SOURCEBOOK ON HIGH-TEMPERATURE ELECTRONICS AND INSTRUMENTATION*

Anthony F. Veneruso, Editor
GeoEnergy Instrumentation Division 4754
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

This sourcebook summarizes the high-temperature characteristics of a number of commercially available electronic components and materials required in geothermal well-logging instruments that must operate to 275°C. The sourcebook is written to provide a starting place for instrument designers, who need to know the high-temperature electronic products that are available and the design and performance limitations of these products. The electronic component information given includes the standard repertoire of passive devices such as resistors, capacitors, and magnetics; the active devices and integrated circuits sections emphasize silicon semiconductor JFETs and CMOS circuits; and, to complete the electronics, interconnections and packaging of hybrid microelectronics are described. Thermal insulation and refrigeration alternatives are also presented in the sourcebook. Finally, instrument housing materials and high-temperature cables and cablehead connectors are listed. This information was compiled as part of the Geothermal Logging Instrumentation Development Program that Sandia National Laboratories conducted for the U.S. Department of Energy's Division of Geothermal Energy from 1976 to 1981.

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*Work performed under Sandia National Laboratories Contract No. DE-AC04-76DP00789 for the U.S. Department of Energy, Division of Geothermal Energy.

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Expanding the Geothermal Frontier, Transactions, Volume 3, Geothermal Resources Council Annual Meeting, September 24-27, 1979, Reno, Nevada.

Geothermal: Energy for the Eighties, Transactions, Volume 4, Geothermal Resources Council Annual Meeting, September 9-11, 1980, Salt Lake City, Utah.

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ACKNOWLEDGMENT

This sourcebook represents the efforts of many individuals in compiling information from diverse sources and in presenting the information as part of a coherent document. The contributions of the following individuals are gratefully acknowledged:

- C. Arnold, Sandia National Laboratories, Division 5811, adhesives and elastomers
- P. A. Bonn, Sandia National Laboratories, Division 2145, hybrid microcircuits
- J. A. Coquat, Sandia National Laboratories, Division 4742, cables and cableheads
- B. L. Draper, Sandia National Laboratories, Division 2151, active devices and integrated circuits
- D. W. Palmer, Sandia National Laboratories, Division 2145, passive devices
- G. D. Urioste, Tech. Reps., Inc., data compilation
- S. F. Weiss, Tech. Reps., Inc., report preparation and editing

DISCLAIMER

Although this sourcebook contains information on commercially available products, much of the data presented was taken from testing conducted above the maximum temperature limits recommended by the manufacturer. The products tested were not designed for high-temperature applications, and there is no intent to endorse any specific manufacturer's product.

This sourcebook presents test data regarding commercial products that may be usable at elevated temperatures. No claim is made as to the completeness or all-inclusiveness of the information given. Furthermore, no attempt was made to perform an exhaustive search for competitive or alternative products; the omission of certain relevant high-temperature materials results solely from the limitations of time and of available information. This sourcebook is intended to be used as an aid for designers and does not necessarily offer the best available description or representation of the performance of the components and materials described. The responsibility of determining which products perform best lies with the user, based on the information given and on additional testing and evaluation conducted by the user.

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SOURCEBOOK ON HIGH-TEMPERATURE ELECTRONICS AND INSTRUMENTATION

INTRODUCTION

This sourcebook summarizes the high-temperature characteristics of a number of commercially available electronic components and materials required for instrumentation that must operate above the conventional 125°C limitation. Descriptions, bibliographies, and references are also given on the various aspects of high-temperature electronic design, fabrication, and testing. The need for this sourcebook arises out of the growing number of applications requiring higher temperature capability and the inadequacy of published information on available materials, components, and fabrication techniques.

The information was compiled as part of the Geothermal Logging Instrumentation Development Program that Sandia National Laboratories conducted for the U.S. Department of Energy's (DOE's) Division of Geothermal Energy during the period 1976 to 1981. The industry-based advisory committee to this geothermal program strongly recommended the publication of this sourcebook in order to stimulate the rapid industrial development and application of high-temperature technology.

High-temperature electronics and instrumentation are needed in many important and growing application areas. For example, geothermal well-logging instruments are needed to explore and aid in the assessment of geothermal resources; the economically recoverable majority of these resources are in the temperature range 150° to 275°C.

High-temperature borehole instruments are also needed in fossil energy applications. As an example, oil recovery by steam injection requires downhole monitoring of critical production parameters at temperatures of about 250°C. Also, as readily accessible oil and gas reservoirs are depleted, the search for fossil fuels is being expanded into more hostile, high-temperature regions in the earth. A case in point

is the vast geopressed formations of the U.S. Gulf Coast area, from which oil and gas are recovered. These formations are typically 8,000 to 12,000 feet deep and have temperatures in the 180° to 200°C range with pressures of 12,000 to 20,000 psi. In addition, the geological overthrust zone in the western U.S. is now being explored for gas at depths of 15,000 to 25,000 feet where temperatures range from 150° to 220°C.

Finally, high-temperature electronics are also needed in instrumentation for jet engines (260°C maximum), nuclear power reactors (240°C), and space exploration (300°C and higher).

Unfortunately, conventional instrumentation is limited in that the components used are usually rated only to the Mil Standard 125°C maximum. Above the 125°C rating, many critical material properties degrade, and electronic components become unreliable or fail. For example, the commonly used 60% lead/40% tin solder melts at 189°C, and typical silicon semiconductor diodes and transistors exhibit excessive leakage current above about 200°C and become intrinsic conductors above 300°C. Most of the common polymers and elastomers used in insulators and packaging lose their desired mechanical and electrical properties above about 200°C, and most quickly degenerate above 250°C.

Although many components and materials degrade or fail above 125°C, there are numerous commercially available products that are suitable for operation beyond 125°C, as this sourcebook demonstrates. In many cases, because there have not been sufficient market incentives, manufacturers may not be aware of the high-temperature performance capabilities of their products nor may they provide performance and applications data, even though their products may perform satisfactorily above 125°C. Occasionally, a straightforward design or manufacturing change, such as removing a low-temperature plastic jacket from a capacitor, results in dramatic improvement in high-temperature performance. Hopefully, this sourcebook will help stimulate the marketplace to provide incentives for U.S. industry to supply additional high-temperature products and application information.

The sourcebook provides a starting place for instrument designers, who need to know the high-temperature products that are available and the design and performance limitations of those products. It is important for the designer to recognize the

limitations of this sourcebook. The information contained herein was compiled during the course of a U.S.-taxpayer-funded program to develop geothermal borehole instrument technology. Within the limits of the program funding and personnel resources available, literature was searched, manufacturers were contacted, and a limited quantity of a few promising products were tested in the laboratory and under field conditions. In many cases, the test conditions were beyond the manufacturers' recommended limits for their products. Due to these limitations, this sourcebook is neither a complete listing of all available high-temperature products nor necessarily a complete, or even adequate, representation of the few products listed. Nevertheless, the sourcebook is offered in the hope that it will benefit the designer by making available the information obtained during the geothermal program.

Within the limits of the DOE program, diligent efforts have been made to obtain all available information in the area of high-temperature electronics. To those manufacturers whose products have gone unnoticed and been omitted from the sourcebook, sincere apologies are offered. Hopefully, consolation will be provided by the expanded market that may result from the availability of this document.

The electronic component information given in the following sections includes the standard repertoire of passive devices such as resistors, capacitors, and magnetics; the active devices and integrated circuits sections emphasize silicon semiconductor JFETs and CMOS circuits; and, to complete the electronics, hybrid microcircuit interconnections and packaging are described. Thermal insulation and refrigeration technologies are also presented as alternatives. Finally, instrument packaging and high-temperature cables and cablehead connectors are listed. Wherever possible, manufacturer and distributor addresses and telephone numbers are included so the user can obtain the product or acquire additional information.

In most cases, the data were obtained by testing a very small sampling, a sampling too small to be statistically representative. Each item described is included with the understanding that the user is responsible for determining the actual use conditions and performance limits of these items in the user's application. Due to the limited testing performed on the components listed, the results a user obtains may vary significantly from the results described herein. Careful note is given in those cases where no tests were performed but only manufacturer's data were included.

In recognizing the growing need for this information and the limited nature of the DOE program that initiated this sourcebook, the editor and authors hope that this effort will stimulate an entrepreneur to update the information and make it available to the public.

References

References 1 through 21, which are listed in the reference section in the back of this sourcebook, are relevant to the sourcebook as a whole.

Bibliography/Abstracts

Following is a bibliography of reports and articles that serve as an introduction to the subject of high-temperature electronics and instrumentation. The bibliography at the end of each major section of this sourcebook provides sources of information on the specific components, devices, and/or materials discussed in that section.

Ball, L. et al. "The National Geothermal Exploration Technology Program," Geophysics, 44:10, October 1979, p 1721.

In response to the Geothermal Energy Research, Development, and Demonstration Act of 1974, a federal geothermal program has been established with the objective of stimulating the commercial development of geothermal resources. The program goal is to increase the annual rate of energy utilization from the present 0.04 quads (500 MWe) to 0.3-0.5 quads in the near term (about 1985), 4.0-9.0 quads in the midterm (1985-2000), and 16.0-28.0 quads in the long term (by about 2020). The realization of these goals depends upon the discovery and exploitation of many new geothermal resource areas. The Department of Energy program for geothermal exploration and assessment has been structured to address technological barriers presently hindering the economical discovery and delineation of geothermal resources. We describe the program elements--exploration technology, reservoir assessment, reservoir confirmation, and reservoir engineering--in light of the need to evaluate some 1,500 new prospects in order to meet the federal midterm electric power goal of 20,000 MWe on-line by the year 2000.

Bonn, P. A. "Geothermal Logging Instrumentation Development," Electronic Packaging and Production Magazine. International Society for Hybrid Microelectronics (ISHM). Presented at a meeting of ISHM, October 20-22, 1980. Available from Microelectronic Manufacturing and Testing, P.O. Box 159, Libertyville, IL 60048.

This exhibit displays electronic components, thick-film hybrid microcircuitry, transducers, and complete prototype tools that have been developed and field tested to 282°C in a geothermal well. This continuing development expands the capability of geothermal instrumentation as part of a national program conducted by Sandia National Laboratories for the Department of Energy's Division of Geothermal Energy. The transfer of high-temperature technology to the marketplace in order to stimulate further development and application has been accomplished through a contract with Teledyne Philbrick-Boston.

Heckman, R. C. "High-Temperature Electronics--An Overview," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 39.

The purpose of this paper is to provide an overview of contemporary high-temperature electronics. To that end, the paper contains brief remarks on the history of high-temperature electronics, an enumeration of the groups or individuals known to us who are now active in the field with their interests and objectives, a discussion of the current state of the art, and an attempt to identify the major areas where new developments are needed for the future.

Major, B. H. High Temperature Geothermal Logging Instrumentation. SAND80-1676J. Albuquerque: Sandia National Laboratories, July 11, 1980. In Proceedings of Scale Control Workshop, April 1980. Los Alamos: Los Alamos Scientific Laboratory.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities (~ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program being conducted by Sandia National Laboratories for the Department of Energy's Division of Geothermal Energy is an industry-based effort to develop and apply the high-temperature instrumentation needed to make geothermal borehole measurements. This program emphasizes the development and field test performance verification of severe-environment components such as 275°C electronics, high-temperature/high-resolution pressure transducers, elastomeric and metal tool seals, cableheads, and cables. Instrumentation for geothermal borehole measurements is being expanded beyond today's limited capabilities. Prototype logging tools have been successfully field tested to 275°C; a high-resolution quartz pressure transducer and a GaP diode have been successfully tested. Near-term goals of current programs are to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi).

Northrup, D. A. and Veneruso, A. F. Instrumentation for Earth Resources Extraction. SAND79-0522. Albuquerque: Sandia Laboratories, May 1979. In Lawrence, R. J. and Mead, P. L., eds, Sandia Technology.

The needs of geothermal technology focused upon the development of high-temperature instrumentation hardware and the development of fossil-energy

extraction technologies requiring field-oriented instrumentation efforts aimed at characterization and understanding of in situ processes are described.

Veneruso, A. F., Polito, J., and Heckman, R. C. Geothermal Logging Instrumentation Development Program Plan. SAND78-0316. Albuquerque: Sandia Laboratories, August 1978.

This Geothermal Logging Instrumentation Development Program Plan outlines a 9-year, industry-based program to develop and apply high-temperature instrumentation technology which is needed by the borehole logging industry to serve the rapidly expanding geothermal market. Specifically, this program will upgrade existing materials and sondes to improve their high-temperature reliability. To achieve this goal, specialized equipment such as high-temperature electronics, cables, and devices for measuring formation temperature, flow rate, downhole pressure, and fractures will be developed. In order to satisfy critical existing needs, the near-term (FY80) goal is for operation at or above 275°C in pressures up to 48.3 MPa (7,000 psi). The long-term (FY84) goal is for operation up to 350°C and 138 MPa (20,000 psi). This program plan has been prepared for the Department of Energy's Division of Geothermal Energy (DGE) and is a portion of the DGE Long-Range Geothermal Well Technology Program.

and Coquat, J. A. Geothermal Logging Instrumentation. SAND78-1142J. Albuquerque: Sandia Laboratories, September 1978. In Proceedings of MIDCON/78 Conference, December 12-14, 1978 (sponsored by IEEE).

This paper describes the progress and plans of the Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy. This is an industry-based program to develop and apply the high-temperature instrumentation needed to make geothermal borehole measurements. Specifically, this program is upgrading existing materials and sondes for improved high-temperature performance, as well as developing component technology such as high-temperature cables and electronics to make measurements such as formation temperature, flow rate, and high-resolution downhole pressure. In order to satisfy critical existing needs, the near-term goal is for operation at 275°C and 48.3 MPa (7,000 psi) by the end of FY80. The long-term goal is for operation up to 350°C and 138 MPa (20,000 psi) by the end of FY84.

