentrate its resources and efforts if it is to have the desired impact—*accelerating* the technical and economic readiness of currently unavailable technologies.

The selection criteria were:

1. The technology is environmentally preferred.
2. The technology uses resources which are abundant and indigenous to Northern California or abundant and accessible via PG&E electric and natural gas transmission systems.
3. It has reasonable probability of cost-effectiveness in 2000-2010 without ratepayer subsidy.
4. It requires PG&E initiative to capture acceleration potential.
5. The California Energy Commission (CEC) targeted it as an "opportunity technology."

The technologies that met these criteria are identified in Figure PP-2. PG&E "try and apply" activity is justified in each case for the following reasons:

- *Wind* will be a least-cost supply option, but resources in northern/central California are limited. No other utility or national program is addressing the need to get the maximum amount of economy energy from a limited wind resource.

Figure PP-2. Target technologies meet selection criteria.

- Commercial *solar thermal* technology is stalled as a result of LUZ's bankruptcy. The U.S. national program is focused on alternatives to the LUZ approach. These alternatives have little if any hope of meeting PG&E's selection criteria. PG&E is the only U.S. utility addressing the need to revive and improve the only commercial solar bulk power technology.
- *Compressed air energy storage* resources in the San Joaquin Valley are outstanding, but improving the understanding of underground reservoir development and performance issues is the key to managing technical risk. No other utilities or programs will be dealing with exactly the same geology or plant optimization boundary conditions that apply to PG&E. Therefore, no successful development and application will occur in Northern California unless PG&E does its technical homework.
- *Advanced aeroderivative gas turbine* applications are not unique to PG&E, but leadership of utility efforts to adapt aircraft turbines to the electric power market is. PG&E's commercially successful effort with GE in developing its LM5000 steam-injected gas turbine (STIG) product, PG&E's subsequent intercooled steam-injected gas turbine (ISTIG) development initiative, the CEC's intense interest, and the California utilities' large share of the nation's natural-gas-based generation—all argue for PG&E to take the lead in catalyzing accelerated development of advanced turbine concepts.
- Emerging *solar photovoltaic and fuel cell* technologies have also captured the imagination and interest of many utilities. Multiple fuel cell and solar photovoltaic products will be introduced to the electric power market over the next decade. If successful, these products could accelerate the evolution of the regional electric supply infrastructure toward the "distributed utility" model championed by R&D. PG&E has more firsthand experience with solar photovoltaics and carbonate fuel cell systems than any utility in the United States, operates world-class test facilities in both technologies, and receives royalties on the internal reforming carbonate fuel cell innovation it sponsored in the mid-1980s. Continuation of cost-shared test activity will position PG&E to make accurate and timely assessments of technology readiness, market timing, and business opportunities.
- Other *distributed generation and storage* technologies such as *batteries* and *modular natural gas engine-based generation* offer a shorter term potential to improve electric and gas distribution system asset utilization and improve PG&E's ability to offer competitive prices to customers. Regrettably, the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), the U.S. Department of Energy (DOE), and traditional utility equipment vendors have yet to formulate focused programs that are responsive to the market need and opportunity, so it is in PG&E's interest to be more proactive than might otherwise be required.

Certainly, these choices will have to be continually revalidated as development and demonstration proceeds. Within each target technology category, a range of basic system configuration and component choices must be made (e.g., the choice of carbonate fuel cell technology within the fuel cell category, the choice of a once-through internal reforming system configuration, and the choice of a burner vs. a catalytic conversion device for heating inlet air with unconverted fuel). Thus, ongoing technology assessment activity will continue as a key part of the AES program, providing R&D program managers and their business unit clients with a radar screen showing the location, speed, and direction of emerging generation options.

TIM Project Managers

Donna S. Lindquist/David W. Behrens/Ronnie A. Holland

TIM Program Manager

George A. Hay III

Research Director
Advanced Energy Systems

Gerald W. Braun

ACKNOWLEDGMENTS

The completion of a broad-ranging effort like the Technology Information Module Project required the cooperation and perseverance over several years by many people. In addition to the authors, contributors, and reviewers listed below, special thanks go to AES Director Gerry Braun; Program Manager George Hay; Project Managers Dave Behrens, Donna Lindquist, and Ronnie Holland; and project team members including John Doyle, Jim Eyer, Franjee Hay, Ralph Hollenbacher, Jennifer Martin, and Susan Moxley. The support services provided by the Desktop Publishing and Graphics groups helped finalize the production and assembly of text and art, and we thank these individuals: John Buchholz, Laraine Chaney, Carol Crews, Shirley Dexter, Sheila Doherty, Mel Douglas, Lauren Eastman, Sue K. Grubb, Mickey Hops, Judie Hurtz, Gema Lopez, Roslyn Raley, and Donna Smailes.

CONSULTANTS

AeroVironment Inc.
Bechtel Group, Inc. (Nuclear Power Systems, R&D)
Kay Firor (Blue Mountain Energy)
Ralph H. Hollenbacher (Energy Options)
John F. Doyle (Engineering Perspectives, Inc.)
Future Resources Associates, Inc.
Charles Greene Consultants
International Engineering Services Corporation
Meridian Corporation
EA Mueller, Inc.
George Wiltsee (NEOS Corporation)
Melissa M. Reading, Ph.D.
Dr. Susan Schoenung and Dr. Wayne Meier
(W. J. Schafer Associates, Inc.)
Science Applications International Corporation (SAIC)
SEASUN Power Systems
D.J. Wilhelm, D.R. Simbeck, S. Vejtasa,
R.L. Dickenson (SFA Pacific, Inc.)
TENERA Environmental Services

CONTRIBUTORS/REVIEWERS

Ken Abreu
Clint Ashworth
Jonne Berning
Max Blanchet
Gerald W. Braun
Sally M. C. de Becker
Ray J. Dracker
EDAW Inc.
Roberto Gutierrez
Robert L. Hammond
Douglas J. Herman
Tom Hillesland
Joseph J. Iannucci
Mary A. Ilyin
Christina Jennings
James A. Kimball
Paul Langholz
Thomas A. Lott
Jo L. Meglen
Karen Morris
Dan Quesenberry
Jay Raggio
Robert B. Schainker (EPRI)
Daniel S. Shugar
Don R. Smith
William J. Steeley
Jane H. Turnbull
Howard J. Wenger
Charles O. White
Rick O. Winter

GLOSSARY

ANSI	American National Standards Institute
API	American Petroleum Institute
Baseload	Minimum load demanded over time on a power company's generation system.
BLM	Bureau of Land Management
BOS	Balance of system
BPA	Bonneville Power Administration
CAES	Compressed air energy storage. Air is compressed using off-peak electric energy and stored underground for later use in an expansion turbine.
Capacity	Amount of electric power for which a generating unit, generating station, or other electrical apparatus is rated either by the user or manufacturer.
Capacity Factor	Ratio of the average operating load of an electric power generating unit for a period of time to the capacity rating of the unit during that period.
CEC	California Energy Commission
Cogeneration	Production of thermal energy and electrical or mechanical power from the same fuel source.
CPUC	California Public Utility Commission
Distributed Generation	Any modular generation or storage technology that can be sited so that the characteristics match local electricity, economic, and environmental demands.
DOE	Department of Energy
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
GRI	Gas Research Institute
HHV	Higher heating value. Any fuel containing hydrogen yields water as one product of combustion. High heat value is calculated assuming all water vapor condensed. The HHV efficiency for natural gas conversion is about 10% lower than Low Heat Value (LHV) (see below).
Hybrid Systems	Combinations of generators, non-dispatchable technologies such as wind or photovoltaics, and storage.
IEA	International Energy Agency

IPP	Independent Power Producers. A private entity building new generation facilities to sell in wholesale (i.e., bulk power) markets.
LHV	Lower heating value. Any fuel containing hydrogen yields water as one product of combustion. Low heat value is evaluated assuming no water vapor condensed. In Germany, the low heat value of the fuel is used in calculating efficiencies of internal-combustion engines. In the United States, the high value is specified by the American Society of Mechanical Engineers (ASME) Power Test Codes (see HHV).
NOI	Notice of Intent
NREL	National Renewable Energy Lab (formerly: Solar Energy Research Institute (SERI))
Nuclear	As used in this report, nuclear refers to fission and fusion energy technologies.
O&M	Operation and maintenance
Peak Load	Maximum demand for electric power that determines the generating capacity required by the utility.
PURPA	Public Utility Regulatory Policies Act of 1978. The act required utilities to purchase power and provide back-up services to cogenerators and certain small power production facilities (qualifying facilities) that made use of renewable energy sources and various waste fuels.
QF	Qualifying facility (under PURPA). A small power producer or cogenerator that can sell its electricity to public utilities.
Retail Wheeling	The use of a transmission system by a utility or an independent power producer to send power directly to a retail customer (see Wholesale Wheeling).
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SMUD	Sacramento Municipal Utility District
SNLA	Sandia National Laboratories
Wholesale Wheeling	The use of a transmission system by a utility or an independent power producer to send electricity to a wholesale customer, usually another utility.

COST AND PERFORMANCE DATABASE

COST AND PERFORMANCE DATABASE

The PG&E Advanced Energy Systems (AES) R&D Program funds over \$5 million annually to investigate future electric supply options in California. Information on the cost and performance of future PG&E electric supply options is a major product of these investigations. The intent of the AES Cost and Performance Database was to compile the most recent information available from the program for R&D and business unit users of information on new generation technologies. The database evolved out of the R&D 1988 *Scenario Evaluation* and *R&D Choices (SEARCH) Study*, Phase 1,¹ and it drew extensively on the 17 Technology Information Module (TIM) reports, which attempt to document qualitative as well as quantitative information. Although no future updates are planned, the database is also intended to serve as a repository for new information as it becomes available and as a reference for evaluating the significance of new information.

Tables 1 through 7 summarize the results of the cost and performance study for each technology case. Summary Tables 1 through 7 are:

1. Advanced Gas/Oil Baseload Generation Options
2. Advanced Gas Intermediate Load Generation Options
3. Advanced Gas Distributed Generation Options
4. Peak Load Generation and Storage Options
5. Renewable Technologies Baseload Generation Options
6. Renewable and Storage Technologies Intermediate/Peak Load Generation Options
7. Advanced Coal and Nuclear Baseload Central Station Options

This database is being incorporated into a software database management program ("E-TRENDS"), which can extract relevant information and perform financial and economic analyses.

¹J. F. Doyle, J. M. Eyer, and G. A. Hay III, *Scenario Evaluation and Research Choices (SEARCH) Study* (San Ramon, California: PG&E, Report 005.88-1, 1988).

Table 1
Advanced Gas/Oil Baseload Generation Options
(1990 Dollars)

TABLE NO.	TECHNOLOGY CASE NAME (Refer Appendix D Tables 'BG1 thru BG9' For Detailed Data Sheets)	Commercial Operation Time Frame (Note 1)	Unit Size (MWe)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 3)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Efficiency (HHV-%)	Quality of Data (Scale (1)-Best To (5)-Worst)
					(Low)	(Ref)	(High)					
BG1	Combined Cycle (one Frame 7E;one steam turb)	Near	123	4	500	600	700	9	3	7867	43.4	3
BG1a	Combined Cycle (one Frame 7F;one steam turb)	Near	222	2	475	575	650	9	3	7400	46.1	3
BG1a	Combined Cycle (one Frame 7F;one steam turb)	Long	235	2	475	575	650	9	3	7100	48.1	3
BG2	PG&E IDR Combined Cycle (Fr 7F-Dry Cooling)	Near	217.3	1	600	600	600	30	0.9	7686	44.4	2
BG3	Current Aeroderivative(eg LM6000 Combined Cycle)	Near	50	4	600	700	800	9	7	7760	44.0	3
BG3a	LM6000 Com Cyc(two 42 MW GT;one 25MW steam)	Near	109	2	500	600	700	9	3	7650	44.6	3
BG3b	Advanced Aeroderivative (See Note 2)	Long	160	1	500	600	800	9	7	6100-6700	51-56%	5
BG3c	LM6000 Simple Cycle	Near	40	4	450	500	600	9	7	9230	37	3
BG3d	Advanced Simple Cycle LM6000 (Intercooled)	Long	80	2	400	450	550	9	7	8754	39.0	5
BG4	Thermally Enhanced Oil Recovery (Frame 7E)	Near	84	4	600	660	720	9	3	11740	29.1	3
BG4	Thermally Enhanced Oil Recovery (Frame 7F)	Long	150	2	600	660	720	9	3	10964	31.1	4
BG5	Repowering Gas Turbine Topping Cycle (See Note 5)	Near	215	1	800	1000	1500	8	6	8000	42.7	2
BG6	Phosphoric Acid Fuel Cell	Near	10	1	1400	1500	1900	9	6.5	8300	41.1	3
BG6	Phosphoric Acid Fuel Cell	Long	25	4	900	1000	1200	8	5	7000	48.8	4
BG7	Molten Carbonate Fuel Cell	Near	2	1	1500	2000	2500	7	10	6825	50.0	4
BG7	MCFC (20 MW steam turb bottoming cycle)	Long	100	1	800	1000	1500	6	9	5700	59.9	4
BG8	Solid Oxide Fuel Cell (16.2 MW Fuel Cell;3.8 MW Steam Turbine)	Long	20	1	1000	1450	1750	8	11	6200	55.1	5
BG9	Solid Oxide Fuel Cell (194 MW Fuel Cell;106 MW Steam Turbine)	Long	300	1	800	900	1000	6	9	5700	59.9	5

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. LONG TERM COST AND PERFORMANCE GOALS - COMPLEX OR COMBINED CYCLE
3. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COSTS
4. CAPACITY FACTOR - 80% FOR ALL CASES
5. REPOWERING STUDIES ARE ONGOING, AND THESE ESTIMATES COULD CHANGE SIGNIFICANTLY

Table 2

**Advanced Gas Intermediate Load Generation Options
(1990 Dollars)**

TABLE NO.	TECHNOLOGY CASE NAME (Refer Appendix D Tables "IG1 thru IG7" For Detailed Data Sheets)	Commercial Operation Time Frame (Note 1)	Unit Size (MWe)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 2)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Efficiency (HHV-%)	Quality of Data (Scale (1)-Best To (5)-Worst
IG1	Combined Cycle Power Plant (Frame 7E)	Near	123	4	500	600	700	4	6	7990	42.7	3
IG1	Combined Cycle Power Plant (Frame 7F)	Long	222	2	475	575	650	4	6	7514	45.4	
IG3	Gas Turbine STIG - LM1600 - 17 MW	Near	17	3	800	900	1000	10	9	9320	36.6	4
IG4	Gas Turbine STIG - LM5000 - 50 MW	Near	51	4	700	800	900	9	9	8700	39.2	3
IG2	LM6000 Com cyc (two 42 MW GT; one 25MW steam)	Near	109	4	500	600	700	4	6	7770	43.9	3
IG2a	Advanced aeroderivative (See Note 3)	Long	160	1	500	600	800	9	8	6100-6700	51-56%	5
IG5	LM6000 Simple Cycle	Near	40	4	450	500	600	9	7	9230	37.0	3
IG5	Advanced Simple Cycle LM6000 (Intercooled)	Long	80	2	400	450	550	9	7	8754	39.0	5
IG6	Phosphoric Acid Fuel Cell	Near	10	1	1400	1500	1900	9	6.5	8300	41.1	3
IG6	Phosphoric Acid Fuel Cell	Long	25	4	1000	1000	1200	8	5	7000	48.8	
IG7	Molten Carbonate Fuel Cell	Near	2	1	1500	2000	2500	7	10	6825	50.0	4
IG7	MCFC (20 MW steam turb bottoming cycle)	Long	100	1	800	1000	1200	6	9	5700	59.9	4

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COSTS
3. LONG TERM COST AND PERFORMANCE GOALS - COMPLEX OR COMBINED CYCLE
4. CAPACITY FACTOR - 35% FOR ALL CASES

Table 3
Advanced Gas Distributed Generation Options
(1990 Dollars)

TABLE NO.	TECHNOLOGY CASE NAME (Refer Appendix D Tables "BD1 thru BD4" and "BDC1 THRU BDC4" for Detailed Data Sheets)	Commercial Operation Time Frame (Note 1)	Unit Size (MWe)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 3)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Efficiency (HHV-%)	% Input Btus Recovered As Useable Heat	Quality of Data (Scale (1)-Best To (5)-Worst)
					(Low)	(Ref)	(High)						
BD1	Commercial Reciprocating Engine	Near	0.2	1	610	710	1100	8	15	10000	34.1		3
BD1	Commercial Reciprocating Engine	Long	0.2	1	560	660	1000	8	13	9250	36.9		3
BD2	Commercial Molten Carbonate Fuel Cell	Near	0.2	1	1500	2000	2500	25	17	7166	47.6		4
BD2	Commercial Molten Carbonate Fuel Cell	Long	0.2	1	1100	1250	1500	25	16	6825	50.0		4
BD3	Small Industrial Reciprocating Engine	Near	2	1	850	950	1300	4	10	10000	34.1		3
BD3	Small Industrial Reciprocating Engine	Long	2	1	700	800	1150	4	8	9000	37.9		3
BD4	Small Industrial Molten Carb Fuel Cell	Near	2	1	1500	2000	2500	7	10	6825	50.0		4
BD4	Small Industrial Molten Carb Fuel Cell	Long	2	1	900	1000	1500	6	9	6200	55.1		4
BDC1	Commercial Reciprocating Engine (Cogen)	Near	0.2	1	775	1000	1300	10	15	6700	51.0	33.0	3
BDC1	Commercial Reciprocating Engine (Cogen) (Note 4)	Long	0.2	1	750	900	1200	10	13	5735	59.5 (Note 6)	38.0	3
BDC2	Commercial Molten Carb Fuel Cell (Cogen)	Near	0.2	1	1650	2200	2750	25	17	6163	55.4	14.0	4
BDC2	Commercial Molten Carb Fuel Cell (Cogen) (Notes 4,5)	Long	0.2	1	1210	1375	1650	25	16	5801	58.8 (Note 6)	15.0	4
BDC3	Small Industrial Recip Engine (Cogen)	Near	2	1	1000	1100	1600	5	11	6500	52.5	35.0	3
BDC3	Small Industrial Recip Engine (Cogen) (Notes 4,5)	Long	2	1	800	900	1300	5	10	5580	61.2 (Note 6)	38.0	3
BDC4	Small Indl Molten Carb Fuel Cell (Cogen)	Near	2	1	1650	2200	2750	7	10	6091	56.0	15.0	4
BDC4	Small Indl Molten Carb Fuel Cell (Cogen) (Notes 4,5)	Long	2	1	990	1100	1650	6	9	5334	64.0 (Note 6)	16.0	4
BDC5	Industrial Gas Turb Cogen (Notes 4,5,6)	Near	50	1	624	1125	1400	15.4	6.6	6714	50.8	41.0	4
BDC5	Industrial Gas Turbine Cogen (Notes 4,5,6)	Long	50	1	604	1007	1358	15.4	5.5	5690	60.0	45.0	4

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. CAPACITY FACTOR - 80% FOR ALL CASES
3. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COSTS
4. HEAT RATES FOR COGENERATION CASES ARE ADJUSTED TO REFLECT A CREDIT FOR RECOVERED THERMAL ENERGY
5. COGENERATION CONFIGURATIONS ARE REPRESENTATIVE ONLY, AND THE ACTUAL HEAT RECOVERABLE AND COSTS WILL BE HIGHLY DEPENDENT ON THE MACHINE TYPE, CONFIGURATION AND SITE SPECIFIC ARRANGEMENTS AND PLANT CAPACITY FACTOR
6. EFFICIENCY IS THE EFFECTIVE ELECTRICAL EFFICIENCY AFTER A CREDIT IS TAKEN FOR THE HEAT RECOVERED.
THE OVERALL PLANT EFFICIENCY FOR BOTH ELECTRICAL AND HEAT IS A HIGHER NUMBER, AND IS NOT SHOWN IN THIS TABLE