. Geothermal Energy Resources and Utilization. SAND78-0138A. Albuquerque: Sandia Laboratories, November 21, 1978. In Proceedings -- Institute of Environmental Sciences, 940 E. Northwest Highway, Mount Prospect, IL 60056. (Conference, December 6, 1978.)

Geothermal energy is obtained from naturally generated heat within the earth. This heat is thought to result from the radioactive decay of naturally occurring radioisotopes deep within the earth's crust. Certain geologic formations create significant concentrations of this heat and give rise to surface manifestations such as hot springs and geysers.

These areas have been used since ancient times for recreation and medical purposes. Today, geothermal energy is a vast potential source of useful power which, although highly site specific, should become available for a wide variety of important applications. Although a particular reservoir may be depleted after several decades of use, the overall supply is virtually inexhaustible.

and Coquat, J. A. Technology Development for High Temperature Logging Tools. SAND79-0013. Albuquerque: Sandia Laboratories, March 14, 1979. In Transactions of the 20th Annual Logging Symposium, Society of Professional Well Logging Analysts, June 3-6, 1979.

A set of prototype, high-temperature logging tools (temperature, pressure, and flow) were tested successfully to temperatures up to 275°C in a Union Geothermal well in northern New Mexico during November 1978 as part of the Geothermal Logging Instrumentation Development Program. This program is being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy. This paper describes the progress and plans for this industry-based program to develop and apply the high-temperature instrumentation technology needed to make reliable geothermal borehole measurements. Specifically, this program is upgrading existing sondes for improved high-temperature performance, as well as applying new materials (elastomers, polymers, metals, and ceramics) and developing component technology such as high-temperature cables, cableheads, and electronics to make borehole measurements such as formation temperature, flow rate, high-resolution pressure, and fracture mapping. In order to satisfy critical existing needs, the near-term goal is for operation up to 275°C and 7,000 psi by the end of FY80. The long-term goal is for operation up to 350°C and 20,000 psi by the end of FY84.

. High Temperature Electronics for Geothermal Energy. SAND79-1524J. Albuquerque: Sandia Laboratories, July 29, 1979. In IEEE Circuits and Systems Magazine, 1:3, September 1979.

The worldwide production of electric power from geothermal energy sources at present is 1.2 GW. The largest facility is in the United States at The Geysers, in northern California, where 605 MW is on-line. Recent estimates indicate that geothermal energy sources could produce over 10 GW of power in the U.S. by 1990; however, to achieve this goal, there must be accelerated exploration and development. Developers and investors may be reluctant to make the necessary commitments if there is a high risk of uncertainty in a geothermal reservoir's production potential. Also, once a system is in operation, engineers periodically need accurate and timely downhole information from each well in order to obtain production. Instrumentation for geothermal borehole measurements is being expanded beyond today's limited capabilities. Prototypical logging tools have been successfully field-tested to 275°C; a high-resolution quartz pressure transducer and a GaP diode have been successfully tested. Near-term goals of current programs are to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi).

and Stoller, H. M. High Temperature Instrumentation Development and Commercialization for Geothermal Applications. SAND79-1371A. Albuquerque: Sandia Laboratories, June 1979. In Transactions of the Geothermal Resources Council Annual Meeting (September 1979), vol 3. p 745.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities ($\sim 180^{\circ}\text{C}$) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program is being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy. This program emphasizes the development and field test performance verification of severe-environment components such as 275°C electronics, high-temperature/high-resolution pressure transducers, elastomeric and metal tool seals, cableheads, and cables. Since the report to the Geothermal Resources Council last year, a number of these essential developments have come to fruition: a set of prototype geothermal logging tools (temperature, pressure, and flow), cables, and cableheads were successfully field tested to temperatures up to 275°C in a geothermal well during November 1978; an experimental high-resolution quartz pressure transducer was successfully tested up to 275°C and 1,000 psi; a GaP diode was developed and found to operate successfully up to 400°C ; and the mechanical clocks in the Amerada gauge were upgraded in temperature and reliability.

. "A Perception of the Geothermal Industry." Proceedings of Publication Invitation to the October 1979 Organizational Meeting for Geothermal Energy Standards, American Society for Testing and Materials, Philadelphia, PA.

One of the primary beneficiaries of appropriate geothermal standards is that fledgling industrial structure that we refer to as the U.S. Geothermal Industry. What makes up this structure, how can it benefit from standards, and how can it participate in setting up those standards?

. "Standardization to Accelerate the Development and Use of Geothermal Logging Instrumentation," Standardization News, 7:10, October 1979, p 29.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities ($\sim 180^{\circ}\text{C}$) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy is an industry-based effort to develop and apply the high-temperature instrumentation needed to make geothermal borehole measurements. The near-term goal is to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi); subsequent goals are to extend the capabilities to 350°C and 138 MPa (20,000 psi). Working closely with geothermal producers, logging service companies are conducting research and development to correct technical deficiencies so the companies may adequately serve the growing geothermal market. The basic impediments they face involve special technologies that are not normally required in their trade and for which there are insufficient incentives to develop. It is precisely those technologies that are being developed by the logging instrumentation program.

_____. "High Temperature Technology -- Potential, Promise, and Payoff," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 17.

The purpose of this 2-day seminar is to review the state of the art and the recent substantial progress in high-temperature electronics and instrumentation. This seminar comes at a critical time and it addresses a vital subject. The frontiers of technology are rapidly moving beyond the conventional 125°C boundary. Already, special "hostile environment" instruments routinely operate up to 180°C, a few prototype systems have been field tested for 275°C, new development is under way for 300°C integrated circuits, and research continues on components up to 500°C.

_____. and Chang, H. "Detection, Diagnosis and Prognosis in Geothermal Well Technology," Proceedings of 32nd Meeting of the Mechanical-Failures Prevention Group, National Bureau of Standards, October 7-9, 1980.

For successful and safe operation of a geothermal well, the condition of the casing and cement must be accurately determined. Measurements on casing wall thickness, corrosion damage, holes, cracks, splits, etc., are needed to assess casing integrity. Cement bond logs are needed to detect channels or water pockets in cement behind pipe and to determine the state of the cement bond to the pipe and formation. Instrumentation for making such measurements is limited by the temperature capabilities (< 175°C) of existing logging equipment developed for the oil and gas industry. This paper reviews the instruments that are needed for geothermal casing and cementing inspection, identifies the principal deficiencies in their high-temperature use, and describes Sandia's upgrade research program on the multi-arm caliper and acoustic cement bond logging tool. The key electronic section in a multi-arm caliper will consist of 275°C circuits designed by Sandia. In an acoustic cement bond logging tool, a simple circuit with possibilities of using commercially available components for high-temperature operation is being developed. These new tools will be field tested for operation at a minimum temperature of 275°C and pressure of 7,000 psi for up to 1,000 hours.

_____. and Heckman, R. C. "The Frontiers of High Temperature Electronics," Components, Hybrids, and Manufacturing Society Newsletter, New York, January 1981.

This paper provides an overview of contemporary high-temperature electronics that can operate beyond the conventional 125°C limit. The needs and applications for this technology in such vital areas as oil, gas, and geothermal downhole instrumentation are reviewed. The state of the art of components and circuits is then presented along with a specific design example of a 275°C voltage regulator. Finally, the direction of future R&D is discussed.

1.0 PASSIVE DEVICES

1.1 CAPACITORS

1.1.1 SYNOPSIS

In general, capacitors to be used at high temperatures should have the following desirable characteristics: no more than a 5% change in capacitance over the temperature range, at least a 1,000-hour lifetime at maximum temperature, a dissipation factor of less than 10%, an insulation resistance of at least $1 \text{ M}\Omega\text{-}\mu\text{F}$ at maximum temperature, and a small physical size. These criteria are not rigid and depend on the application.

A few selected commercial capacitor types, having capacitance values ranging from 100 pF to 0.1 μF , have been found that perform well up to 300°C. In general, however, deficiencies exist in capacitors. Devices having capacitances greater than 100 pF present problems related to large size, high cost, and the degradation of functional characteristics at high temperatures. Elevated temperatures also affect the performance of most commercial discrete and chip capacitors, of whatever capacitance value, in that the heat degrades the standard solder and organics used in these devices. Most types of capacitors must be severely derated in lifetime and voltage capability at high temperatures. Figure 1 shows the types of capacitors that appear to be appropriate for the voltage levels and capacitance values given for operation to 275°C.

Table 1 describes typical types of discrete capacitors. Many manufacturers commonly refer to a "discrete" capacitor when they mean an individually packaged capacitor equipped with wire electrodes or solder leads; the "chip" capacitor designation typically refers to an individually packaged capacitor device having integral electrodes ready to bond onto a hybrid substrate or printed circuit.

1.1.1 SYNOPSIS

Table 2 refers to thick-film dielectric inks with which capacitors can be made as part of the hybrid microcircuit process. For related information, see Section 3.2. Hybrid Microcircuits and Section 3.3 Microcircuits, Components.

The characteristics of capacitors listed in this sourcebook in no way represent a guaranteed performance. First, many of the stated characteristics were derived from the testing of a small sampling of capacitors. Second, the characteristics described by the manufacturers do not necessarily apply to individual capacitors under combined operating and severe environmental conditions. Given these circumstances, it is strongly suggested that each of these devices be tested under the expected conditions of use before being placed in a high-temperature circuit.

References 2 and 22 through 33, which are listed in the reference section of this sourcebook, contain information relevant to capacitors.

MANUFACTURERS AND SOURCES OF DATA

(1) SPRAGUE AND SEMIFILMS	(4) CERMALLOY
(2) NORTH AMERICAN PHILIPS	(5) PURDUE
(3) UNIVERSITY OF ARIZONA	(6) SANDIA

Figure 1. High-Temperature Capacitor Types for 275°C Operation. (Figure provided by R. C. Heckman, Sandia National Laboratories.)

Table 1
Discrete and Chip Capacitors

Manufacturer	Type of Construction	Capacitance Range	Voltage Range, V	Size, inches	Maximum Temperature, °C	Page Listing
ATC	Porcelain	130 pF, 1,000 pF	100	--	< 275	1-11
AVX	Ceramic multilayer	1,000 pF	--	--	< 275	1-15
Custom	Teflon®*	25 pF, 2.0 μ F	50 to 600	0.218 dia. x 0.688 length to 1.0 dia. x 2.0 length	250	1-24
	Mica	0.001 μ F to 10 μ F	400 to 15,000	0.341 dia. x 0.780 length to 1.000 dia. x 19.875 length; 1.562 x 1.562 x 1.562 to 8.810 x 1.938 x 1.438	300	1-16, 1-26
El Menco	Mica/silver	50 pF	--	0.125 x 0.5 x 0.1875	< 500	1-30
Fujitsu	Aluminum foil	1.0 μ F to 10 μ F	2.5 to 16	--	200	1-7
Gen. Labs. Assocs.	Mica	0.1 μ F to 1.0 μ F	500	--	300	1-6
KD	Ceramic	1 pF to 1.0 μ F	100 to 5,000	0.2 x 0.2 x 0.1 to 1.2 x 1.2 x 0.6	200	1-22
	Mica	1 pF to 0.1 μ F	100 to 1,000	--	300	1-23
Mallory	Tantalum	2 μ F to 1,300 μ F	8 to 720 WVDC	0.656 dia. x 0.438 length to 1.13 dia. x 2.81 length	200	1-23
Philips (Mepco)	Aluminum foil	1.0 μ F to 100 μ F	10 to 40	--	275	1-6
Simmonds	Mica/aluminum	0.03 μ F	--	0.5 dia. x 2.75 length	< 500	1-30
Sprague	Mica	4 μ F	150	--	< 175	1-9
Union Carbide	Tantalum	0.22 μ F to 22 μ F	20	--	250	1-12
United Chemi-Con	Aluminum foil	150 μ F	4	--	275	1-14
U.S. Capacitor Corp.	Monolithic ceramic	10 pf to 4 μ F	25 to 100	--	200	1-16
USCC Centralab	Ceramic	0.01 μ F	50	--	275	1-10
Viclan	Ceramic	0.022 μ F, 0.055 μ F	50 to 200	--	300	1-14

*Teflon® is a registered trade name of E. I. Du Pont de Nemours and Co.

1.1.1 SYNOPSIS

Table 2

Thick-Film Dielectric Materials

<u>Manufacturer</u>	<u>Capacitance Range</u>	<u>Maximum Temperature, °C</u>	<u>Page Listing</u>
Cermalloy	$\leq 1,000$ pF	500	1-21
Du Pont	100 pF to 5,000 pF	300	1-19
ESL	100 pF to 0.02 μ F	300	1-18
TFS	$\leq 1,000$ pF	350	1-21.

NOTE: Du Pont = E. I. Du Pont de Nemours and Co.
ESL = Electro-Scientific Laboratories, Inc.
TFS = Thick Film Systems

1.1.2 CAPACITORS, DISCRETE AND CHIP

Sandia tested several samples of the following capacitors from 25° to 300°C.