Table 4

**Peak Load Generation and Storage Options
(1990 Dollars)**

TABLE NO.	TECHNOLOGY CASE NAME (Refer Appendix D Tables *P1 thru P5* for Detailed Data Sheets)	Commercial Operation Time Frame (Note 1)	Unit Size (MWs)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 2)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Efficiency (HHV-%)	Quality of Data (Scale (1)-Best To (5)-Worst)
					(Low)	(Ref)	(High)					
P1	IDR Combustion Turbine (Gas)	Near	101.5	1	435	435	435	6	4.45	11930	28.6	2
P2	Current aeroderivative (LM6000-Simple Cycle)	Near	40	4	450	500	600	8	9	9230	37.0	3
P2	Advanced Simple Cooled LM6000 (Intercooled) (See Note 4)	Long	80	2	400	450	500	8	9	8754	39.0	5
P3	Lead Acid Battery (Note 3)	Near	20	1	650	850	950	1.4	6.5			4
P3	Lead Acid Battery	Long	20	1	500	560	670	1.4	6.5			4
P4	Small Hydroelectric Plant	Near	10	1	1000	2500	3000	12	3.3			4
P5	Conventional Pumped Hydro Plant (Note 3)	Near	333	3	440	880	1150	4	5			4

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COST
3. STORAGE OPTION WHICH REQUIRES LOW COST CHARGING ELECTRICITY
4. LONG TERM COST AND PERFORMANCE GOALS
5. CAPACITY FACTOR - 10% FOR ALL CASES

Table 5
Renewable Technologies - Baseload Generation Options
(1990 Dollars)

TABLE NO.	TECHNOLOGY CASE NAME (Refer Appendix D Tables 'BI1 thru BI11' for Detailed Data Sheets)	Commercial Operation Time Frame (Note 1)	Unit Size (MWe)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 2)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Plant Av Cap Factor (%)	Quality of Data (Scale (1)-Best To (5)-Worst)
					(Low)	(Ref)	(High)					
BI1 BI1	Geothermal - Hot Water (excl. field costs)	Near	50	4	1710	1710	2050	58	4.7	33000	80	3
		Long	50	4	1500	1500	1700	58	4.7	33000	80	3
BI2 BI2	Geothermal - Hot Water Modular Wellhead (excluding field costs)	Near	10	5	2100	2700	3300	40	2	33000	80	3
		Long	20	5	1900	2100	2500	40	2	33000	80	3
BI3	Geothermal - Hot Dry Rock (excl. field costs)	Long	20	5	1900	2100	2500	40	2	33000	80	5
BI4	Geothermal Steam (excl. field costs)	Near	140	1	1500	1500	1500	21.7	3	21544	80	1
BI5	Large Biomass Plant	Near	36	1	1620	1960	2900	30	12	16225	80	3
BI6	Small Biomass Plant (used equipment)	Near	5	1	500	750	1000	50	12	17500	80	3
BI7	Biomass Gasifier STIG (LM5000)	Long	53	1	1300	1500	2000	30	12	10500	80	4
BI8	Municipal Solid Waste to Energy Plant	Long	19	1	4240	5030	6540	142	8	15000	80	3
BI8a	Municipal Solid Waste (Retrofit-Opt 1A)	Long	38	1	2530	2530	2785	225	25	16300	80	3
BI8b	Municipal Solid Waste (Retrofit-Opt 1B)	Long	67	1	1940	1940	2134	166	21	15500	80	3
BI9	Small Hydroelectric Plant	Near	5	1	1370	3420	4100	23	5.5		50	3
BI10	Large Hydroelectric Plant	Near	50	3	1076	4480	5377	19.8	4.4		40	3
BI11	Wind Power Plant	Near	0.2	250	900	1100	1300	23	3.8		23	2
BI11	Wind Power Plant	Long	0.5	100	600	800	1100	16	2.5		24	2

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE, AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COST

Table 6

Renewable and Storage Technologies - Intermediate Load Generation Options (1990 Dollars)

TABLE NO.	TECHNOLOGY CASE NAME (Note 1)	Commercial Operation Time Frame (Note 2)	Unit Size (MWe)	Plant Size No Units	Total Plant Cost (\$/kW) (Note 3)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Plant Av Cap Factor (%)	Quality of Data (Scale (1)-Best To (5)-Worst)
	RENEWABLES											
IR2	Solar Thermal Central Receiver	Near	100	2	2900	3290	3950	49	1		37.0	3
IR2	Solar Thermal Central Receiver	Long	200	1	2240	2465	2960	31	1		38.0	3
IR3	Solar Thermal - Parabolic Trough	Near	80	5	2700	2800	3100	40	4.5	10760	28.4	2
IR3	Solar Thermal - Parabolic Trough	Long	200	1	2000	2100	2500	30	2.5	9970	28.4	2
IR4	Solar Thermal-Parabol Dish/Stirling	Near	0.025	3200	2500	3000	5000	130	0		27.0	5
IR4	Solar Thermal-Parabol Dish/Stirling	Long	0.025	3200	1400	1400	1700	61	0		27.0	5
IR5	Photovoltaic - Concentrators	Near	1	100	2000	5000	8000	0	30		33.0	3
IR5	Photovoltaic - Concentrators	Long	1	100	1200	2200	3500	0	20		33.0	3
IR6	Photovoltaic - Flat Plate	Near	0.5	1	2400	4500	5700	0	8		30.0	3
IR6	Photovoltaic - Flat Plate	Long	0.5	1	1400	2200	3800	0	5		30.0	3
IR7	Small Hydroelectric Plant	Near	5	1	1240	3105	3730	21	5		35.0	3
IR8	Large Hydroelectric Plant	Near	50	3	980	4075	4890	18	4		35.0	3
IR9	Hydroelectric Plant Upgrade	Near	2.5	1	840	1250	3800	0	0		10.0	1
IR1	Ocean Wave Energy	Long	10	3	1365	2100	2950	99	0		29.0	4
STORAGE TECHNOLOGIES (Note 4)												
IS1	Modular Pumped Hydro Plant	Near	100	1	550	595	900	1.3	1.4		20.0	4
IS2	Large Compress Air Energy Storage Plant	Near	110	1	390	560	690	1.2	2	4000	20.0	3
IS2	Large Compress Air Energy Storage Plant	Long	110	1	390	560	690	1.2	2	3800	20.0	3
IS3	Superconducting Magnetic Energy Storage	Long	1000	1	790	1030	1600	5	0.2		20.0	4

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE, AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COST
3. STORAGE TECHNOLOGIES WILL REQUIRE LOW COST ELECTRICITY CHARGING

Table 7

**Advanced Coal and Nuclear - Baseload Central Station Options
(1990 Dollars)**

TABLE NO.	TECHNOLOGY CASE NAME (Note 1)	Commercial Operation Time Frame (Note 2)	Unit Size (MWe)	Plant Size No Of Units	Total Plant Cost (\$/kW) (Note 3)			O&M Fixed (\$/kW-Yr)	O&M Variable (Mills/kWh)	Full Load Heat Rate HHV (Btu/kWh)	Efficiency (HHV-%)	Quality of Data (Scale (1)-Best To (5)-Worst)
	COAL				(Low)	(Ref)	(High)					
BC1	Current Pulverized Coal (Small)	Near	275	1	1820	2135	2350	43	5.5	9750	35.0%	3
BC2	Advanced Pulverized Coal (Small)	Near	204	1	1920	2255	2480	45	5.5	8821	38.7%	3
BC3	Advanced Pulverized Coal (Large)	Long	606	1	1420	1670	1840	26.5	4.4	8446	40.4%	3
BC4	Atm Fluidized Bed Combustion (Medium)	Near	200	1	1800	2195	2525	45	6.6	9765	35.0%	3
BC4	Atm Fluidized Bed Combustion (Medium)	Long	200	1	1615	1995	2295	45	6.6	8825	38.7%	3
BC5	Coal Gasification Combined Cycle (Small)	Near	227	1	1900	1900	2280	45	5	9350	36.5%	3
BC5	Coal Gasification Combined Cycle (Small)	Long	203	1	1700	1700	2040	40	5	9000	37.9%	3
BC6	Coal Gasification Combined Cycle (Large)	Long	410	1	1600	1600	1920	38	4	8850	38.6%	3
BC7	Integrated Coal Gasification/Molten Carbonate Fuel Cell Combined Cycle	Long	200	1	1780	1870	2500	45	5.5	7100	48.1%	4
NUCLEAR												
BN1	High Temperature Gas-Cooled (Nth of a Kind)	Long	175	4	1586	1586	2062	55	0.2	8860	38.5%	4
BN2	Advanced Passive LWR (AP600, ABWR)	Long	600	1	1475	1475	1770	72.7	1.1	10220	33.4%	4
BN3	Light Water Reactor (Current)	Long	1200	1	1300	1300	1600	61.1	1.1	10220	33.4%	4

NOTES:

1. NEAR TERM - 1991-1995; LONG TERM - 1996-2007
2. TOTAL PLANT COST IS OVERNIGHT COST AND DOES NOT INCLUDE, AFUDC, ESCALATION DURING CONSTRUCTION, LAND OR OWNER'S COST
3. CAPACITY FACTOR - 80% FOR ALL CASES

RENEWABLES

GEOTHERMAL ENERGY

Geothermal energy is the heat of the earth. Resources are typically classified as hydrothermal (steam or hot water), hot dry rock, geopressured, and magma. All four resources exist in Northern California. Only hydrothermal resources are currently used commercially for power production. Dry steam resources are very rare. Geothermal energy resources offer the potential for increasing PG&E's resource diversity in an environmentally acceptable manner. Representative costs of recent commercial geothermal projects are summarized in Table 13. Major insights are:

- PG&E and several other utilities developed over 2,000 MW of dry steam geothermal plants at The Geysers, the largest geothermal facility in the world. Dry steam plants use mature, relatively conventional steam turbines. Plant costs for the most recent units were close to \$2,000/kW, with unit sizes over 120 MW including 30% for steam field related costs. The plants are operated in a baseload duty cycle, with capacity factors of over 80%. Conversion efficiencies exceed 22,000 Btu/kWh because of relatively low steam temperatures (350°F).
- Flash and binary plants utilize lower temperature, liquid-dominated geothermal resources. Flash technology employs similar turbines, but utilizes steam produced by reducing pressure on hot water/brine fluids (flashing). Binary plants use heat in geothermal fluids to vaporize a separate working fluid, via heat exchangers, to turn a turbine in a closed cycle (fluids never come into contact with the atmosphere). Recent flash plants have cost about \$2,500 to \$3,000/kW, including well costs. Binary plant costs are somewhat higher for individual projects. Binary units do not have large economies of scale, and costs reflect relatively small unit sizes (2-10 MW). Binary plants may be fabricated in a shop and erected in the field to keep costs low. Both have been commercially demonstrated and deployed almost exclusively by independent power producers, mostly in Southern California.
- The Department of Energy, (DOE) Geothermal R&D Program is primarily focused on hydrothermal technology (exploration, drilling, and binary power conversion), hot dry rock, and geopressured geothermal. Performance and cost improvements in binary cycles in the range of 20-30% are targeted. DOE is planning a 1992 initiative to demonstrate higher efficiency hydrothermal technology. However, a next generation technology is not clearly defined. Hot dry rock technology is undergoing a 30-MW thermal technical demonstration at Fenton Hill, New Mexico. Research into magma and geopressured geothermal is largely exploratory. The Electric Power Research Institute (EPRI) no longer sponsors an advanced geothermal R&D program.
- Approximately 20,000 MW of hydrothermal resource potential are thought to exist in the Pacific Northwest, in Southern California, and east of the Sierra Nevada. The Pacific Northwest has not had any power plant development to date, although some resource assessment and exploratory drilling have occurred. BPA is currently planning three separate 10-MW projects to confirm the resource potential of several large fields. Recent exploration at Medicine Lake, California, near the Oregon border indicates a potentially significant resource is relatively near transmission lines running to Northern California. One of the BPA demonstration projects could be sited there. Resource development east of the Sierra Nevada will be limited by transmission access to major power markets, particularly Northern California.

Table 13
Capital Costs for Recently Constructed Geothermal Plants

Plant	Date of Commercial Operation	Gross Capacity (MW)	Costs Not Converted to Any Common Year Basis		
			Plant Capital Cost (\$/kW net)	Field Capital Cost (\$/kW)	Total Capital Cost (\$/kW)
Steam Plant					
PG&E Unit 16	1985	120	1,088	466 ^a	1,554 ^a
PG&E Unit 20	1985	120	911	390 ^a	1,301 ^a
PG&E Unit 21 ^b	----	151	1,500	643 ^a	2,143 ^a
Bear Canyon	1989	22	1,550	643 ^a	2,143 ^a
CCPA	1988	132	1,500	643 ^a	2,143 ^a
Flash Plant					
Coso #1 ^c	1987	30	1,715	715 (net)	2,430 (net)
Coso Project (230 MW)	1989	230	1,820 ^a	780 ^a	2,600 (net)
Blundell #1	1984	23	1,800	770 ^a	2,570 ^a
Leathers #1	1989	38	2,100 ^a	900 ^a	3,000 (net)
Binary					
ORMESA I	1987	30	2,100 ^a	900 ^a	3,000 (gross)
Wendel-Amendee	1988	3	1,500	640 ^a	2,140 ^a

^aBased on allocating 70% to plant and 30% to field.

^bPlant never constructed; projected cost used.

^cBased on California Energy Company literature.

- The potential for further hydrothermal development in PG&E's service area is relatively small (300-MW range), and consists of primarily hot water resources in dispersed and unconfirmed fields. Only one 2-MW binary cycle plant has been developed outside of The Geysers. The Clear Lake area represents the largest identified potential resource in Northern California, with a potential of up to 900 MW of hot dry rock and some hot water resources. The city of Clearlake and the California Energy Commission are in the process of assessing this resource, which might be the next site for commercializing hot dry rock technology if the DOE Fenton Hill Hot Dry Rock Long-Term Flow Test Project in New Mexico is successful.
- Geothermal energy is relatively environmentally benign; however, many of the best geothermal sites are in environmentally sensitive areas and can be difficult or impossible to develop, (e.g., Lassen National Park).
- Power output at The Geysers had dropped from a peak of 1,350 MW (PG&E-owned units) to around 800 MW by mid-1991 as the result of a decline of the steam field. Output is forecasted to decline to 400 MW by the mid-1990s and to under 200 MW in the post-2000 timeframe. Non-PG&E-owned Geysers units are experiencing similar difficulties. Approaches being investigated to halt the decline include innovative plant operation regimes, new reservoir management techniques, improved reservoir modeling, additional water supply for reinjection, and dry cooling and binary cycle retrofit concepts.
- PG&E's Advanced Energy Systems R&D Program has previously participated in the DOE Heber binary cycle geothermal project and in an evaluation of EPRI's advanced modular wellhead binary system. PG&E's current technology assessment efforts have focused on characterizing the regional geothermal resources and identifying technology R&D needs. Modular, higher efficiency binary cycles could help to confirm and lower the development risks for the remaining dispersed and small hot water reservoirs in Northern California. HDR development at Clear Lake might represent a project opportunity if the Fenton Hill tests are successful. Advanced geothermal and high efficiency natural gas hybrid configurations might offer attractive market features for hydrothermal resources outside the service area, possibly a joint project to confirm the resource at Medicine Lake.
- Advanced geothermal has not been targeted as a major new generation opportunity technology for demonstration by PG&E's R&D Program because of the relatively mature nature of the hydrothermal technology, the limited potential for further hydrothermal resource development in the service area, and the embryonic state of development of hot dry rock technology.

TECHNOLOGY DESCRIPTION

Several power conversion systems, all utilizing the Rankine cycle, are used to convert heat from geothermal resources to electric energy. Systems currently in operation are described below.

Direct Steam

The direct steam system is used with "dry steam" geothermal resources that almost exclusively contain water vapor (steam) with little or no liquid water. After removing rocks and/or other debris, steam from the geothermal reservoir is piped directly to a steam turbine. The expanding steam spins the turbine rotor and electric generator. Exhaust steam from the turbine is condensed. The resulting liquid (condensate) is used as cooling water and/or reinjected into the reservoir.

Flash Steam (Single and Dual)

Flash systems utilize hot water geothermal resources. Hot water or hot water/steam mixtures produced from the reservoir is piped to a flash tank, where the pressure is reduced to produce additional steam. In single flash systems, steam is piped to a turbine for electric generation as for steam turbines. After flashing, the (still) hot brine is reinjected into the reservoir.

For a dual flash system, exhausted brine (from the first flash) is piped to a second flash tank, where the pressure is further reduced to generate more steam, but at a lower pressure than at the first stage. This lower pressure steam is piped either to a lower stage of the turbine or to a separate turbine to generate additional electric power.

Dual flash systems generally have higher thermodynamic efficiencies and higher capital cost. Single flash systems are generally utilized if the geothermal fluid temperature is greater than about 500°F. Dual flash systems generally are used if the geothermal fluid temperature is 350°F to 500°F. Use of single flash versus dual flash systems may also depend on plant size and equipment availability.

Binary

Whereas the direct steam and flash steam systems utilize the actual geothermal fluid to spin a turbine generator, binary systems utilize a separate working fluid (thus the name binary). Geothermal fluid heats and boils the binary system's working fluid in a heat exchanger. The binary working fluid vapor spins the generator as it expands through the turbine. The working fluid vapor exhausted from the turbine is condensed and pumped up to turbine inlet pressure, to repeat the cycle. Binary working fluids have generally been Freons or hydrocarbons (isobutane and/or isopentane). The optimum working fluid depends on geothermal fluid temperature.

Any hot fluid could be used to heat binary working fluids; however, only hot water geothermal resources have been used to date. Binary plants are more efficient than steam plants at moderate temperatures. They have been installed for geothermal fluid temperatures ranging from 220°F to 360°F.

Binary plants can be designed as modules ranging in size from 300 kW, an example of which is the EPRI modular wellhead binary plant design that utilizes a 300°F to 450°F range of geothermal fluid temperatures with a single basic turbine design. Power generation ranges from 2.7 MWe to 5.3 MWe net per module depending on geothermal fluid temperature and heat rejection (wet or dry). ORMAT manufactures and installs modular, fully commercial binary plants. It has approximately 100 MW on line.

PG&E APPLICATIONS

Potential geothermal energy applications primarily include baseload power generation. Other plant operation regimes (e.g., seasonal dispatch) may be practical. Hybrid natural gas/geothermal plant operations may provide cost-effective energy, as may plant designs incorporating direct use of lower temperature waste heat from geothermal power production. Some potential for direct use of geothermal heat or waste heat from geothermal power generation exists within PG&E's service territory. Heat could be used for such applications as central heating systems, hothouse heating, aquaculture, and crop drying operations; however these are typically seasonal thermal loads. There is potential for use of geothermal energy for thermal enhanced oil recovery in Kern County.

DEVELOPMENT AND COMMERCIALIZATION STATUS

PG&E and several other utilities developed over 2,000 MW of dry steam geothermal plants at The Geysers, the largest geothermal facility in the world. Dry steam technology is mature and uses relatively conventional steam turbines. If the cost of the production wells are included, plants costs for the most recent units were close to \$2,000/kW, with unit sizes over 120 MW. The power plant and the steam fields are operated as separate businesses. The steam field represents roughly 30% of the capital cost. The plants are operated in a baseload duty cycle, with capacity factors of over 80%. Conversion efficiencies are relatively low (over 22,000 Btu/kWh) because of relatively low steam temperatures (350°F).