Manufacturer

North American Philips
Mepco/Electra, Inc.
Columbia Road
Morristown, NJ 07960
(201) 539-2000

Series 121

Solid Electrolyte

Aluminum Foil

Capacitance Range: 1.0 to 100 μF

Voltage Range: 10 to 40 volts

Device Tested: 2.2- μF /40-volt capacitor

Capacitance Change: +18%

Dissipation Factor: 8% maximum at 1,000 Hz

Insulation Resistance: 1 to 5 $\text{M}\Omega\text{-}\mu\text{F}$ typically

Manufacturer

General Laboratories Associates, Inc.
Simmons Precision
Box 310
Norwich, NY 13815
(607) 335-5000
(address and telephone number not verifiable)

1.1.2 CAPACITORS, DISCRETE AND CHIP

Mica Paper

Capacitance Range: 0.1 to 1.0 μF

Device Tested: 0.1- μF /500-volt capacitor

Capacitance Change: $\leq 2\%$

Dissipation Factor: 7% at 60 Hz

Insulation Resistance: 1 to 100 $\text{M}\Omega$ - μF at 150°C

Note: These capacitors are expensive and large in size.

Manufacturer

Fujitsu Ltd.

8 2 Chm Marunouchi Chiyoda-Ku

Tokyo, Japan

Solid Electrolyte Aluminum

Capacitance: 3.3 μF

Voltage: 16 volts

Capacitance Change: 32% at 300°C

Dissipation Factor: 1% at 225°C

Minimum Leakage Resistance: 50 $\text{M}\Omega$ at 300°C

Note: Solder fails at 180°C.

1.1.2 CAPACITORS, DISCRETE AND CHIP

Solid Electrolyte
Aluminum

Capacitance: 3.3 μF

Voltage: 10 volts

Capacitance Change: 32% at 300°C

Dissipation Factor: < 10% at 300°C

Minimum Insulation Resistance: 1,000 $\text{M}\Omega$ at 200°C

Solid Electrolyte
Aluminum

Capacitance: 1 μF

Voltage: 2.5 volts

Capacitance Change: 37% at 275°C

Dissipation Factor: 17% at 300°C; 10% at 100°C

Minimum Insulation Resistance: 200 $\text{M}\Omega$ at 275°C

Solid Electrolyte
Aluminum

Capacitance: 4.7 μF

Voltage: 16 volts

Capacitance Change: 49% at 300°C; 13% at 250°C

Dissipation Factor: 55% at 275°C; 7% at 225°C

Minimum Insulation Resistance: 500 $\text{M}\Omega$ at 275°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

**Solid Electrolyte
Aluminum**

Capacitance: 10 μ F

Voltage: 10 volts

Capacitance Change: 16% at 275°C

Dissipation Factor: 4% at 225°C; > 60% at 275°C

Minimum Insulation Resistance: 100 MΩ at 275°C

Manufacturer

Sprague Electric Company
87 Marshall Street
North Adams, MA 01247
(413) 664-4411

Mica

Capacitance: 4 μ F

Voltage: 150 volts

Capacitance Change: 39% at 175°C

Dissipation Factor: > 60% at 175°C

Note: Capacitor opens above 175°C.

1.1.2 CAPACITORS, DISCRETE AND CHIP

Manufacturer

USCC Centralab
4561 Colorado Boulevard
Los Angeles, CA 90039
(213) 240-8440

NPO Multilayer
Ceramic

Capacitance: 0.01 μF

Voltage: 50 volts

Capacitance Change: 1% from 25° to 275°C

Dissipation Factor: 1.5% at 275°C

Note: Capacitor opens above 300°C.

Ceramic Multilayer

Capacitance: 0.22 μF

Voltage: 50 volts

Capacitance Change: 59% from 25° to 300°C

Dissipation Factor: 0.1% at 275°C

Minimum Insulation Resistance: < 10 MΩ at 175°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

Ceramic

Note: 4000 Series good in the -30° to 200°C range

Manufacturer

American Technical Ceramics (ATC)

1 Norden Lane

Huntington Station, NY 11746

(516) 271-9600

100B series

Porcelain

Capacitance: 130 pF

Voltage: 100 volts

Capacitance Change: 8% at 300°C

Dissipation Factor: 7% at 275°C

Minimum Insulation Resistance: $400\text{ M}\Omega$ at 300°C

Porcelain

Capacitance: 1,000 pF

Voltage: 100 volts

Capacitance Change: 6% at 300°C

Dissipation Factor: 3.1% at 300°C

Minimum Insulation Resistance: $240\text{ M}\Omega$ at 300°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

CYFM Series
Glass

Capacitance: 1,000 pF

Voltage: 300 volts

Note: Capacitor performs well up to 275°C.

Manufacturer

Electronics Division

Union Carbide/Kemet

P. O. Box 5928

Greenville, SC 29606

(803) 963-6300

Solid Electrolyte
Tantalum

Capacitance: 15 μF

Voltage: 20 volts

Capacitance Change: 141% at 300°C

Dissipation Factor: > 60% at 50°C

Minimum Insulation Resistance: 1.4 MΩ at 300°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

Solid Electrolyte
Tantalum

Capacitance: 0.02 μF

Voltage: 20 volts

Capacitance Change: 800% at 275°C

Minimum Insulation Resistance: 0.13 M Ω at 280°C

Solid Electrolyte
Tantalum

Capacitance: 22 μF

Voltage: 20 volts

Capacitance Change: 105% at 300°C

Dissipation Factor: > 60%

Minimum Insulation Resistance: 1.7 M Ω at 300°C

Note: Temperature cycling tests were conducted from 25° to 300°C. The capacitor exhibited no major changes as a result of the tests that followed the first 18 cycles.

1.1.2 CAPACITORS, DISCRETE AND CHIP

Manufacturer

United Chemi-Con Corp., Dept. G
731 Janes Street, Suite 306
Syracuse, NY 13203
(315) 474-2954

Solid Electrolyte
Aluminum

Capacitance: 150 μF

Voltage: 4 VDC

Capacitance Change: 23% at 300°C

Dissipation Factor: 37% at 300°C

Minimum Insulation Resistance: 5 M Ω at 300°C

Note: Heat cycling tests reveal no major change in characteristics.

Manufacturer

Viclan, Inc.
7373-A Engineer Road
San Diego, CA 92111
(714) 292-1411

NPO
Ceramic Chip

Capacitance: 0.055 μF

Voltage: 200 volts

Capacitance Change: 2% at 300°C

Dissipation Factor: 4% at 275°C

Minimum Insulation Resistance: 1 M Ω at 275°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

NPO, Model W5R-50
Ceramic Chip

Capacitance: 0.022 μ F
Voltage: 50 volts
Capacitance Change: 10% at 300°C
Dissipation Factor: $\geq 10\%$
Minimum Insulation Resistance: 1 MΩ- μ F

Manufacturer

AVX Corp.
98 Cutter Mill Road
Great Neck, NY 11021
(516) 829-8500

Beam Lead

Capacitance: 1,000 pF
Capacitance Change: 5% at 300°C
Dissipation Factor: 6.9% at 300°C
Minimum Insulation Resistance: 500 kΩ at 275°C

1.1.2 CAPACITORS, DISCRETE AND CHIP

Manufacturer

Custom Electronic, Inc.

Browne Street

Oneonta, NY 13820

(607) 432-3880

CHR3A154SSP

Paper Mica

Capacitance: 0.1 μ F

Voltage: 500 volts

Capacitance Change: 20% at 300°C

Dissipation Factor: 30% at 300°C and 60 Hz

Minimum Insulation Resistance: 400 M Ω at 275°C

The following characteristics are taken from the manufacturer's specifications.

Because of program limitations, Sandia performed no tests on these capacitors.

Manufacturer

U.S. Capacitor Corp.

11144 Penrose Street

Unit 7

Sun Valley, CA 91352

(213) 767-6770

1.1.2 CAPACITORS, DISCRETE AND CHIP

Monolithic Ceramic Series

C28, X28; Axial

C38, X38; Radial

Capacitance: 10 pF to 4 μ F

Voltage: 25, 50, 100 volts

Capacitance Change: $\pm 15\%$ from -55° to 125°C

Dissipation Factor: 2.5% maximum at 125°C

Minimum Insulation Resistance: 500 $\text{M}\Omega$ or 5 $\text{M}\Omega\text{-}\mu\text{F}$,
whichever is less, at 300°C

Temperature Rating: -55° to 200°C

Note: Characteristics are given to 260°C . A rectangular
configuration for use over the range -55° to 300°C is
in R&D.

1.1.3 CAPACITORS, THICK FILM

Sandia tested the following capacitors from 25° to 300°C.

Manufacturer

Electro-Science Laboratories, Inc. (ESL)
2211 Sherman Avenue
Pennsauken, NJ 08110
(609) 663-7777

4110

Capacitance Range: 100 to 2,200 pF
Capacitance Change: 10% at 275°C
Dissipation Factor: 15% for 60 Hz at 275°C
Minimum Insulation Resistance: 100 M Ω at 300°C
Dielectric Constant: K = 10 to 15

4301

Capacitance Range: 100 to 2,200 pF
Capacitance Change: < 5% at 275°C
Dissipation Factor: 18% for 60 Hz at 300°C
Minimum Insulation Resistance: 100 M Ω at 300°C
Dielectric Constant: K = 10 to 15

1.1.3 CAPACITORS, THICK FILM

4515

Capacitance Range: 10,000 to 20,000 pF

Capacitance Change: 10% to 20% over temperature test range; 5% at 300°C

Dissipation Factor: 3% at 300°C

Minimum Insulation Resistance: 0.3 MΩ-μF at 300°C

Dielectric Constant: $K \approx 200$

Manufacturer

E. I. Du Pont de Nemours and Co.

Electro Chemicals Department

1007 Market Street

Wilmington, DE 19898

(302) 774-1000

8299

Capacitance Range: 100 to 5,000 pF

Capacitance Change: 5% at 300°C

Dissipation Factor: <6% for 1,000 Hz at 300°C

Minimum Insulation Resistance: 2,000 MΩ at 300°C

Dielectric Constant: $K = 8$ to 10

8315

Capacitance Range: 100 to 5,000 pF

Capacitance Change: 10% at 275°C; 20% at 300°C

Dissipation Factor: 18% for 60 Hz at 300°C

1.1.3 CAPACITORS, THICK FILM

Minimum Insulation Resistance: 100 M Ω at 275°C

Dielectric Constant: K = 8 to 12

9428

Capacitance Range: 100 to 5,000 pF

Capacitance Change: 18% at 300°C

Dissipation Factor: 8% for 60 Hz at 300°C

Minimum Insulation Resistance: 3,000 M Ω at 300°C

Dielectric Constant: K = 8 to 12

Note: Other inks manufactured by Du Pont include 8799, 9101, and 9429.

1.1.3 CAPACITORS, THICK FILM

The following characteristics are taken from manufacturers' specifications. Because of program limitations, no tests were performed on these components by Sandia.

Manufacturer

Cermalloy
Bala Electronics Corp.
Union Hill Industrial Park
West Conshohocken, PA 19428
(215) 825-6050

9105HT

Capacitance Range: < 1,000 pF
Capacitance Change: 1.5% at 300°C; 7% at 500°C
Dissipation Factor: 0.5% at 300°C; 6% at 500°C
Note: Capacitor can be used to 500°C

9205HT

Capacitance Range: 0.01 pF to 0.1 pF
Dielectric Constant: K = 75

Manufacturer

Thick Film Systems
324 Palm Avenue
Santa Barbara, CA 93101
(805) 963-7757

1005

Capacitance Range: < 1,000 pF
Capacitance Change: 3% at 300°C
Dielectric Constant: K = 5
Note: Capacitor functions to 350°C

1.1.4 CAPACITORS, DISCRETE

The following characteristics are taken from manufacturers' specifications. No tests were performed on these components by Sandia because of program limitations.

Manufacturer

KD Components, Inc.
3016 S. Orange Avenue
Santa Ana, CA 92707
(714) 545-7108
Attn: Mike W. Day

HSD Series

Ceramic

Capacitance Range: 10 pF to 0.01 μ F
Voltage Range: 1,000 to 20,000 WVDC
Temperature Range: -55° to 200°C
Dissipation Factor: 2.5% maximum at 1 kHz
Temperature Coefficient: $\pm 15\%$, X7R characteristic
Insulation Resistance: 100,000 $M\Omega$ or 1,000 $M\Omega/\mu$ F at 500 VAC; 10,000 $M\Omega$ or 100 $M\Omega/\mu$ F at 125°C
Size, inches: 0.3 x 0.3 x 0.2 to 1.2 x 1.2 x 0.6

HT Series;

NPO, K600, K1200

Ceramic

Capacitance Range: NPO, 10 pF to 0.10 μ F; K600, 1,500 pF to 0.470 μ F; K1200, 0.047 μ F to 1.0 μ F
Voltage Rating: 100 VDC at -55° to 125°C derated to 60 V at 200°C
Temperature Range: -55° to 200°C
Dissipation Factor, Maximum Values: NPO, 0.1%; K600, 2.25%; K1200, 2.5%
Temperature Coefficient: NPO, ± 30 ppm; K600, +10%, -18%; K1200, +15%, -30%
Insulation Resistance: 10 $M\Omega$ - μ F minimum
Size, inches: Rectangular, 0.2 x 0.2 x 0.1 to 0.8 x 0.5 x 0.3; Tubular, 0.125 dia. x 0.26 length to 0.375 dia. x 0.8 length

1.1.4 CAPACITORS, DISCRETE

HV Series Ceramic

Capacitance Range: 100 pF to 0.25 μ F
Voltage Range: 500 to 5,000 VDC
Temperature Range: -55° to 200°C
Dissipation Factor: 2.5% maximum
Temperature Coefficient: +5%, -20%
Insulation Resistance: 1,000 M Ω - μ F or 100,000 M Ω at 25°C; 10 M Ω - μ F or 100 M Ω at 200°C
Size, inches: 0.2 x 0.2 x 0.15 to 0.8 x 0.7 x 0.4

Mica

Capacitance Range: 1 pF to 0.1 μ F
Voltage Range: 100 to 1,000 volts
Temperature Range: -55° to 300°C
Capacitance Change: 3% at 300°C
Dissipation Factor: 1% at 300°C
Insulation Resistance: 100 M Ω - μ F at 300°C

Manufacturer

P. R. Mallory and Co., Inc.
3029 E. Washington St.
Indianapolis, IN 46206
(317) 636-5353

Distributor

Lenert Company
Box 2184, 1420 Hutchins
Houston, TX 77001
(713) 225-1465

1.1.4 CAPACITORS, DISCRETE

XTV Series Tantalum

Capacitance Range: 12 to 2,200 μ F
Voltage Range: 12 to 630 WVDC, derated to 67% at 175°C
Temperature Range: -50° to 175°C and possibly 200°C
Capacitance Change: +35% maximum at 175°C
Size, inches: 1.125 dia. x 0.600 length to 1.125 dia. x
2.812 length

XTH and XTL Series Tantalum

Capacitance Range: 2.5 to 240 μ F
Voltage Range: 18 to 900 WVDC
Temperature Range: -55° to 175°C and possibly 200°C
Capacitance Change: 40% maximum at 175°C
Size, inches: 0.875 dia. x 0.540 length to 0.875 dia. x
4.062 length

XTK and XTM Series Tantalum

Capacitance Range: 2 to 140 μ F
Voltage Range: 8 to 360 WVDC
Temperature Range: -55° to 175°C
Capacitance Change: 30% maximum at 175°C
Size, inches: 0.656 dia. x 0.438 length to 0.656 dia. x
1.781 length

Note: For information on the operation of the XTV, XTH,
and XTL Series at 200°C, contact the Mallory Engineer-
ing Department at (317) 636-5353.

Manufacturer

Custom Electronic, Inc.
Browne Street
Oneonta, NY 13820
(607) 432-3880

Distributor

Lenert Company
Box 2184, 1420 Hutchins
Houston, TX 77001
(713) 255-1465

1.1.4 CAPACITORS, DISCRETE

TFHT Series,
Extended Foil
Teflon®*

Capacitance Range: 0.0001 to 1.00 μ F
Voltage Rating: 50 to 600 VDC
Temperature Range: -65° to 200°C without voltage
derating
Dissipation Factor: 0.02% maximum
Temperature Coefficient: -100 $\pm$ 100 ppm/°C
Insulation Resistance: 1,000 M Ω - μ F at 200°C
Size, inches: 0.235 dia. x 0.750 length to 1.0 dia. x
2.0 length

TMHT Series,
Metallized Film
Teflon®

Capacitance Range: 0.05 to 2.00 μ F
Voltage Rating: 50 to 600 VDC
Temperature Range: -65° to 200°C without voltage
derating
Dissipation Factor: 0.10% maximum
Temperature Coefficient: -90 $\pm$ 40 ppm/°C
Insulation Resistance: 1,000 M Ω - μ F at 200°C
Size, inches: 0.312 dia. x 0.938 length to 1.000 dia. x
1.938 length

*Teflon® is a registered trade name of E. I. Du Pont de Nemours and Co.

1.1.4 CAPACITORS, DISCRETE

TFBX Series, Film/Foil
Teflon®

Capacitance Range: 25 pF to 0.1 μ F
Voltage Rating: 50 and 100 VDC
Temperature Range: -55° to 200°C without voltage
derating (250°C with 50% voltage derating)
Dissipation Factor: 0.02% maximum
Temperature Coefficient: -5% maximum
Size, inches: 0.218 dia. x 0.688 length to 0.445 dia. x
1.312 length

TMBX Series,
Metallized Film
Teflon®

Capacitance Range: 0.05 to 2.5 μ F
Voltage Rating: 50 and 200 VDC
Temperature Range: -55° to 200°C without voltage
derating (250° with 50% voltage derating)
Dissipation Factor: 0.1% maximum
Temperature Coefficient: -5% maximum
Size, inches: 0.345 dia. x 0.688 length to 0.985 dia. x
1.812 length

Note: Custom Electronic, Inc., is now producing Teflon®
capacitors for use in well logging at 55° to 250°C.
These items are available in 25-VAC to 400-VAC and
50-VDC to 600-VDC ratings.

200ET Series, Epoxy
Encapsulated
Mica

Capacitance Range: 0.005 to 4 μ F
Voltage Rating: 400 to 15,000 VDC
Temperature Range: 0° to 200°C
Capacitance Change: +2% maximum at 200°C

1.1.4 CAPACITORS, DISCRETE

Dissipation Factor: 1% maximum at 200°C

Insulation Resistance: 30 MΩ-μF at 200°C

Size, inches: 0.547 dia. x 1.5 length to 1.750 dia. x
6.000 length

Note: See electrical characteristics curves following
description of 200ST Series.

200ST Series

Mica

Capacitance Range: 0.001 to 7.5 μF

Voltage Rating: 400 to 5,000 VDC

Temperature Range: -55° to 200°C

Capacitance Change: +2% at 200°C

Dissipation Factor: 1% maximum at 200°C

Insulation Resistance: 30 MΩ-μF at 200°C

Size, inches: Tubular, 0.341 dia. x 0.780 length to
1.000 dia. x 19.875 length; rectangular, 1.562 x 1.562
x 1.562 to 8.810 x 1.938 x 1.438

1.1.4 CAPACITORS, DISCRETE

200MT Series
Mica

Capacitance Range: 0.05 to 8 μ F
Voltage Rating: 220 VAC, 2,000 VDC, 4,500 VDC
Temperature Range: -55° to 200°C
Capacitance Change: +2% maximum at 200°C
Dissipation Factor: 1% at 200°C
Size, inches: 1.010 dia. x 1.500 length to 1.031 dia. x 19.875 length

260MT
Mica

Capacitance Range: 0.25 to 10 μ F
Voltage Rating: 220 VAC, 1,000 to 4,500 VDC
Temperature Range: -55° to 260°C
Capacitance Change: -3% at 200°C
Dissipation Factor: 1% at 200°C
Temperature Coefficient: 3% at 200°C
Insulation Resistance: 50 MΩ- μ F at 200°C
Size, inches: Tubular, 2.530 dia. x 5.000 length to 1.930 dia. x 15.812 length; Rectangular, 2.5 x 2.0 x 0.5 to 2.695 x 2.040 x 0.540
Note: See electrical characteristics curves following description of 300MT.

300MT
Mica

Capacitance Range: 1.0 μ F
Voltage Rating: 3,000 VDC
Temperature Range: -55° to 300°C
Capacitance Change: -3% at 200°C
Dissipation Factor: 1.75% at 300°C

1.1.4 CAPACITORS, DISCRETE

Temperature Coefficient: -12% at 300°C

Insulation Resistance: 2 MΩ-μF at 300°C

Size, inches: 1.940 dia. x 8.770 length

Note: Custom Electronic, Inc., is now producing

Reconstituted Mica capacitors for use in well logging
at -55° to 300°C. These items are available in 220-VAC
to 400-VAC and 600-VAC to 40,000-VAC ratings.

1.1.4 CAPACITORS, DISCRETE

The following capacitors were tested by System Development Corp. (formerly Mechanics Research, Inc.,) to 500°C.²³

Manufacturer

El Menco

(Address and telephone number not available.)

Mica/Silver

Capacitance: 50 pF

Capacitance Change over 25° to 500°C: < 10% for first
9 days; rapid change thereafter

Dissipation Factor over 25° to 500°C: 9.5% over first 9
days

Size, inches: 0.125 x 0.5 x 0.19

Manufacturer

Simmonds Precision

150 White Plains Road

Tarrytown, NY 10591

(914) 631-7500

Mica/Aluminum

Capacitance: 0.03 μ F

Capacitance Change over 25° to 500°C: 28% to 51% in 15
days

Dissipation Factor: 16% to 28%

Size, inches: 0.5 dia. x 2.75 length

1.2 RESISTORS

1.2.1 SYNOPSIS

Many resistors of both the discrete and the microcircuit types have been tested and found to operate up to 300°C. A few resistors also are available that operate satisfactorily at 500°C. For high-temperature operation, the following properties are desirable: no more than a 5% change in resistance over the temperature range, at least a 1,000-hour lifetime at maximum temperature, and a small physical size.

It appears that a satisfactory number of resistor systems and components are commercially available for microcircuit applications. For example, thin- and thick-film resistor chips and printed thick-film resistors satisfy the requirements for high-temperature use to 300°C. In addition, thick-film inks have been developed at Cermalloy that operate at 500°C. Finally, deposited thin-film tungsten-silicon resistors have been developed at the University of Arizona for use at 300°C. The characteristics of the resistors listed in this sourcebook represent either manufacturers' performance claims or the results of the laboratory testing of a few typical commercial resistors.

Table 3 describes discrete and chip resistors that are ready to use as individual components in circuit fabrication. Table 4 refers to various thick-film resistor inks with which resistors may be manufactured as part of the hybrid microcircuit process. For related information, see Section 3.2 Hybrid Microcircuits and Section 3.3 Microcircuits, Components.

References 2, 22 through 24, and 30 through 35, which are listed in the reference section of this sourcebook, contain information relevant to resistors.

Table 3

Discrete and Chip Resistors

<u>Manufacturer</u>	<u>Type of Construction</u>	<u>Resistance Range</u>	<u>Wattage, W</u>	<u>Size, inches</u>	<u>Maximum Temperature, °C</u>	<u>Page Listing</u>
Caddock Electronics	Discrete-film resistors	30 Ω to 2,000 M Ω	0.12 to 30	0.065 dia. x 0.160 length to 0.35 dia. x 6.0 length	275	1-34, 1-40
Corning	Metal film	--	--	--	250	1-45
Dale Electronics	Discrete, wirewound	0.1 Ω to 273 k Ω	0.5 to 5	0.31 dia. x 1.0 length to 0.38 dia. x 2 length	500	1-44
Omnitronics	Wirewound, coated	10 k Ω	5	0.13 dia. x 0.38 length	500	1-45
Semifilms	Thin-film chip	--	--	< 50 mils x 50 mils	300	1-39
Vishay	Precision metal foil	1 Ω to 100 k Ω	--	--	250	1-43

1.2.1 SYNOPSIS

Table 4

Thick-Film Resistor Inks

<u>Manufacturer</u>	<u>Resistivity</u>	<u>Maximum Temperature, °C</u>	<u>Page Listing</u>
Cermalloy	100 Ω to 100 k Ω /sq	300, 500	1-35
Du Pont	1 Ω to 10 M Ω /sq	300	1-35
ESL	1 Ω to 10 M Ω /sq	300	1-36
TFS	100 Ω /sq	300	1-37

Note: Du Pont = E. I. Du Pont de Nemours and Co.
ESL = Electro-Scientific Laboratories, Inc.
TFS = Thick Film Systems

1.2.2 RESISTOR, CHIP

The following resistor type was tested by Sandia.

Manufacturer

Caddock Electronics Incorporated
3127 Chicago Avenue
Riverside, CA 92597
(714) 683-5361

Cermet

Resistance Change: < 0.1% for 100 hours at 300°C for the
average resistor

1.2.3 RESISTORS, THICK FILM

The following characteristics are taken from Sandia's test results.

Manufacturer

Cermalloy
Bala Electronics Corp.
Union Hill Industrial Park
West Conshohocken, PA 19428
(215) 825-6850

500HT Series

Sheet Resistance: 100 Ω to 100 k Ω /sq
Resistance Change: < 0.5% at 300°C

900HT Series

Sheet Resistance: 100 Ω to 100 k Ω /sq
Resistance Change: < 10% at 500°C

Manufacturer

E. I. Du Pont de Nemours and Co.
Electro Chemicals Department
1007 Market Street
Wilmington, DE 19898
(302) 774-1000

1200 and 1500 Birox Series

Resistance Change: 5% at 300°C for 1200
Resistance Change: < 1% at 300°C for 1500

1.2.3 RESISTORS, THICK FILM

Manufacturer

Dale Electronics
1356 28th Avenue
Columbus, NE 68601
(402) 564-3131

RC550-21

Resistance Change: 0.8%; 3% drift during 400 hours at 300°C

Manufacturer

Electro-Science Laboratories, Inc.
2211 Sherman Avenue
Pennsauken, NJ 08110
(609) 663-7777

3800 Series

Resistance Change: < 4% from 25° to 300°C

1.2.3 RESISTORS, THICK FILM

Manufacturer

Thick Film Systems
324 Palm Avenue
Santa Barbara, CA 93101
(805) 963-7757

800 Series

Material Tested: 850
Sheet Resistance: 100 M Ω /sq
Resistance Change: $\approx$ 2% at 300°C

1.2.4 RESISTORS, THIN FILM

The following resistor type was tested by the University of Arizona under a contract from Sandia.

R&D Contractor

University of Arizona
Department of Electrical Engineering
Tucson, AZ 85721
(602) 626-2434

Tungsten-Silicon
(Experimental)

Resistivity: $2.5 \times 10^{-3} \Omega\text{-cm}$
Sheet Resistance: Typically 500 to 1,000 Ω/sq
Temperature Range: 25° to 500°C
Temperature Coefficient: $< \pm 100 \text{ ppm}/^\circ\text{C}$

The following characteristics are taken from Sandia's test results.

R&D Organization

Sandia National Laboratories
Albuquerque, NM 87185
(505) 844-2132
Attn: Bruce Draper

1.2.4 RESISTORS, THIN FILM

Tantalum Nitride
(Experimental)

No. of Samples Tested: 1

Sheet Resistance: 100 Ω /sq

Test Temperature Range: 25° to 300°C

Note: Aging tests have shown significant degradation for periods above 100 hours. Further testing may show merit in the use of a passivation layer on resistor films.