Flash and binary plants utilize lower temperature, liquid-dominated geothermal resources. Flash technology employs similar turbines, but utilizes steam produced by reducing pressure on hot water/brine fluids (flashing). Binary plants use heat in geothermal fluids to vaporize a separate working fluid, via heat exchangers, to turn a turbine in a closed cycle (fluids never come into contact with the atmosphere). Recent flash plants have cost about \$2,500 to \$3,000/kW if well costs are included. Binary plant costs are somewhat higher for individual projects. Both have been commercially demonstrated and deployed almost exclusively by independent power producers, mostly in Nevada, Utah, and Southern California.

GEOHERMAL RESOURCES

Types of Geothermal Resources

Geothermal fluids can be produced from natural or man-made reservoirs. Most reservoirs naturally contain hot water or hot brine (comprised of water, salt, and other substances) in permeable rock. Naturally occurring hot water is extracted from the reservoir for electric generation. Normally, several wells must be drilled into the reservoir to extract geothermal fluids. Tables 14 to 17 provide a summary of hydrothermal and hot dry rock resources in or near PG&E's service area.

Table 14
Hydrothermal Resources Within PG&E's Service Area

KGRA or Resource	USGS 790 Mean Res. Temp. (°F)	Estimates Energy ^a (MWe/30 Yr)	Measd. Res. Temp. (°F)	Current Capacity Gross/Net (MWe)	Plant Type ^b
Dry Steam Reservoirs					
The Geysers	459	1,610	470-590	2,115/1,970	DS ^c
Lassen	459	676	—	—	—
Total		2,286		2,115/1,970	
Hot Water Reservoirs					
Big Bend Hot Springs	240	16	—	—	—
Calistoga Hot Springs	290	40	—	—	—
Chalk Mountain	235	15	—	—	—
Clear Lake/Sulfur Bank Mine	380	975	—	—	—
Kelly Hot Springs	245	16	—	—	—
Morgan/Growler Springs	425	116	—	—	—
Scovern Hot Springs	225	13	—	—	—
Sespe Hot Springs	270	17	—	—	—
Sierra Valley	260	50	—	—	—
Wendell-Amadee	260	54	220-230	3.6/2.7	B ^d
West Valley	290	20	—	—	—
Wilbur Springs	290	73	—	—	—
Total		1,405		3.6/2.7	

^aUnless otherwise noted, temperatures and reservoir potential estimates are from PG&E, *Indigenous Energy Resource Assessment*, 1988; J. D. Geyer, L. M. Kellerman, and R. G. Bloomquist, *Assessment of Geothermal Resources for Electric Generation in the Pacific Northwest*, Northwest Power Planning Council, 1989.

^bB = Binary, DS = Direct Steam.

^cInstalled capacity - due to steam production decline, actual operating capacity is less (G. R. Priest and G. L. Black, "Geothermal Exploration in Oregon, 1988," *Oregon Geology*, Vol. 51, No. 5, 1989).

^dA 30-MWe net woodwaste/geothermal hybrid plant is operating at Susanville, California. Geothermal fluid is used for feedwater heating. About 1.5 MWe of the total plant output is credited to geothermal energy.

Table 15
Hydrothermal Resources in the Salton Trough, California

KGRA or Resource	USGS 790 Mean Res. Temperature (°F)	Estimated Energy ^a (MWe/30 Yr)	Measured Res. Temperature (°F)	Current Capacity (Gross/Net MWe)	Plant Type ^b
Border	320	31	—	—	—
Brawley	487	640	400-500	— ^c	1F
Dunes	270	46	—	—	—
East Mesa	360	360	293-350	85/65	B
East Mesa				44/40	2F
Glamis	270	43	—	—	—
Heber	347	650	360	— ^d	B
Heber				52/47	2F
Salton Sea	613	3,400	520-575	10/10	1F
Salton Sea				225/200	2F
Westmoreland	423	1,710	—	—	—
Total		6,880		416/362 ^e	

^aThe USGS did not estimate electric energy for resources less than 150°C (302°F). These estimates are based on USGS wellhead thermal energy estimates using conversion factors from J. D. Geyer, L. M. Kellerman, and R. G. Bloomquist, *Assessment of Geothermal Resources for Electric Generation in the Pacific Northwest*, Northwest Power Planning Council, 1989.

^bB = Binary, 1F = Single Flash, 2F = Dual Flash.

^cA 10-MWe gross/9-MWe net 1F demonstration plant was operated at Brawley from 1980 to 1986.

^dA 61-MWe gross/44-MWe net demonstration binary plant was operated at Heber from 1985 to 1987.

^eOESI has announced a 37-MWe net binary plant to be installed at Heber. Magma has announced a total 34-MWe expansion from Magma's four 2F plants at Salton Sea.

Table 16
Hydrothermal Resources in the Basin and Range, Oregon Plateaus,
Snake River Plain, and Northern Rockies Provinces

KGRA or Resource	USGS 790 Mean Res. Temperature (°F)	Estimated Energy ^a (MWe/30 Yr)	Measured Res. Temperature (°F)	Current Capacity (Gross/Net MWe)	Plant Type ^b
Alvord Desert, OR	358-401	300	305	—	—
Baltazor, NV	316	46	—	—	—
Beowawe, NV	444	127	420	17/15	2F
Big Creek Springs, ID	324	26	—	—	—
Brady, Hot Springs, NV	331	157	309	—	—
Colado, NV	207	13	300	—	—
Coso Hot Springs, CA	428	650	400-700	264/240	2F
Cove Fort, UT	333	330	260/340	14/10	H&DS
Crane/Cove Creek, ID	340	360	—	—	—
Crump Hot Springs, OR	333	61	—	—	—
Darrough Hot Springs, NV	270	74	—	—	—
Desert Peak, NV	430	750	400	10/9	2F
Dixie Valley, NV	c	c	415-482	60/55	2F
Fallon Navy Base, NV	c	c	—	—	—
Fernely area, NV	360	33	—	—	—
Fish Lake, NV	c	c	315	—	—
Gerlach/Empire, NV	352	32	?	5/3	B
Humboldt House/Rye Patch, NV	423	47	360-379	—	—
Kyle Hot Springs, NV	318	97	—	—	—
Lakeview, OR	302	105	217	—	B
Leach Hot Springs, NV	324	77	—	—	—
Lee Hot Springs, NV	331	28	—	—	—
Long Valley/Mammoth, CA	441	2,100	330-352	40/31	B
McCoy, NV	c	c	216	—	—
Neal Hot Springs, Or	370	36	—	—	—
Pinto Hot Springs, NV	343	90	—	—	—
Raft River, ID	300	138	279-300	—	B
Randsburg area, CA	342	84	—	—	—
Roosevelt Hot Springs, UT	509	970	482-520	24/22	1F
Ruby Valley, NV	352	74	—	—	—
Salt Wells, NV	c	c	260-350	—	—
San Emidio Desert, NV	341	28	298	—	—
Soda Lake, NV	319	146	342-370	19/16	B
Steamboat Springs, NV	392	350	340-442	9/7	B
Steamboat Springs, NV				13/12	1F
Stillwater, NV	318	450	310-340	17/13	B
Surprise Valley, CA	302	1,490	338	—	—
Thermo, UT	288	12	—	—	—
Trout Creek, OR	309	24	—	—	—
Tuscarora, NV	329	27	297	—	—
Vale, OR	315	870	—	—	—
Wabuska, NV	268	94	223	1.7/1.2	B
Wendel-Amadee	259	54	220-230	3.6/2.7	B
Total		>10,350		497/438	

^aThe USGS did not estimate electric energy for resources less than 150°C (302°F). Estimates are based on USGS wellhead thermal energy estimates using conversion factors from J. D. Geyer, L. M. Kelleman, and R. G. Bloomquist, *Assessment of Geothermal Resources for Electric Generation in the Pacific Northwest*, Northwest Power Planning Council, 1989.

^bB = Binary, 1F = Single Flash, 2F = Dual Flash, H = Hybrid.

^cNot included in USGS Report 790.

Table 17
Hydrothermal Resources in the Cascades

KGRA or Resource	Temperature (°F)	Current Capacity (MWe)	Plant Type	Potential Energy (MWe/30 Yr)
Bearwallow Butte, OR	400?	—	—	400 ^a
Cappy-Burn Butte, OR	400?	—	—	378
Crater Lake, OR	400?	—	—	400 ^a
Glass Buttes, OR	400?	—	—	278
Glacier Peak, WA	400?	—	—	— ^b
Klamath Falls, OR	380	—	—	160 ^c
Klamath Hills area, OR	380	—	—	240 ^d
Medicine Lake, CA	500	—	—	—
Melvin-3 Creek Butte, OR	400?	—	—	400 ^c
Mt. Adams, WA	400?	—	—	400 ^c
Mt. Baker, WA	400?	—	—	400 ^c
Newberry Caldera, OR	500	—	—	250 ^e
Wart Peak Caldera, OR	400?	—	—	116
Total		0		>3,422

Note: USGS Report 790 did not include electric energy estimates for most of the young volcanics in the Cascades. Unless otherwise noted, temperatures and reservoir potential estimates are from PG&E, "Prepared testimony of the Informational Hearing," Energy Conservation Resource Development Commission, 1989.

^aLargest potential estimate used in PG&E, "Prepared testimony"; resource may be larger.

^bUSGS Rpt. 790 estimates resource energy = 27 MWe/30 yr and temperature = 329°F.

^cUSGS Rpt. 790 estimates resource energy = 500 MWe/30 yr and temperature = 232°F.

^dUSGS Rpt. 790 estimates resource energy = 52 MWe/30 yr and temperature = 255°F.

^eUSGS Rpt. 790 estimated resource energy = 740 MWe/30 yr and temperature = 446°F. Resource energy has also been estimated as 1557 MWe/30 yr and temperature = 496°F. However, these were before Newberry was declared a national monument, which removed the best geothermal prospect area, the caldera, from development.