Manufacturer

Semi-Films

Route 28 N, Box 188

West Hurly, NY 12491

(914) 338-7714

SFM 10R 1001

SFR 10R 100

Resistance Change: 0.4% from 25° to 300°C

Note: Aging tests show a 5% resistance change after 50 hours at 300°C.

1.2.5 RESISTORS, DISCRETE

The following characteristics are taken from manufacturers' specifications. No tests were performed on these components by Sandia because of program limitations.

Manufacturer Caddock Electronics Incorporated
3127 Chicago Avenue
Riverside, California 92507
(714) 683-5361

Distributor Lenert Company
Box 2184, 1420 Hutchins
Houston, TX 77001
(713) 225-1465

Models MS126, MS151,
MS176
Power Film

Resistance: $30\ \Omega$ to $5\ \text{M}\Omega$, $\pm 1\%$
Wattage: 0.25, 0.5, 0.75 watts
Voltage Rating: 200, 300, 500 volts
Resistance Change: $< 0.5\%$ or $0.5\ \Omega$ for 1,000 hours at
rated power
Load Derating: $0.67\%/^{\circ}\text{C}$ from 125° to 275°C
Temperature Coefficient: $50\ \text{ppm}/^{\circ}\text{C}$
Size, inches: $0.070\ \text{dia.} \times 0.188\ \text{length}$ to $0.350\ \text{dia.} \times$
 $2.00\ \text{length}$

1.2.5 RESISTORS, DISCRETE

Models MS150, MS175;
Certain Models
between MS210 and
MS315

Resistance: 30 Ω to 50 M Ω , $\pm 1\%$

Wattage: 0.5 to 15 watts

Voltage Rating: 500 to 6,000 volts

Load Derating: 0.4%/°C from 25° to 275°C

Temperature Coefficient: 50 ppm/°C

Note: Tests performed by Sandia National Laboratories
show that the resistance change $< 4\%$ from 24° to 275°C.

Certain Models between
MG650 and MG815
High Voltage

Resistance: 200 Ω to 2000 M Ω , $\pm 1\%$

Wattage: 0.5 to 15 watts

Voltage Rating: 600 volts to 30 kV

Load Derating: 1%/°C from 125° to 225°C

Temperature Coefficient: 80 ppm/°C

Size, inches: 0.094 dia. x 0.313 length to 0.35 dia. x
6.00 length

Certain Models between
MH651 and MH713

Resistance: 200 Ω to 50 M Ω , $\pm 1\%$

Wattage: 0.5 to 1 watt

Voltage Rating: 600 to 4,000 volts

Resistance Change: $< 0.8\%$ for 1,000 hours at rated power

Load Derating: 1%/°C from 125° to 225°C

Temperature Coefficient: 80 ppm/°C

Size, inches: 0.095 dia. x 0.313 length to 0.114 dia. x
1.000 length

Certain Models between
MM112 and MM236

Resistance: 30 Ω to 15 M Ω , $\pm 1\%$

Wattage: 0.12 to 3 watts

Voltage Rating: 200 to 2,000 volts

Resistance Change: $< 0.5\%$ or 0.5 Ω for 1,000 hours at
rated power

1.2.5 RESISTORS, DISCRETE

Load Derating: 0.67/°C from 125° to 275°C

Temperature Coefficient: 50 ppm/°C

Size, inches: 0.065 dia. x 0.160 length to 0.330 dia. x 1.00 length

Certain Models between
ML104 and ML226

Resistance: 30 Ω to 100 M Ω , $\pm 1\%$

Wattage: 0.08 to 2 watts

Voltage Rating: 200 to 2,000 volts

Resistance Change: $\leq 0.5\%$ or 0.5 Ω for 1,000 hours at
rated power

Load Derating: 2%/°C from 125° to 175°C

Temperature Coefficient: 60 ppm/°C

Size, inches: 0.065 dia. x 0.160 length to 0.33 dia. x 1.00 length

Certain Models between
MP311 and MP330
Chassis Mounted
Power, Longlife

Resistance: 10 Ω to 200 k Ω $\pm 1\%$

Wattage: 15, 30 watts

Voltage Rating: 300, 450 volts

Resistance Change: $\leq 1\%$ or 0.2 Ω for 1,000 hours at
rated power

Load Derating: 0.4%/°C from 25° to 275°C

Temperature Coefficient: 50 ppm/°C

Size, inches: 0.188 dia. x 0.600 length to 0.250 dia. x 0.850 length

1.2.5 RESISTORS, DISCRETE

Certain Models between
MK120 and MK632
Precision

Resistance: 30 Ω to 100 M Ω , $\pm 1\%$
Wattage: 0.5, 0.75 watts
Voltage Rating: 200, 400 volts
Resistance Change: $< 0.5\%$ for 1,000 hours at rated power
Load Derating: 2%/°C from 125° to 175°C
Temperature Coefficient: 50 ppm/°C
Size, inches: 0.095 dia. x 0.245 length, 0.095 dia. x 0.290 length

Certain Models between
TK121 and TK639
Precision

Resistance: 1 k Ω to 10 M Ω , $\pm 1\%$
Wattage: 0.2, 0.3 watts
Voltage Rating: 200, 300 volts
Resistance Change: $< 0.2\%$ for 2,000 hours at 125°C and the rated load
Load Derating: 0.2%/°C from 125° to 175°C
Temperature Coefficient: 5, 10, 20 ppm/°C
Size, inches: 0.095 dia. x 0.245 length, 0.095 dia. x 0.290 length, 0.105 dia. x 0.305 length

Manufacturer

Vishay Intertechnology, Inc.
Vishay Resistive Systems Group
63 Lincoln Highway
Malvern, PA 19355
(215) 644-1300
Attn: Anthony Troianello, Director of Marketing

Models S102C and HS102C
Bulk Metal
Foil Precision

Resistance: 1 Ω to 100 k Ω
Stability: 0.05% for 2,000 hours at 175°C
For 30 3.3-k $\Omega \pm 0.01\%$ resistors tested by the manufacturer to 250°C for 24 hours,
Resistance Change: $\leq 0.05\%$
Temperature Coefficient: < 5 ppm/°C

1.2.5 RESISTORS, DISCRETE

The following resistors were tested by System Development Corp.²³ These tests demonstrate that the preliminary baking of resistors at high temperature results in a desirable decrease in resistance change during subsequent use.

Manufacturer

Dale Electronics
1356 28th Avenue
Columbus, NE 68601
(402) 564-3131

RS-5, High-Temperature
Coating
Wirewound Evanohm
Resistance: 0.1 Ω to 95 k Ω
Wattage: 5 watts
Resistance Change: 1.6% maximum from 25° to 500°C; drops
to 0.1% after 100 hours
Size, inches: 0.375 dia. x 1.0 length

RS-10, High-Temperature
Coating
Wirewound Evanohm
Resistance: 0.1 Ω to 273 k Ω
Wattage: 13 watts
Size, inches: 0.375 dia. x 1.875 length

RS-5, High-Temperature
Coating
Wirewound Cupron
No. of Samples Tested: 4
Resistance: 1 k Ω
Wattage: 0.5 watts
Test Temperature Range: 25° to 500°C
Resistance Change: 1.7% maximum; varies randomly at high
temperatures
Size, inches: 0.31 dia. x 1.0 length

HL25, Coated and
Uncoated
Wirewound Kauthal A-1
No. of Samples Tested: 3
Resistance: 7 k Ω
Wattage: 0.5 watts
Test Temperature Range: 25° to 500°C
Resistance Change: 1.7% maximum; decreases to 0.1% after
10 hours
Size, inches: 0.313 dia. x 2.0 length

1.2.5 RESISTORS, DISCRETE

Manufacturer

Omnitronics Research Corp.
267 South Main Street
Akron, OH 44308
(216) 762-2431

Wirewound, Coated

Resistance: 10 k Ω ,
Wattage: 0.5 watts
Test Temperature Range: 25° to 500°C
Resistance Change: 2.8% maximum
Size, inches: 0.125 dia. x 0.375 length

The following resistors were tested by Sandia.

Manufacturer

Corning Glass Works
Electronic Products Division
Houghton Park, AB2
Corning, NY 14830
(607) 974-9000

FP Series

Metal film, flameproof resistors; tested by Sandia for
250°C operation

TSR Series.

Temperature-sensitive resistors

1.3 MAGNETICS

1.3.1 SYNOPSIS

Desirable high-temperature magnetic materials should exhibit high permeability and low hysteresis and eddy current losses. These materials must also have a high magnetic saturation and a high Curie point. In this section, magnetic materials are reviewed that have capabilities above 250°C. Magnetically hard and soft materials are discussed in separate subsections (see Tables 5 and 6, respectively). Information is also given on the wire needed for transformer windings and on suppliers of magnetic products.

References 2, 22, 31, and 36 through 41, which are listed in the reference section of this sourcebook, contain information relevant to magnetics.

1.3.2 MAGNETICS, DEVICES

The following characteristics are taken from manufacturers' specifications. Because of program limitations, no tests were performed on these devices by Sandia.

Manufacturer

Ceramic Magnetics, Inc.
87 Fairfield Road
Fairfield, NJ 07006
(201) 227-4222

Type: Rotating transformer sets for power coupling applications in sizes from 1/2-in. to 10-in. o.d.

Temperature Data: Have been used at 275°C

Note: Ceramic Magnetics, Inc., also makes high-temperature ferrite materials such as nickel-zinc and magnesium-zinc; nickel-zinc sample C2050 was in-house tested to 325°C.

Manufacturer

General Magnetics, Inc.
211 Grove Street
Bloomfield, NJ 07003
(201) 743-2700

PT-750

Type: Isolation transformer, 1:30, 300 Vrms

Operational Range: 500 hours at 1000°F, 1,000 hours at 750°F

Features: Hermetically sealed package

Price: Approximately \$3,000 in 1979

PT-751

Type: Step-up transformer, 1:10, 3,000 volts

Temperature Data: Tested over the temperature range 25° to 500°C; recommended for temperatures up to 350°C

Output/Input: Voltage changed from 27 to 25 from 25° to 300°C and stabilized thereafter.

1.3.2 MAGNETICS, DEVICES

Features: Fabricated with fine-gauge ceramic-coated copper wire and 2V Permendure core

Size, cm: 2 x 2 x 15

Price: Approximately \$4,000 in 1979

PT-752

Type: Power transformer

Operational Range: 500 hours at 1000°F, 1,000 hours at 750°F

Input: 50 volts ptp, 400 hertz at 20 mA

Output: 700 volts ptp at ≥ 1 mA

Size, inches: 1 dia. x 6 length

Price: Approximately \$3,000 in 1979

Type: Magnetic multiplier

Output: Linear, only a few percent deviation over the 25° to 400°C temperature range

Aging Tests: No drift in characteristics at 400°C after 100 hours

Manufacturer

Houston Transformer Co.

5725 Braxton

Houston, TX 77036

(713) 977-6009

Attn: Paul E. Plumb

Type: High-temperature transformers

Temperature Data: For operation at 220°C

Manufacturer

The Arnold Engineering Co.

Marengo, IL 60152

(815) 568-2000

1.3.2 MAGNETICS, DEVICES

Distributor

Charles T. Fink and Associates

Box 434

Scottsdale, AZ 85252

(602) 992-9884

Product: Core materials for transformers and other
magnetic products

1.3.3 MAGNETICS, HARD MATERIALS

The following information was provided by Sandia.

Table 5

Hard Magnetic Materials

Magnet Material	Nominal Chemical Composition wt. %	Curie Point (T_c), °C	Residual Flux Density (B_r), gauss	Coercive Force (H_c) Oe	Maximum Energy Product [(BH) max.] ^a MG.Oe ^b	Maximum Operating Temperature (T_{op}), ^c °C
Alnico 5	8 Al, 14 Ni, 24 Co, 3 Cu, 51 Fe	860	12,800	640	5.5	~ 540
Alnico 8	7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti, 34 Fe	850	8,200	1,650	5.3	~ 540
Rare earth cobalt	Sm-Co	—	7,200	6,500/10,000	12.0	~ 220
Ceramic 5	Ba _{0.6} Fe ₂ O ₃	450	3,950	2,400	3.5	~ 280

^a(BH) max.: Maximum energy product; this parameter is used to compare materials on the basis of the amount of energy available to an external magnetic circuit.

^bMG.Oe: Unit of (BH) max.; it is megagauss oersted in cgs units.

^cMaximum operating temperature: That temperature below which the magnetization of a magnet is reversible.

1.3.4 MAGNETICS, SOFT MATERIALS

The following information was taken from Proceedings of 30th Electronic Components Conference, April 28-30, 1980, IEEE.⁷⁰

Table 6
Soft Magnetic Materials

Core Material	Curie Temp., °C	Advantages	Aging	Comments
Amorphous METGLAS 2605S ^a $\text{Fe}_{82}\text{B}_{12}\text{Si}_6$	330	Low loss	Large changes with aging, probably due to crystallization	Low Curie temperature
Deltamax ^b $\text{Fe}_{50}\text{Ni}_{50}$	480	Common core material	500°C aging occurs during first 400 hours	Unoriented
Supermendur ^b $\text{Fe}_{49}\text{Co}_{49}\text{V}_2$	940	High permeability	Degradation at 500°C; large change in saturation after 100 hours	Magnetically ordered
2V Permendur ^b $\text{Fe}_{49}\text{Co}_{49}\text{V}_2$	940	Excellent stability	Minimal aging after 1,000 hours	Unoriented
Silectron ^b $\text{Fe}_{97}\text{Si}_3$	730	Standard transformer material	Large change in permeability after 100 hours	Grain oriented
Mix 63 ferrite ^c	460	High frequency	Sensitive to oxygen at high temperatures	--

^aProvided by Allied Chemical

^bProvided by Arnold Engineering

^cProvided by Amidon Associates

1.3.4 MAGNETICS, SOFT MATERIALS

1.3.5 MAGNETICS, WINDINGS

Manufacturer

Hy-Temp Transducer
Box 11522
Philadelphia, PA 19116
(215) 947-1200

Product: Ceramic-coated copper wire for windings in
500°C applications; the company also provides wire with
polyimide coating.

Data Source: Sandia

Distributor

M.W.S. Precision Wire Industries
(formerly Magnet Wire Supply Company)
P.O. Box 826
Chatsworth, CA 91311
(213) 882-7620

Product: Polyimide-coated copper wire good to 220°C;
also anodized aluminum wire

Data Source: Sandia

Manufacturer

Permaluster, Inc.
1844 N. Keystone Street
Burbank, CA 91504
(213) 849-4543

Product: Anodized aluminum wire with aluminum oxide
thin-film insulation for 500°C applications; annealed
and unannealed

Wire Sizes: 10 to 46 AWG

Strip Sizes, inches: 0.0008 to 0.060 thick and to 8
inches on coils

1.3.5 MAGNETICS, WINDINGS

Insulation Resistance: 10^8 to 10^{12} Ω/cm

Melting Point: 3722°F

Voltage Breakdown: > 200 volts at 300°C

Data Source: Manufacturer's data

Manufacturer

Magnet Wire, Inc.

112-01 Northern Boulevard

Corona, NY 11368

(212) 651-0900

Product: Copper wire coated with heavy polyimide
lacquer; good to 220°C

Data Source: Sandia

1.4 THERMISTORS

1.4.1 SYNOPSIS

Thermistors can be used in high-temperature circuits as resistance compensation devices and sensors. A few thick-film thermistor inks and many discrete devices will function to 300°C. These thermistors are available with either a positive or a negative temperature coefficient of resistance (TCR). Negative temperature dependence characteristics are either linear or exponential; positive TCRs are typically linear.

References 30 and 31, which are listed in the reference section of this source-book, contain information relevant to thermistors.

1.4.2 THERMISTORS

The following thermistors were tested by Sandia.

Manufacturer

Electro Materials Corp. of America
2301 Coco Palm Drive
Tustin, CA 92680
(714) 731-4373
Attn: Larry Yglesia

Firon TM100
and TM500 Series

Type: Thermistor inks
TCR for TM100 Series: ± 100 to $10,000$ ppm/ $^{\circ}\text{C}$
Features for TM104: Tested for stability over the 25° to 300°C range; resistance change is $< 2\%$ due to aging

Manufacturer

Thick Film Systems
324 Palm Avenue
Santa Barbara, CA 93101
(805) 963-7757

1.4.2 THERMISTORS

850N and 850P Series

Type: Thermistor ink

Features: Linear or exponential over the 25° to 300°C range; stable with time

Manufacturer

Fenwal Electronics

63 Fountain Street

Framingham, MA 01701

(617) 872-8841

Type: Discrete thermistors

Features: Available in positive and negative TCR

1.4.2 THERMISTORS

No test data were available for the following thermistors.

Manufacturer

Midwest Components, Inc.
P.O. Box 787
1983 Port City Boulevard
Muskegon, MI 49443
(616) 777-2602

Type: Discrete thermistors

Manufacturer

Cal-R, Inc.
1601 Olympic Boulevard
Santa Monica, CA 90404
(213) 450-1761

Type: Chip and discrete thermistors

1.5 PASSIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

Draper, B. L. and Palmer, D. W. "Extension of High-Temperature Electronics," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-2, no 4, December 1979. See abstract in Section 2.4 Active Devices, Bibliography/Abstracts.

Pandey, R. K., Weichold, M. H., and Palmer, D. W. "Materials Characterization for High Temperature Transformers," IEEE Transactions on Magnetics, vol Mag-16, no 5, 1980. p 749.

_____ and Weichold, M. H. "Search for High Temperature Transformer Materials," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 133.

The worldwide scarcity of petroleum has warranted a vigorous search for other sources of energy. It is anticipated that, like nuclear and solar energies, geothermal energy will play a significant role in meeting the accelerating demands of energy. According to the U.S. Geological Survey, it is possible that by 1990 about 10 GW of electricity will be made available in the United States by geothermal sources. In order to achieve this goal, new technologies have to be developed which would reduce drilling costs and provide means to monitor the geothermal boreholes reliably. Since the temperature of a geothermal well varies significantly with its depth -- for example, it is about 300°C at 3 km and about 400°C at 4 km -- the logging instruments must have components which can operate reliably at elevated temperatures. Logging tools available currently are mostly those which are suitable for the oil and gas industry. They operate efficiently only up to 180°C; their reliability and life expectancy are reduced substantially above 180°C. Therefore, there is a need to develop electronic and magnetic components capable of operating between 200° to 400°C. Furthermore, the components must be able to withstand severe environmental conditions of a geothermal well.

_____, Van Hees, E., and Palmer, D. W. IEEE Intermag 1981 Digest, paper no 21-2, May 1981.

_____. "Effect of Temperature and Annealing on the Performance of Permanent Magnets," IEEE Transactions on Magnetics, November 1981 (to be published).

Raymond, L. S. et al. "Compatible Thin-Film Components for High-Temperature Electronics," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 125.

1.5 PASSIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

This paper describes the fabrication of thin-film resistors which can operate at 500°C and capacitors which can operate at 350°C. These components are deposited by Low Pressure Chemical Vapor Deposition (LPCVD) and are compatible with each other as well as with MOS devices. Fabrication and modeling of metal-gate NMOS devices which operate at 300°C is also discussed.

Veneruso, A. F., Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

This report presents the results of a 2-day seminar that reviewed the state of the art and the recent substantial progress in High Temperature Electronics and Instrumentation. Over 350 people participated in this meeting, which was held in Houston, Texas. This seminar was tailored to address the needs of the borehole logging industry and to stimulate the development and application of this technology for logging geothermal, hot oil and gas, and steam injection wells. The technical sessions covered the following topics: hybrid circuits, electronic devices, transducers, cables and connectors, materials, mechanical tools, and thermal protection. The frontiers of this technology were shown to be rapidly moving beyond the 125°C Mil-Spec boundary. Special "hostile environment" instruments routinely operate up to 180°C, a few prototype systems have been field tested to 275°C, and new development is under way for 300°C hybrid and integrated circuits. Sandia National Laboratories organized and conducted this seminar with funding provided by the U.S. Department of Energy's Division of Geothermal Energy and Division of Fossil Fuel Extraction.

Vest, R. W. "High Temperature Thick Film Research," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 57.

Hybrid microelectronics appears to be the most promising approach for the downhole electronics required for geothermal well logging, and thick film is the logical technology for the passive components of the hybrids. Since thick film circuits are typically processed at temperatures of 800°C and above, it might be expected that they would perform satisfactorily and remain stable at temperatures well above 300°C. However, this is not the case because thick film resistors and capacitors are non-equilibrium systems which are optimized for use in a lower temperature range, typically -55° to 125°C. Commercially available materials have much larger temperature coefficients at higher temperatures than in their optimum range, and exhibit an irreversible drift of their properties at temperatures much above 300°C. The research at Purdue was undertaken to better understand the phenomena which occur in thick film resistors and capacitors in the

1.5 PASSIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

temperature range 350° to 500°C, and to apply the knowledge gained to the development of resistors and capacitors which have acceptable temperature coefficients and which exhibit minimal drift after extended periods at high temperatures. The basic approach has been to select systems which perform well at normal use temperatures, and to make small changes in the materials which our models predict are limiting the performance at elevated temperatures.

2.0 ACTIVE DEVICES

2.1 DIODES

2.1.1 SYNOPSIS

The lack of high-performance diodes is often the weak link in circuit designs above 250°C. Silicon diodes, the only readily available commercial devices, become extremely leaky at these temperatures. Compound semiconductor diodes, such as GaP, $\text{Ga}_x\text{Al}_{1-x}\text{As}$, and $\text{GaAs}_x\text{P}_{1-x}$, seem to be the obvious choices for high-temperature diodes, but commercial sources are either scarce or nonexistent. Listed below are the characteristics of some diodes tested at high temperatures.

Table 7 lists the manufacturers of the diodes that were tested and are described in Section 2.1.2 Diodes.

References 22, 36, 42, 43, and 44 through 46, which are listed in the reference section of this sourcebook, contain information relevant to diodes.

2.1.1 SYNOPSIS

Table 7^a

Manufacturers of Diodes Tested

<u>Name</u>	<u>Address</u>	<u>Telephone No.</u>
Dionics	65 Rushmore St. Westbury, NY 11590	(516) 997-7474
General Instruments, Discrete Semiconductor Div.	602 West John St. Hicksville, NY 11802	(516) 733-3333
McDonnell Douglas Electronics Co.	2600 North Third St. St. Charles, MO 63301	(314) 925-4000
Sandia National Laboratories ^b	Albuquerque, NM 87185	(505) 844-2132 (Bruce Draper)
Semtech Corp.	652 Mitchell Rd. Newbury Park, CA 91320	(213) 628-5392
Western Electric Co.	222 Broadway New York, NY 10038	(212) 571-2345

^aInformation supplied by Sandia.

^bExperimental, not for sale.

2.1.2 DIODES

Manufacturer Semtech

Types 3L03, F1, and M2

2.1.2 DIODES

Manufacturer Semtech
Type 1N4954 Zener Diode

2.1.2 DIODES

Manufacturer Semtech
Type 16-V Zener Diode

2.1.2 DIODES

Manufacturer Dionics
Type 1N914

Manufacturer McDonnell Douglas
Type GaAs

Manufacturer Western Electric
Type GaP

Manufacturer Sandia Nat'l. Labs.
Type Silicon FLOP Cell

2.1.2 DIODES

Manufacturer General Instruments

Type MMH32V

GaAs_{0.6}P_{0.4}

Manufacturer Siliconix

2.2 FIELD EFFECT TRANSISTORS

2.2.1 SYNOPSIS

At temperatures up to about 200°C, a wide selection of commercial silicon transistors can be used successfully with only minor degradation occurring in circuit performance as temperatures increase. However, as the ambient temperature approaches the 250° to 300°C range, the selection greatly narrows. Only a very limited number of devices, almost all of which are JFETs, have been found to be suitable for general purpose use at 275°C. MOSFETs tend to have large leakage currents, and many exhibit instabilities at high temperatures. Bipolar devices also leak heavily but are often useful in amplifier configurations. As can be seen from the characteristics presented in this section, many JFETs have a 25° to 275°C "zero temperature coefficient" (ZTC) region in their transfer characteristics; if biased in this area, the transistor will have drain-source current relatively independent of temperature. Critical circuits, such as current sources for voltage references, can be implemented in this fashion. Also, because of the physical details of JFET construction, the collection volume for leakage current is severely limited. For this reason, JFET leakages are very low when compared to other device types with similar gain.

References 22 through 24, 36, 42, 43, and 47 through 52, which are listed in the reference section of this sourcebook, contain information relevant to field effect transistors.

2.2.2 TRANSISTORS, JFET

2.2.2 TRANSISTORS, JFET

2.2.2 TRANSISTORS, JFET

2.2.3 TRANSISTORS, JFET SWITCHES

Manufacturer: Texas Instruments

Testing Organization: Sandia National Laboratories

TYPE: 2N4882
TEST TEMPERATURE: 275 °C

TYPE: 2N4883
TEST TEMPERATURE: 228 °C

TYPE: 2N4884
TEST TEMPERATURE: 276 °C

TYPE: 2N4885
TEST TEMPERATURE: 276 °C

2.2.3 TRANSISTORS, JFET SWITCHES

TYPE: 2N4886
TEST TEMPERATURE: 283°C

TYPE: 2N5278
TEST TEMPERATURE: 281°C

TYPE: 2N6450
TEST TEMPERATURE: 274°C

2.2.4 TRANSISTORS, MOSFET

2.2.5 TRANSISTORS, VMOS

2.3.1 SYNOPSIS

The high-temperature capability of vacuum tubes has been recognized for many years. However, because the tubes are relatively large, require high plate voltage and filament power, and are expensive, little R&D effort has been directed toward expanding the high-temperature capability of these tubes. These devices functioned as 500°C having tests conducted by the System Development Corporation. Nevertheless, the tubes are used only at lower temperatures because of the lack of compact circuit components such as high-voltage electrolytic capacitors, that can operate at higher temperatures.

References 1, 2, 3, and 4, which are listed in the reference section of this document, contain information relevant to vacuum tubes.

2.3 CERAMIC VACUUM TUBES

2.3.1 SYNOPSIS

The high-temperature capability of vacuum tubes has been recognized for many years. However, because the tubes are relatively large, require high plate voltage and filament power, and are expensive, little R&D effort has been directed toward exploiting the high-temperature capability of these tubes. These devices functioned to 500°C during tests conducted by the System Development Corporation. Nevertheless, the tubes are used only at lower temperatures because of the lack of compatible circuit components, such as high-voltage, high-value capacitors, that can operate at higher temperatures.

References 2, 23, and 42, which are listed in the reference section of this sourcebook, contain information relevant to ceramic vacuum tubes.

2.3.2 CERAMIC VACUUM TUBES

The following ceramic vacuum tubes were tested by System Development Corp., which does not recommend these tubes for use above 250°C for periods greater than 1,000 hours.