Dry steam reservoirs produce dry or nearly dry steam (without liquid water). Dry steam reservoirs are very rare. The United States Geological Survey (USGS) lists only three dry steam resources in the United States: The Geysers, Mt. Lassen, and Yellowstone National Park.

Hot water reservoirs produce hot water or steam/water mixtures. Fluid temperatures range from less than boiling to 675°F at Puna, Hawaii. The liquids usually contain various quantities of dissolved salts, so they are also called brines. The potential for further hydrothermal development in PG&E's service area is relatively small (300-MW range), and consists of primarily hot water resources in dispersed and unconfirmed fields. Only one 2-MW binary cycle plant has been developed outside of The Geysers.

As the name implies, hot dry rock resources are rocks deep in the earth that become hot from contact with the earth's molten core, which contains no water. A well is drilled into a region of the hot dry rocks, where a reservoir (permeable region) is created by hydraulically fracturing the hot rocks. Additional wells are drilled into the reservoir. Water is pumped through the reservoir to extract the heat from the hot rocks for electric generation. The Los Alamos National Laboratory, under DOE funding, has developed and successfully tested two hot dry rock reservoirs at Fenton Hill, New Mexico. Great Britain and Japan have had less success with their hot dry rock reservoirs. The Clear Lake area represents the largest remaining geothermal resource in Northern California, with a potential of 900 MW of hot dry rock and some hot water resources. The city of Clearlake and the California Energy Commission are in the process of assessing this resource, which might be the next site for commercializing hot dry rock technology if the Fenton Hill project is successful.

Approximately 20,000 MW of hydrothermal resource potential are thought to exist in the Pacific Northwest, in Southern California, and east of the Sierra Nevada. The Pacific Northwest has not had any development to date. BPA is currently planning three separate 10-MW projects to confirm the resource potential of several large fields. Recent exploration at Medicine Lake, California, near the Oregon border indicates a potentially significant resource is near transmission lines running to Northern California. Resource development east of Sierra Nevada will be limited by transmission access to major power markets, particularly Northern California.

Geopressured geothermal resources are deeply buried (generally >15,000 feet), high pressure (generally >10,000 psia), hot water hydrothermal reservoirs. Brine temperatures range from 300°F to 360°F in the Gulf Coast region. The brines also contain dissolved natural gas. Thus, heat, natural gas, and hydraulic energy can be utilized for electric generation. Heat is created by pressure on the brines caused by the weight of the earth's crust above.

Magma resources are "near-surface" molten, or partially molten, rocks from relatively recent volcanic activity that can be reached with current drilling techniques. Under DOE sponsorship, Sandia National Laboratories is performing magma experiments.

ENVIRONMENTAL IMPACTS

Compared to most electric generation technologies, geothermal power is environmentally benign, with minimal to no air emissions, water impacts, and land-use impacts. However, many of the best geothermal sites are in environmentally sensitive areas and can be difficult or impossible to develop (e.g., Lassen National Park).

Most geothermal fluids contain some noncondensable gases, including hydrogen sulfide (H_2S) and the "greenhouse gases," carbon dioxide and methane. Several processes have been developed to remove H_2S before the other noncondensable gases are released to the atmosphere. These have been installed on the direct steam plants at The Geysers and Cove Fort, Utah. Except at one plant, H_2S removal has not been required at hot water geothermal plants to meet air quality regulations. Greenhouse gases are released from dry steam plants, but in very small quantities compared to fossil-fueled power plants. All of the noncondensable gases can be reinjected at most hot water geothermal reservoirs with either flash steam or binary power plants.

Surface water impacts are minimal. The steam condensate from direct steam and flash steam plants is generally used to supply cooling tower water. Waste brines, excess condensate, and waste chemicals for H_2S emissions control are reinjected into the geothermal reservoir safely below the potable water table. Binary plants can be air cooled so that surface waters are not required for plant cooling.

Land-use impacts are also minimal. Only a few acres must be dedicated to the power plant, well pads, cooling towers, roads, and geothermal fluid gathering and reinjection lines. Agricultural use and livestock grazing are generally compatible with geothermal power generation. With proper siting, scenic/recreational land uses also can be compatible.

The hot water hydrothermal resources in the Salton Trough in Southern California produce high solid content brines. Silica is removed from the brines before they are piped into the power plant to control in-plant scaling. Silica disposal is a potential land waste disposal problem. However, beneficial uses, such as road base and brick material, have been developed for the silica.

Hazardous wastes have been generated from H_2S removal processes at The Geysers. Process improvements have been developed to minimize hazardous wastes production. Hazardous chemicals may be used for H_2S

emissions control. Drilling wastes, some of which may be hazardous, also require surface disposal. The working fluid used in most binary power plants is flammable.

DEPLOYMENT CONSIDERATIONS AND HURDLES

Development of a geothermal power plant involves many important issues and considerations. Potential hurdles include public "not in my backyard" reactions, regulatory opposition, lengthy and rigorous permitting processes, environmental issues, transmission access. Independent power producers must also contend with availability of power sales agreements, project financing, and competitive bidding for power.

If third-party financing is required, financial risk can be a major consideration/hurdle. Financial risk includes both development risks and technical risks. Development risks include design changes, cost overruns, delays, and regulatory changes. The greatest technical risk is that the geothermal resource performance and, consequently, power revenues may be less than predicted.

Underperformance could be due to lower than predicted geothermal fluid temperatures or production rates. A recent steam supply decline at The Geysers Power Plant is an example of underperformance. Too much water reinjection can cause reservoir temperature to drop, affecting power plant performance. Geothermal power generation technology is reliable; there is little power plant performance risk. Geothermal/fossil hybrids can reduce reservoir risk by guaranteeing a minimum revenue stream from the "fossil side" of the hybrid plant.

TECHNOLOGY TRENDS AND FORECAST

Geothermal energy conversion technology is relatively mature, but incremental cost and performance improvements can, and will, be made. DOE plans to sponsor an initiative for higher efficiency hydrothermal technologies.

Reservoir management (exploration, development, and operation) requires significant R&D, which would address improved techniques to reduce geothermal power project risk, leading to improved project financing availability and lower interest costs. Geothermal reservoir/plant underperformance at The Geysers, Heber, and Larderello, Italy, are examples of the need of additional reservoir R&D. Reservoir risk uncertainty could represent a major hurdle for financing future geothermal projects. In the United States, DOE, the USGS, state governments (including the CEC), and several private firms are sponsoring reservoir research, and it is also underway in many other nations. Reservoir R&D covers all four types of geothermal resources. However, the geothermal industry can only move up the reservoir exploration/development/operation learning curve by the experience gained from installing and operating geothermal power plants.

In addition to reservoir risk, cost competition from natural gas-fueled combined cycle power plants will impede the future development of geothermal power. Geothermal power can compete more effectively if its indigenous and low environmental impact attributes are considered in benefit/cost evaluations.

Expansion of geothermal generation from hot water hydrothermal plants will continue on a regional basis through the 1990s. The expansion rate will be impacted by the factors discussed above. Installation and operation of geothermal/fossil hybrid power plants can "bridge" over the natural gas supply "bubble" while providing the needed geothermal reservoir management experience. Then, the geothermal industry, including both reservoir management and power generation, will be available and mature when needed by the United States.

There are no known developable new dry U.S. steam resources. Electric generation from hot dry rock may occur early in the next century if the DOE Fenton Hill tests are successful. The CEC is currently sponsoring evaluation of the Clear Lake, hot dry rock resource. Geopressed geothermal resources will probably not be developed for electric generation alone. In the future, electric generation from geopressed geothermal energy may occur in the southwest, including California, in conjunction with thermal enhanced oil recovery. Magma resources are not likely to be exploited commercially for some time.

PG&E AND UTILITY IMPACTS AND IMPLICATIONS

Technology improvements are expected to reduce the 1986 life cycle cost of electric energy from hot water hydrothermal resources by 25% to 35% by 1997. Depending on the generation costs and fuel supply of competing technologies, the geothermal cost reduction will increase the supply of economic geothermal capacity in the Western United States. Most of this new generation will be developed to the east (in the Basin and Range) and south (in the Salton Trough) in PG&E's service area. Because of transmission constraints, etc., it is not clear how PG&E's ratepayers can benefit from this future low-cost hot water geothermal generation.

The state of California and its utilities have the opportunity to decrease their dependence on conventional fuels by further developing California's geothermal resources. The USGS estimates that over 10,000 MWe of generation are available for 30 years at the major geothermal resources within California in the Salton Trough, and at Coso, Mammoth/Long Valley, Clear Lake, and Medicine Lake.

Power output at The Geysers had dropped from a peak of 1,350 MW (PG&E-owned units) to around 800 MW by mid-1991 as a result of the steam field decline. Output is forecasted to decline to 400 MW by the mid-1990s and to under 200 MW in the post-2000 time frame. Non-PG&E-owned Geyser units are experiencing similar

difficulties. Approaches being investigated to halt the decline include innovative plant operation regimes, new reservoir management techniques, improved reservoir modeling, additional water supply for reinjection, and dry cooling and binary cycle retrofit concepts.

In addition, PG&E should promote the development of additional low-cost geothermal resources within its service area. The only currently identified significant geothermal resource within PG&E's service area is at Clear Lake. Present information is that Clear Lake is primarily a hot dry rock resource, although hot water hydrothermal resources may also exist. The CEC is sponsoring an evaluation of this resource.

PG&E ADVANCED ENERGY SYSTEMS GEOTHERMAL R&D PROGRAM

Geothermal has not currently been targeted as a major opportunity technology for demonstration by PG&E's R&D Program because of the relatively mature nature of the hydrothermal technology, the limited potential for further hydrothermal resource development in its service area and the embryonic state of development of hot dry rock technology.