Manufacturer

General Electric
Tube Products Department
916 East 9th Street
Owensboro, KY 42301
(502) 685-6200

7462

Triode

Use: In low-noise VHF amplifiers
Heater Voltage: 4.3 volts
Amplification Factor: 94 normally; -2% change at 500°C
($E_b = 100$ volts)
Transconductance: 10,500 MU normally; +77% maximum
change at 500°C ($E_b = 200$ volts)
Plate Current: 7.2 mA normally; +47% maximum change at
500°C ($E_b = 100$ volts)
Size, inches: 0.33 dia. x 0.5 length
Note: Reasonable cost, small size

7625

Triode

Use: In low-level audio amplifiers
Heater Voltage: 5.3 volts
Amplification Factor: 80 normally; -28% maximum change
at 500°C ($E_b = 100$ volts)
Transconductance: 1,400 MU normally; -18% maximum change
at 500°C ($E_b = 200$ volts)
Plate Current: 0.95 mA normally; +52% maximum change at
500°C ($E_b = 100$ volts)
Note: High cost

7296

Triode

Use: In VHF oscillators and amplifiers
Heater Voltage: 5.3 volts

2.3.2 CERAMIC VACUUM TUBES

Amplification Factor: 90 normally; +7% change at 500°C

($E_b = 100$ volts)

Transconductance: 16,500 μU normally; +6% change at 500°C ($E_b = 200$ volts)

Plate Current: 17 mA normally; -16% change at 500°C

($E_b = 100$ volts)

7588

Use: In VHF amplifiers

Triode

Heater Voltage: 5.3 volts

Amplification Factor: 174 normally; -33% maximum change at 500°C ($E_b = 100$ volts)

Transconductance: 45,000 μU normally; -35% maximum change at 500°C ($E_b = 200$ volts)

Plate Current: 24 mA normally; +24% maximum change at 500°C ($E_b = 200$ volts)

The following characteristics are taken from J. Byron McCormick and Dale Wilde, Los Alamos National Laboratory.²

R&D Organization

Los Alamos National Laboratory

Los Alamos, NM 87545

(505) 667-5061

Integrated Thermionic Operating Temperature: Successfully operated to 550°C

Circuits (ITC) Voltage Amplification Factors: 10 to over 100

Planar Vacuum Transconductances: $> 1,000 \mu\text{U}$ for a 0.25 cm by 0.25 cm

Triodes device

Operating Lifetime Test: In an active load circuit, device survived 500°C for 1,176 hours; gain = 10.

2.3.2 CERAMIC VACUUM TUBES

Chaffin, R. J. Progress Report on GAF, Grown Junction, High Temperature Diodes. SAND80-1063. Albuquerque: Sandia National Laboratories, August 1980.

This report discusses current results of an effort to develop GAF (Gallium phosphide) diodes for high-temperature, > 275°C, applications. It discusses the theory, fabrication and testing of devices made at Sandia National Laboratories.

Cooper, J. A., Palmer, D. W., Finkbeiner, R. W., and Hovener, W. B. "GaAs Omicron Contacts for High Temperature Devices." Proceedings of the IEEE Electronics Components Conference, April 29-30, 1980, pp. 108-111.

Instrumentation requirements for geothermal wells, jet engines, and nuclear reactors have prompted the high-temperature capability of silicon semiconductor devices. As one program to develop high-temperature GaAs semiconductor devices, a basic omicron contact system for n-type GaAs have been evaluated for contact resistance and function of temperature (25° to 350°C) and time (at 300°C): $g/Al/AlSi$ and $g/Al/AlSi$; $Al/AlSi$ and $Al/AlSi$; and $Al/AlSi$ and $Al/AlSi$. The function of processing parameters produced viable high-temperature contacts with all but the $Al/AlSi$ systems. Aging at 300°C changed the contact resistance in only the $Al/AlSi$ contacts. Film adhesion was excellent for the $Al/AlSi$, $Al/AlSi$, and $Al/AlSi$ systems as measured with ultrasonic aluminum wire bond pull strength. Lower adhesion was noticed with $Al/AlSi$ systems measured with gold wire bond pull strength.

THIN METAL FILM

INSULATING SUBSTRATE HEATED TO ~600°C
PHOTOLITHOGRAPHICALLY DELINEATED CATHODE
BASIC GAN DEVICE FOR ITC

Semiconductors for High Temperature Applications. SAND80-0379. Albuquerque: Sandia National Laboratories, February 28, 1980. In Proceedings of Electronic Components Conference, May 13-15, 1980.

This paper reviews developments during the past 3 years in the area of high-temperature active semiconductor devices for use in instrumentation needed to characterize geothermal resources. Surveys of silicon bipolar, MOS, and JFET devices operated at high temperatures and development work on high-temperature silicon CMOS, bipolar, and Bi analog circuits are reviewed. The initial results of developmental work on GaAs and GAF diodes are discussed. These efforts have identified several promising devices for high-temperature applications; however, further development is required to resolve such problems as excessive leakage currents, metalization degradation, device stability, and long-term aging.

AMPLIFICATION FACTOR, μ

GRID-TO-CATHODE SPACING
EQUALS CATHODE WIDTH
EQUALS GRID WIDTH

INTEGRATED THERMIONIC CIRCUIT

0.673

CATHODE-TO-ANODE SPACING TO GRID SPACING, d/a

Prager, S. L. "Behavior of Silicon Devices at High Temperatures." High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds. A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p. 111.

2.4 ACTIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

Chaffin, R. J. Progress Report on GaP, Grown Junction, High Temperature Diodes. SAND80-1763. Albuquerque: Sandia National Laboratories, August 1980.

This report discusses current results of an effort to develop GaP (gallium phosphide) diodes for high-temperature, $> 275^{\circ}\text{C}$, applications. It discusses the theory, fabrication, and testing of devices made at Sandia National Laboratories.

Coquat, J. A., Palmer, D. W., Eknayan, O., and Van der Hoeven, W. B. "GaAs Ohmic Contacts for High Temperature Devices," Proceedings of the IEEE Electronics Components Conference, April 28, 1980.

Instrumentation requirements for geothermal wells, jet engines, and nuclear reactors have exceeded the high-temperature capability of silicon devices. As one part of a program to develop high-temperature compound semiconductor devices, four basic ohmic contact systems for n-type GaAs have been evaluated for contact resistance as a function of temperature (24° to 350°C) and time (at 300°C): Ni/AuGe; Ag/Si and Ag/Ni/Si; Al/Ge and Al/AlGe; and Au/Nb/Si and Pt/Nb/Si. Optimization of processing parameters produced viable high-temperature contacts with all but the Al/Ge systems. Aging at 300°C changed the contact resistivity in only the Ag/Ni/Si contacts. Film adhesion was excellent for the Al/Ge, Ni/AuGe, and Ag/Si systems as measured with ultrasonic aluminum wire bond pull strengths. Lower adhesion was noticed with Nb/Si systems measured with gold wire bond pull strengths.

. Semiconductors for High Temperature Active Devices -- Silicon, GaAs, and GaP. SAND80-0379. Albuquerque: Sandia National Laboratories, February 28, 1980. In Proceedings of Electro/80 Professional Program, May 13-15, 1980.

This paper reviews developments during the past 3 years in the area of high-temperature active semiconductor devices for use at 275°C in instrumentation needed to characterize geothermal resources. Surveys of silicon bipolar, MOS, and JFET devices operated at high temperature and developmental work on high-temperature silicon CMOS logic and DI analog circuits are reviewed. The initial results of developmental work on GaAs and GaP diodes are discussed. These efforts have identified several promising devices for high-temperature applications; however, further development is required to resolve such problems as excessive leakage currents, metallization degradation, device stability, and long-term aging.

Draper, B. L. "Behavior of Silicon Devices at High Temperatures," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 111.

2.4 ACTIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

In the early stages of the high-temperature electronics program at Sandia Laboratories, the selection of active devices received much attention. The use of bipolar transistors was largely avoided because it was felt that the collector-base leakage currents were excessive. MOS devices were shunned because of large drain-substrate leakage currents and large, uncontrolled flat-band voltage shifts created by mobile charge in the gate oxide. In fact, JFETs seemed to be the only acceptable active devices for long-term (> 1,000 hours) high-temperature use. In general, they displayed a well-defined zero-temperature-coefficient (ZTC) region and suffered from no inherent instability mechanisms. For these reasons, down-hole instrumentation designed at Sandia uses discrete JFETs exclusively. However, computer modeling, device redesign, and better fabrication techniques have now shown that silicon MOSFETs may be used at temperatures well in excess of 300°C. Likewise, Harris Semiconductor is also now developing a 300°C op-amp using a dielectrically isolated bipolar technology. Hence, it is becoming apparent that almost any silicon device type, if properly designed, can be used at temperatures near 300°C.

and Palmer, D. W. "Extension of High-Temperature Electronics," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-2, no 4, December 1979.

Commercial and Sandia-fabricated silicon MOSFETs, thick-film resistors and capacitors, and magnetic components were investigated in an effort to increase the versatility of micro-electronics used at 300°C and to form a foundation for a higher temperature technology. Commercial MOSFETs were found susceptible to parameter drifts and have unacceptable electrical characteristics when tested at 300°C, whereas redesigned low-alkali-impurity devices were able to maintain stable operation at 300°C for 1,000 hours with improved characteristics. Thus, although MOSFETs are prone to aging, it is possible to use fabrication procedures which allow MOSFET use at high temperature. A specially developed ceramic-filled, high-silica frit dielectric thick-film material exhibited a sufficiently high resistivity to permit development of 300°C, 1.0 μ F capacitors. Procedures were developed to make this material compatible with the multilayer brick capacitor format which is necessary for miniaturization. Both this dielectric and a ruthenium-based resistor material were shown useful to 500°C. In addition, a spectrum of magnetic components was qualified for use at 500°C.

Eknoyan, O. "Compound Semiconductor for High Temperature Active Devices," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 129.

High-temperature semiconductor devices are desirable in a number of specialized systems. Among these are instrumentation packages used in deep

2.4 ACTIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

well logging, aircraft engine control, and nuclear reactor power generators. The range of application clearly depends on the availability, reliability, and cost of these devices. To date, no commercial active devices have been found useful for operation above 300°C, where the need in geothermal logging lies. This limitation arises from the chosen semiconductor material and/or processing techniques utilized in the realization of final devices. The criterion for choosing an appropriate starting semiconductor material for high-temperature operation is the use of wide energy bandgap semiconductor materials. On the other hand, the design of such devices requires special attention in processing techniques that are not normally considered. This is especially true with respect to dopant species (for junction formation), contact metallization, and passivation (for surface protection).

et al., Laser-Annealed GaP Ohmic Contacts for High-Temperature Devices. SAND80-2679. Albuquerque: Sandia National Laboratories, November 17, 1980.

The results of successful Nd:YAG laser-annealed ohmic contacts on n-type GaP are reported. Comparisons on identical laser and thermally annealed contacts on the same substrates are performed. In addition, aging investigations are also studied. The results indicate that laser-annealed contacts have far superior electrical characteristics, much better surface morphology, and are substantially more stable with aging than the same but thermally alloyed ones.

McBrayer, J. D., Palmer, D. W., and Hickam, C. R. Semiconductors and 300°C Hybrid Microcircuits. SAND77-0392. Albuquerque: Sandia Laboratories (date not available). In Proceedings of ISHM77 International Society of Hybrid Microcircuits Meeting, October 24-26, 1977.

As part of a program to develop hybrid microcircuits capable of operation from 25° to 300°C in a geothermal well, it was necessary to investigate semiconductor devices. Three studies are described which allowed routine use of devices at high temperatures: (1) Si and GaAs devices were characterized from 25° to 300°C and for 1,000 hours at 300°C; (2) the degradation rates of aluminum wire bonds to thick films and to special buffer pads were measured, and (3) methods of prescreening active devices at high temperatures before committing them to a hybrid were developed. These studies revealed that among commercial devices tested only discrete silicon JFETs and MOSFETs were acceptable for high-temperature circuits. In contrast, silicon bipolar, silicon integrated circuits, and GaAs FETs were not suitable. Hybrids functioning at 300°C for 500 hours were fabricated as a result of this work.

Palmer, D. W., et al. Active Devices for High Temperature Microcircuitry. SAND77-11145. Albuquerque: Sandia Laboratories, February 1978.

As part of a program to develop high-temperature electronics for geo-thermal well instrumentation, a number of solid state diode and transistor types have been characterized from room temperature to 300°C. The temperature dependence and aging stability of transport and leakage properties were measured. Included in the study were silicon diodes, bipolar transistors, JFETs, MOSFETs, and GaAs MESFETs and JFETs. In summary, the results are as follows: diodes and bipolar transistors became extremely leaky at high temperature and are therefore of limited use; silicon MOSFETs and GaAs devices showed unacceptable aging instabilities at high temperatures; silicon JFETs from certain manufacturers were sufficiently stable and had suitable temperature-dependent characteristics so that operational circuits could be made. Comparisons were made of experimental device characteristics and those predicted by theory. The theoretical calculations were done using standard equations revised to include appropriate temperature-dependent parameters. Close agreement between theory and experiment was found, indicating that unexpected high-temperature effects were insignificant. In order to facilitate the use of devices in high-temperature hybrids, it was necessary to develop bonding and pre-screening techniques. A large variance of JFET 300°C operating parameters was found even within a single production lot. Consequently, high-temperature prescreening allowed each circuit to be specifically "pre-tuned." Standard solder, epoxy, and chip and wire attachment technologies were not functional at 300°C. Gold-germanium solder, aluminum wire to Du Pont 9910 gold film, and diffusion barrier pads were developed to allow high-temperature attachment.

Veneruso, A. F., Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

Wiley, J. D., Perepezko, J. H., and Nordman, J. E. High Temperature Metallization System for Solar Cells and Geothermal Probes. SAND80-7167. Albuquerque: Sandia National Laboratories, December 1980.