PG&E has previously participated in the DOE Heber binary cycle geothermal project and in an evaluation of EPRI's advanced modular wellhead binary system. PG&E's current technology assessment efforts have focused on characterizing the regional geothermal resources and identifying technology R&D needs. Modular, higher efficiency binary cycles could help to confirm and more effectively develop the remaining dispersed and small hot water reservoirs in Northern California. HDR development at Clear Lake might represent an opportunity if the Fenton Hill tests are successful. PG&E R&D can influence development of the Clear Lake resource as a member of the Phase II Peer Review Group: Hot Dry Rock in the Clear Lake Area. Advanced geothermal and high efficiency natural gas hybrid configurations might offer attractive market features for new hydrothermal resources outside the service area.

Bibliography for Geothermal Energy is on page 279.

GEOTHERMAL ENERGY

- Altshuler, S. L., and T. D. Arcado. 1989. "Ambient air monitoring at The Geysers: A historical perspective and current status." *Geothermal Resources Council Transactions*. v. 13. October 1989.
- Altshuler, S. L., et al. 1985. "Concentrations of non-criteria air pollutants in the vicinity of The Geysers, California." *Geothermal Resources Council Transactions*. v. 9, part 1. August 1985.
- Amir, E., and M. Ringer. 1987. *Relative Cost of Electricity Production*. California Energy Commission. April 1987.
- Anderson, D. N., ed. 1989. "State scene: California and Texas." *Geothermal Resources Council Bulletin*. v. 18. November 1989.
- Annual Report of Pacific Gas and Electric Company to the Public Utilities Commission of the State of California for the year ending December 31, 1988. v. 1. May 1989.
- Arcado, T. D., and S. L. Altshuler. 1989. "Ambient air mercury concentrations at The Geysers." *Geothermal Resources Council Transactions*. v. 13. October 1989.
- Austin, A. L. 1975. "Prospects for Advances in Energy Conversion Technologies for Geothermal Energy Development," *Proceedings of the Second U.N. Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975.
- Ballantine, D. B. 1990. "The Evolution of Power Plant Design at The Geysers." *Geothermal Resources Council Conference*.
- Bartholomew, D. 1989. *Raising \$500 million on steam in the desert*. Corporate Finance. April 1989.
- Bemis, G. R. 1989. *Technology Characterizations*. California Energy Resources Conservation and Development Commission. October 1989.
- Bliem, C. J. 1989. *Aspects of the Kalina Technology Applied to Geothermal Power Production*. EGG-EP-8708. Idaho National Engineering Laboratory. v. 18.
- Bloomquist, R. G., et al. 1985. *Evaluation and Ranking of Geothermal Resources for Electrical Generation on Electrical Offset in Idaho, Montana, Oregon and Washington*. Bonneville Power Administration. Report DOE/BP-13609-1. Portland, OR. June 1985.
- Bloomquist, R. G., J. D. Geyer, and B. A. Sifford. 1989. *Innovative Design of New Geothermal Generating Plants*. DOE/BP-13609-5. July 1989.
- Borgo, P. *The Potential of Using Geothermal Energy as a Peaking Power Source*. Prepared for the U.S. Department of Energy, unpublished.
- Brown, R. J., and W. P. Jordan. 1989. "Element content of rainbow trout and Sacramento sucker in streams of The Geysers region, CA." *Geothermal Resources Council Transactions*. v. 13. October 1989.
- Bureau of Land Management. 1986. "Dixie Valley Geothermal Project, Oxbow Geothermal Corp." *Environmental Assessment*. April 21, 1986.

- . 1985. *Geothermal Resources Operational Order No. 4. General Environmental Protection Requirements*. August 1, 1975.
- California Energy Commission. 1990. Docket No. 88 - ER - 8, "Committee Decision on Phase One Resource Assumptions," Appendix A, p. 1, January 5, 1990.
- . 1989. *Technology Characterizations*. Final Report.
- . 1989. *Electricity 1988 Report*. P106-88-001.
- . 1988. *Energy Technology Status Report*.
- . 1985. *Commercial Status of Electrical Generation Technologies*.
- . 1984. *Technical Assessment Manual*.
- . *Power Plant Siting*.
- Carle, S.F., and N. E. Goldstein. August 1987. "Gravity and fault structures Long Valley Caldera," *Geothermal Resources Council Transactions*, Vol. 11.
- Carrini, D. J., and J. Record. June 1982. "Wellhead power production with a rotary separator turbine." *Geothermal Resources Council Conference on Small Scale Geothermal Power Plants*.
- Cartiere, R. June 22, 1985. *Safety rules tightened at The Geysers*. Santa Rosa, California: The Press Democrat.
- Cedillo, R., and R. N. Yamaoaki. 1981. "The Brawley 10 MWe Power Plant, Unit 1." *Geothermal Resources Council Transactions*. v. 5.
- Code of Federal Regulations*. v. 43. October 1986.
- DiPippo, R. February 1987. "Geothermal power plants worldwide status - 1986." *Proceedings of the Tenth Annual Geothermal Conference and Workshop*, Portland, OR. June 24-26, 1986. EPRI AP 5059-SR, 2-6.
- . 1980. *Geothermal Energy as a Source of Electricity*. U.S. Department of Energy.
- . July 1987. "Kakkonda-shizukuishi, a combined geothermal power- and heating-plant," *The Geothermal Hotline*, vol. 17, no. 1.
- Dunn, J. C. 1990. "Overview: Hardrock Penetration." *Proceedings of the Geothermal Program Review VIII*. San Francisco, California, April 18-20, 1990.
- Energy Information Administration. 1989. *Inventory of Power Plants in the United States, 1988*. Washington, D.C.
- Entingh, D. J. 1990. "Geothermal Electric Costed Supply System: Results for California." Meridian Corporation, Alexandria, Virginia.
- Environmental Impact Statement, Draft*. 1983. Breitenbush II, Geothermal Area., Willamette and Mt. Hood National Forests, Oregon.

Fesmire, R., and R. Vincent. 1985. "Reliability through design The Santa Fe geothermal plant No. 1." *Geothermal Resources Council Transactions*. v. 9, part II.

Fletcher, R. D., and A. Chatterjee. 1988. *Indigenous Energy Resource Assessment*. Pacific Gas and Electric Company. October 7, 1988.

Flynn, T. 1987. *Regulatory Approvals for Electric Generating Plants in Nevada*. Geothermal Resources Council Short Course No. 1. October 1987.

Fontes, R. A. 1984. "NCPA Geysers geothermal development of integrated steam management system." *Geothermal Resources Council Transactions*. v. 8. August 1984.

Geothermal Reports. December 1, 1989. November 15, 1989. November 1, 1989. October 16, 1989. August 1, 1989. April 1, 1989. January 16, 1989. September 1, 1988. April 16, 1984.

Geothermal Resources Council Bulletin. January 1985.

Geyer, J. D., L. M. Kellerman and R. G. Bloomquist. *Assessment of Geothermal Resources for Electric Generation in the Pacific Northwest*. Northwest Power Planning Council, September 1989.

"Geysers promise 3,000 MWe power as world's largest geothermal plant complex." *Geothermal Energy*. v. 12, no. 2. February 1984.

Gipe, P. 1989. "Ormat Heats Up." *Independent Energy*. v. 19, no. 8. October 1989.

Glasstone, S. 1982. *Energy Deskbook*. U.S. Department of Energy.

Goddard, W. B., C. B. Goddard, and D. H. McLain. 1989. "Future Air Quality Maintenance and Improvements Through the Expanded Use of Geothermal Energy." *Geothermal Resources Council Transactions*. v. 13. October 1989.

Hanley, C. R., et. al. 1986. "Geothermal hazardous materials and waste minimization program." Electric Power Research Institute Ninth Annual Geothermal Conference and Workshop. February 1986.

Hays, L. G., and D. G. Elliott. 1975. "Two-Phase Engine." U.S. Patent No. 3,879,949.

Hayes, Putnam and Bartless, Inc. 1988. "Presenting an objective multi-attribute bidding system." California Utilities Bidding Workshop. December 1988.

Henderson, J. M., and Gary P. Dorighi. 1989. "Operating experiences of converting a company's Geysers unit 15." Liquid Redox Stretford to a LO-CAT(R) H₂S Abatement System at Pacific Gas and Electric Conference, Austin, Texas. May 1989.

———. 1989. "Operating Experiences of Converting a Stretford to a LO-CAT(R) H₂S Abatement System at Pacific Gas and Electric Company's Geysers Unit 15," presented at Geothermal Resources Industry Liquid Redox Conference, Austin, TX, May 1989.

Hibara, Y., M. Ikegami, and K. Obinnata. 1988. "Short cut to economical geothermal power generation with wide range portable turbines." *Geothermal Resources Council Transactions*. v. 12.

Hibara, Y., M. Ikegami, and T. Kondo. "Advanced technology for geothermal turbines." *Geothermal Resources Council Transactions*. v. 9, part II.

- Hibara, Y., M. Ikegami, and S. Saito. 1986. "The Heber double flash geothermal power plant." *Geothermal Resources Council Transactions*. v. 10.
- Hinds, A. T. 1982. "Geothermal planning: a tale of two counties." *Geothermal Resources Council Transactions*. v. 6.
- Hinrichs, T. C., and B. W. Dambly. 1980. "East Mesa magmamax power process geothermal generating plant a preliminary analysis." *Proceedings of the Fourth Annual EPRI Geothermal Conference and Workshop*.
- Hirtz, P., and T. MacPhu. 1989. "Development of a safer and more efficient method for abatement of H₂S during geothermal well drilling." *Geothermal Resources Council Transactions*. v. 13.
- Hochstein, M. P. 1988. "Assessment and modelling of geothermal reservoirs (small utilization schemes)," *Geothermics*, vol. 17, no. 1, 1988.
- Hodgson, S. F., ed. December 1989. "The Geothermal Hotline," California Division of Oil and Gas.
- Holt, B., and R. Campbell. 1984. "The mammoth geothermal project." *Geothermal Resources Council Transactions*. v. 8.
- International Energy Agency. 1987. *Renewable Sources of Energy*. OECD Publications.
- Jordan, W. P. and J. R. Brown. 1989. "A review of the Squaw Creek aquatic monitoring program, The Geysers, California." *Geothermal Resources Council Transactions*. v. 13.
- Kaplan, U., Z. Krieger, and A. Dillenberger. 1987. "Innovative design, construction and operation of the Steamboat 5-MW geothermal power plant at Steamboat Springs, Washoe County, Nevada." *Geothermal Resources Council Transactions*. v. 11.
- Kestin, J. ed. 1980. "Sourcebook on the Production of Electricity from Geothermal Energy." U.S. Department of Energy. March 1980.
- Kerna, M. J., and T. S. Allen. 1984. "Roosevelt Hot Springs unit development — a case history." *Geothermal Resources Council Transactions*. v. 8.
- Koenig, J. B. 1989. "Critique of the geothermal exploration R&D program." *Proceedings of the Geothermal Program Review VII*. San Francisco, CA. March 21-23, 1989.
- Lam, L., et al. 1989. "Results on upstream removal of impurities from hashed geothermal steam." *Proceedings: Eleventh EPRI Geothermal Conference and Workshop*. EPRI GS-6380.
- Lienau, P. J. and B. C. Lunis. eds. 1989. *Geothermal Direct Use Engineering and Design Guidebook*. Geo-Heat Center. U.S. Department of Energy. March 1989.
- Lund, J. W. 1989. "Geothermal heat pumps, trends and comparisons." *Geo-Heat Center Quarterly Bulletin*. Fall 1989.
- McClenahan, L. and D. McClain. 1990. "Interagency Cooperation on Geothermal Permitting." Presented to the Interagency Geothermal Coordinating Council.
- Meridian Corporation. 1990. *DOE Geothermal Power Plants Data Base*. April 1990.

- . 1987. *Review of International Geothermal Activities and Assessments of U.S. Industry Opportunities*. v. II. Los Alamos National Laboratory. April 1987.
- . 1987. *The Public Utilities Regulatory Policy Act (PURPA) and U.S. Geothermal Industry: Current Controversies and Trends in Federal and State Implementation*. Prepared for DOE San Francisco Operations Office. November 1987.
- Moss, W.E., et al. 1982. "The Salton Sea 10 MWe power plant, unit 1." *Geothermal Resources Council Transaction*. v. 6
- Muffler, L. J. P. 1981. "Geothermal Resource Assessment." *Geothermal Systems: Principals and Case Histories*. John Wiley and Sons, Ltd.
- National Historic Mechanical Engineering Landmark. 1985. *The Geysers Unit No. 1*. American Society of Engineers. October 1985.
- Negus-de Wys, J. 1989. "Properties of geopressured brines and wells in the Gulf Coast and opportunities for industrial/research participation." *Proceeding of the Geothermal Program Review VII*. U.S. Department of Energy. March 21-23, 1989.
- Nichols, K. E. 1986. "Wellhead powerplants and operating experience at Wendell Hot Springs." *Geothermal Resources Council Transactions*. v. 10. September 1986.
- Nielson, D. L., et al. 1990. "Management of Geothermal Resources." *Proceedings of the Geothermal Program Review VIII*. San Francisco, California, April 18-20, 1990.
- Oman, H. 1986. *Energy Systems Engineering Handbook*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.
- Oregon Department of Energy. *Guide to Oregon's Environmental Permits for Biomass Energy Projects*. Contract No. C50065. October 1984.
- Social Cost of Energy Generation*. Report 007.6-90.3 prepared by Meridian Corporation for the Department of Research and Development. San Ramon, California: Pacific Gas and Electric Company.
- Pacific Gas and Electric Company. 1989. "Prepared Testimony of the Informational Hearing, September 21, 1989. In the Matter of: Geysers KGRA Generating Capacity and Steam Resources." Docket No. 89-INF-1. Energy Conservation Resource Development Commission, State of California.
- . 1988. *Indigenous Energy Resource Assessment*.
- . 1987. *Common Forecasting Methodology 7*. v. III. Electricity Supply Forms 1987-1999. September 1987.
- Priest, G. R., and G. L. Black. September 1989. "Geothermal Exploration in Oregon, 1988," *Oregon Geology*, Vol. 51, No. 5,
- Ponder, S.H., and P. Blaydes. 1987. "The future of geothermal development—ominous trends." *Geothermal Resources Council Transactions*, v. 11.
- Ram, H., and Y. Yahalom. 1988. "Commercially successful large scale binary applications." *Geothermal Resources Council Bulletin*. May 1988.

- Ram, H., and Z. Krieger. "Innovative geothermal power plants: The solution to geothermal resource constraints - the Ormat way." *Geothermal Resources Council Transactions*. v. 13. 1989.
- Renewable Energy Institute. 1986. *Annual Renewable Energy Technology Review-Progress Through 1984*.
- Royce, B. A. 1985. *An Analysis of Environmental Regulations Governing the Disposal of Geothermal Wastes in California*. Brookhaven National Laboratory. September 1985.
- Sagar, R. S., and S. E. Schumacher. 1986. "The Vulcan/BN geothermal power plant, Imperial County, California." BN Geothermal and Magma Power Co. paper. August 1986.
- Schoonmaker, J. L. 1989. "The Coso geothermal power projects." *Geothermal Resources Council Transactions*. v. 12.
- Shackleford, B. W. 1987. "The Geysers: meeting the environmental and operating challenges of geothermal power." *Proceedings: Ninth Annual and Second IIE-EPRI Geothermal Conference and Workshop*. v. 2. August 1987.
- Snetsinger, David. 1989. "Hazardous Waste Management." Panel on Water, Geothermal Resources Council Hazardous Waste Management Course, Santa Rosa, California. September 30, 1989.
- Sorey, M. L. September 1987. "Overview of the Long Valley Hydrothermal System," *Proceedings of the Symposium on the Long Valley Caldera: a Pre-Drilling Data Review*, Lawrence Berkeley Laboratory, LBL-23940.
- . 1985. "Present state of the Hydrothermal System in Long Valley Caldera, California," *Geothermal Resources Council Transactions*, Vol. 9, Part I, August 1985.
- Suemnicht, G. A., and R. J. Varga. 1987. "Constraints on Models of Structure and Hydrothermal Circulation in Long Valley Caldera, California," *Proceedings of the Symposium on the Long Valley Caldera: A Pre-Drilling Data Review*. Lawrence Berkeley Laboratory. September 1987.
- Summit of the Arch, Economic Declaration. Paris, France. July 16, 1989.
- Tester, J. W., D. W. Brown, and R. M. Potter. 1989. *Hot Dry Rock Geothermal Energy -A New Energy Agenda for the 21st Century*. LA-11514-MS. Los Alamos National Laboratory.
- Tetra Tech, Inc. 1979. *Energy Fact Book*. U.S. Department of the Navy.
- The Energy Report. May 11, 1987.
- Tucker, R. E., and R. F. Ward. 1982. "Occidental geothermal No. 1, an innovative plant design." *Geothermal Resources Council Transactions*. v. 6. October 1982.
- U.S. Department of Energy. 1990. *Geothermal Energy Program Summary Volume 1: Overview Fiscal Year 1989*.
- . 1990. "National Energy Strategy and the Role of Geothermal Technology Development." *Proceedings of the Geothermal Program Review VIII*. San Francisco, California, April 18-20, 1990.

- . 1989. *Characterization of U.S. Energy Resources and Reserves*. Prepared by Meridian Corporation for the U.S. Department of Energy. DE-AC01-86CE30844.
- . 1989. *Geothermal Progress Monitor No. 11*. Washington, D.C. December 1989.
- . 1989. *Programmatic Objectives of the Geothermal Technology Division*. v. 1. May 1989.
- . 1989. *Geothermal Energy Program Summary, Volume 1: Overview Fiscal Year 1988*.
- . 1987. *Equipment and Services for Worldwide Applications*. DOE/ID-101 30. August 1987.
- . 1987. *Geothermal Progress Monitor No. 10*. Washington, D.C. July 1987.
- . 1985. *Geothermal Progress Monitor No. 9*. Washington, D.C. June 1985.
- U.S. Environmental Protection Agency. 1987. *Report to U.S. Congress, Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy*. v. 2 of 3: Geothermal Energy. EPA/530-SW-88-003. Office of Solid Waste and Emergency Response. December 1987.
- U.S. Geological Survey. 1982. *Assessment of Low Temperature Geothermal Resources of the United States*, Circular 892. U.S. Department of Interior.
- . 1978. *Assessment of Geothermal Resources of the United States*, Circular 790. U.S. Department of Interior.
- Va San, S., and J. A. Anderson. 1987. "Recent developments in abatement technology of geothermal power plants." *Geothermal Resources Council Transactions*. v. 11.
- Wahl, E. F. 1977. *Geothermal Energy Utilization*. John Wiley & Sons, Inc.
- White, T. 1987. "Strategic planning for geothermal resource confirmation in the Pacific Northwest." *Proceedings of the Tenth Annual Geothermal Conference and Workshop*, Portland, OR. June 24-26, 1986. EPRI AP-5059-SR, 9-6. February 1987.
- Willett, R. F., et al. 1984. "Heber double-flash geothermal power plant, a fast track project." Electric Power Research Institute, *Proceedings: 8th Annual Geothermal Conference and Workshop*. June 1984.
- Williams, R. 1987. "Pacific Gas and Electric Company geothermal operation at The Geysers - 1986 performance perspective." *Proceeding of the Tenth Annual Geothermal Conference and Workshop*. Portland, OR. June 24-26, 1986. EPRI AP-5059-SR, 5-69. February 1987.
- Williams, S., and K. Porter. 1989. *Power Plays*. Investor Responsibility Research Center.
- Yahalom, Y. 1986. "Design and Application Considerations of the Ormesa 30 MWe Geothermal Power Plant at East Mesa, Imperial County, California," *Geothermal Resources Council Bulletin* (Sept/Oct 1986).