Amorphous films of the alloys Ni-Nb, Ni-Mo, W-Si, and Mo-Si were deposited on semiconducting substrates by RF sputtering from composite cathodes. The films adhere extremely well to silicon, GaAs, and GaP during and after thermal cycling from -200°C to at least 500°C. All films investigated to date have remained amorphous during 1 hour anneals at 500°C, and some alloy compositions have been found which remain amorphous after annealing at > 575°C. Rutherford backscatter analysis has been used to study the diffusion of gold in amorphous Ni-Nb. We find $D < 10^{-18} \text{ cm}^2$ at 450°C.

2.4 ACTIVE DEVICES, BIBLIOGRAPHY/ABSTRACTS

Additional diffusion studies have been performed using Auger profiling. Initial results show that amorphous Ni-Nb and W-Si may be excellent diffusion barriers against copper and gold, respectively, at temperatures $< 500^{\circ}\text{C}$.

3.0 MICROCIRCUITS

3.1 INTEGRATED CIRCUITS

3.1.1 SYNOPSIS

It is impractical to give a thorough treatment of integrated circuits (ICs) in the context of this sourcebook. However, some general remarks and references are offered to help guide the circuit designer in the parts selection process.

Digital ICs

For digital ICs, CMOS seems to be the best choice in high-temperature work. Unlike the situation that exists in bipolar logic, such as TTL, CMOS noise margins remain high, $1/3$ to $1/2 V_{DD}$, over a wide range of temperatures. Simple CMOS gates such as NANDs and NORs are often functional at temperatures over 300°C . As chip complexity increases, however, other problems tend to limit high-temperature capability. High isolation-junction leakage currents may by themselves render a device useless, cause thermal runaway, or lead to p-n-p-n latchup. In addition to these problems, at extremely high temperatures, the input leakage current contributed by the electrostatic discharge protection networks may be excessive, causing shifts in the apparent logic-switching threshold or reducing fan-out capability.

Despite the problems, commercial CMOS chips as complex as 4-bit binary counters, such as 74C93, can be used at 250°C . Even 16-channel multiplexers, such as RCA 4067, may be used in many circuit applications up to 225°C ; the RCA 4067 has a 1- to 2- μA switch leakage at 200°C . Reliable memories still have not been found for use at or above 250°C . Above 225°C , only the Harris 3226 silicon-gate CMOS is reliably functional. The only microprocessor found to be reliably functional up to 230°C is the SPB9900 manufactured by Texas Instruments.

Harris Semiconductor currently is developing a line of 300°C CMOS circuits that employ transistors designed for use in the 0° to 300°C environment. Through the use

3.1.1 SYNOPSIS

of SiO_2 , Harris is also substituting dielectric isolation for the leaky junction isolation used in most other commercial ICs. It appears that through this process a very versatile line of 300°C logic will be made available.

By way of example, the high-temperature specifications of some digital ICs are given in this section. High-temperature characteristics may change from lot to lot for any one manufacturer, and these characteristics vary widely among suppliers.

Analog ICs

As in digital ICs, leakage currents are a major factor in the degradation of analog IC characteristics with increasing temperature. In addition to causing drastic increases in input bias and offset currents in op-amps and comparators, the leakage currents can upset internal bias levels, creating poorly functioning circuit stages. The Harris Semiconductor line of dielectrically-isolated analog parts offers some protection against these problems. In fact, the HA2-2600-1, HA2-2620-1, and HA1-4920-1 op-amps and comparators are prescreened and guaranteed for 200°C operation, as are the HI2-0200-1, HI1-0201-1, HI1-0508-1, HI1-0508A-1, and HI1-0509-1 analog switches and multiplexers. The prescreening of many other analog ICs from different manufacturers has also uncovered selected devices usable in high-temperature circuits.

A dielectrically isolated, bipolar op-amp rated for 0° to 300°C operation is nearing completion at Harris Semiconductor. Preliminary specifications are also given in this section.

References

References 2, 36, 43, and 53 through 63, which are listed in the reference section of this sourcebook, contain information relevant to integrated circuits.

3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.2. INTEGRATED CIRCUITS, DIGITAL

3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.2 INTEGRATED CIRCUITS, DIGITAL

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3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.2 INTEGRATED CIRCUITS, DIGITAL

3.1.3 INTEGRATED CIRCUITS, ANALOG

The following characteristics are taken from manufacturers' specifications. Sandia performed no tests on these devices because of program limitations.

Manufacturer

Harris Semiconductor
Box 883
Melbourne, Florida 32901
(305) 724-7190
Attn: P. S. Smith

HA2-2600-1

Operational Amplifier

Specifications at: $V_s = \pm 15$ volts, $T = 200^\circ\text{C}$
Output Voltage Swing: ± 12 volts typically
Command Mode Rejection Ratio: 100 dB typically
Supply Current: 3.7 mA maximum
Internal Power Dissipation: 300 mW maximum
Full-Power Bandwidth: 75 kHz, $V_o = \pm 10$ volts
Temperature Range: 0° to 220°C
Size, inches: 0.355 dia. x 0.180 high

HA2-2620-1

Operational Amplifier

Specifications at: $V_s = \pm 15$ volts, $T = 200^\circ\text{C}$
Output Voltage Swing: ± 12 volts typically
Common Mode Rejection Ratio: 100 dB typically
Supply Current: 4.0 mA maximum
Internal Power Dissipation: 145 mW maximum
Full-Power Bandwidth: 600 kHz, $V_o = \pm 10$ volts
Slew Rate: 35 V/ μs
Temperature Range: 0° to 200°C
Size, inches: 0.355 dia. x 0.180 high

HA-1-4920-1

Specifications at: $V_s = \pm 15$ volts, -55° to 200°C
Input Offset Voltage: 6.5 mV maximum
Input Sensitivity: 0.6 mV typically
Output Voltage Level: 0.4 volt maximum for logic low,
3.5 volts minimum for logic high

3.1.3 INTEGRATED CIRCUITS, ANALOG

Output Current, I_{sink} and I_{source} : 3.2 mA minimum

Power Supply Current, I_{cc} : 22 mA maximum

Internal Power Dissipation: 875 mW at 150°C

Temperature Range: -55° to 200°C

Size, inches: 0.310 x 0.780 x 0.185

3.1.3 INTEGRATED CIRCUITS, ANALOG

3.1.3 INTEGRATED CIRCUITS, ANALOG

Following are preliminary specifications for a new Harris Semiconductor product.

Quad Operational Amplifier

Features: Operates for 100 hours at 300°C and electrically interchangeable for HA-2602 series op amps

Offset Voltage: 6.0 mV maximum at 300°C

Average Offset Voltage Drift: 10 $\mu\text{V}/^\circ\text{C}$ maximum from 25° to 300°C

Input Bias Current: 2 μA maximum at 300°C

Input Offset Current: 0.5 μA maximum at 300°C

Common Mode Input Range: ± 10 volts minimum from 25° to 300°C

Differential Input Signal: > 10 volts from 25° to 300°C

Common Mode Rejection Ratio: 80 dB minimum at 300°C

Voltage Gain: 70 dB minimum at 300°C

Channel Separation: 100 dB minimum at 300°C

Gain Bandwidth: 4 MHz minimum at 300°C

Output Voltage Swing: $> \pm 11$ volts from 25° to 300°C

Slew Rate: ± 4 V/ μs minimum at 300°C

Output Current: 7 mA minimum at 300°C

Power Supply Rejection Ratio: 80 dB minimum at 300°C

Noise: 5 nV/ $\sqrt{\text{Hz}}$ maximum at 25°C

Note: These specifications are based on the use of +15 volt and -15 volt power supplies regulated to within $\pm 10\%$. The 5-mA output current is based on a 2-k Ω minimum total load resistance for full output signal swing. Smaller loads require a restricted signal swing and a derating of circuit output power. The total (four amplifiers) unloaded idling current from supply to supply is approximately 3.2 mA. The above numbers are based on the assumption of a package providing $\sigma_{JA} = 100^\circ\text{C}/\text{watt}$.

3.2 HYBRID MICROCIRCUITS

3.2.1 SYNOPSIS

Sophisticated commercial hybrid microcircuits are readily obtainable for use at temperatures to 200°C as evidenced by manufacturers' specifications and Sandia's Geothermal Instrumentation Program. Improvements in active devices, passive devices, and fabrication techniques have advanced the temperature capabilities of hybrid microcircuits to 275°C, and, therefore, simple circuits that operate at this temperature are now being developed and produced commercially. The hybrid technology is partially limited, however, due to problems regarding bipolar semiconductor devices and stable capacitors having a capacitance near 0.1 μF . Although these devices are rated at 275°C, care should be taken in design, testing, and initial burn-in when hybrids are operated for 1,000 hours and longer at the maximum rated temperature.

References 22, 30, 36, and 62 through 72, which are listed in the reference section of this sourcebook, contain information relevant to hybrid microcircuits.

3.2.2 HYBRID MICROCIRCUITS

The following characteristics are taken from manufacturers' specifications. No testing was performed on these components by Sandia because of program limitations.

<u>Manufacturer</u>	
	Teledyne Philbrick Allied Drive at Route 128 Dedham, MA 02026 (617) 329-1600
2115 Voltage Regulator	Packaging: 10-pin, triple DIP Voltage Output: +15 volts $\pm$ 150 mV Voltage Change: 0.5-volt maximum over a 25° to 275°C range Input Supply Range: +16 to +25 volts Output Current, Maximum: 50 mA at 275°C Temperature Range: 25° to 275°C Size, inches: 1.15 x 0.75 x 0.23
2735 Line Driver	Packaging: 10-pin metal DIP, triple wide Power Supply: +15 volts $\pm$ 5% Line Voltage Input: +25 to +40 volts Input Pulse Width: 5 to 15 μ s Input Pulse Amplitude: +15 volts $\pm$ 5% Temperature Range: 0° to 275°C Size, inches: 1.15 x 0.75 x 0.23
2742 Pulse Stretcher	Packaging: 10-pin metal DIP Feature: Receives a 1.5 to 8 μ s pulse and converts it to a 12 μ s pulse Supply Voltage: +15 volts $\pm$ 5% Input Pulse Width: 1.5 to 8 μ s Input Pulse Amplitude: 10 to 15 volts Output Pulse Width: 12 $\pm$ 2 μ s Output Pulse Amplitude: +15 volts $\pm$ 5%

3.2.2 HYBRID MICROCIRCUITS

Power-On Delay with External 2.2- μ F Capacitor: 100 ms

Temperature Range: 0° to 275°C

Size, inches: 1.15 x 0.75 x 0.23

2774

Voltage to Frequency
Converter

Packaging: 10-pin metal DIP, triple wide

Supply Voltage: +15 volts $\pm$ 5%

Output Pulse Width: 2 to 5 μ s

Output Pulse Amplitude: +12 $\pm$ 3 volts

Output Frequency

1-volt Input: 5 to 10 kHz

2-volt Input: 15 to 20 kHz

Voltage Input Range: 0.5 to 3.5 volts

Resistance Input Range: 500 Ω to 4 k Ω

Operating Temperature: 0° to 275°C

Size, inches: 1.15 x 0.75 x 0.23

4160

12-Bit A/D Converter

Packaging: 32-pin DIP

Features: Internal precision reference, stable clock
circuitry, comparator, successive approximation
register

Supply Voltage ($\pm V_{CC}$): $\pm$ 16 VDC

Logic Supply Voltage: 5 VDC

Analog Input: $\pm$ 11 VDC on a $\pm$ 10-volt scale

Digital Input: 0 to 5 volts

Conversion Time: 125 μ s maximum

Power Consumption: 740 mW maximum

Temperature Range: -25° to 200°C

Manufacturer

Micropac Industries

905 East Walnut Street

Garland, TX 75040

(214) 272-3571

3.2.2 HYBRID MICROCIRCUITS

Voltage Regulator

Packaging: 3 pin

Voltage: 15 volts

Output Voltage Variation: < 1% from 25° to 275°C

Output Voltage Variation (Variable Load): < 1%

Manufacturer

Burr-Brown Research Corp.

Box 11400

Tucson, AZ 85734

(602) 746-1111

ADC10HT

12-Bit A/D Converter

Packaging: 28-pin DIP

Features: Internal clock and reference voltage, serial output, TTL or +5 volts; CMOS compatible

Supply Voltage ($\pm V_{CC}$): ± 15 VDC

Logic Supply Voltage: +5 VDC

Analog Input: ± 5 volts, ± 10 volts

Conversion Time: 50 μ s maximum

Temperature Range: -55° to 200°C

Size, inches: 1.465 x 0.620 x 0.205

DAC10HT

12-Bit D/A Converter

Packaging: 24-pin DIP

Features: TTL and CMOS compatible, monotonic over the full operating temperature range

Supply Voltage ($+V_{CC}$): 4.75 to 15 VDC

Settling Time: 300 ns typically

Noise: 30 μ V, peak to peak

Control-Amplifier Bandwidth: 10 MHz

Slew Rate: 6 mA/ μ s

Temperature Range: -55° to 200°C

Size, inches: 1.215 x 0.610 x 0.170

3.2.2 HYBRID MICROCIRCUITS

OPA11HT

Operational Amplifier,
General Purpose

Packaging: Hermetic, standard type 741

Features: 12-MHz bandwidth, high gain,
high output current,

Open Loop Gain, DC, Single Ended: 103 dB typical with no
load

Input Bias Current: ± 30 nA maximum at 200°C

Input Offset Voltage: ± 6 mV maximum at 200°C

Input Offset Voltage Coefficient: ± 5 μ V/°C typical

Common-Mode Rejection: 100 dB typical

Typical Slew Rate: 7 V/ μ s

Temperature Range: -55° to 200°C

Size, inches: 0.370 dia. x 0.185 length

OPA12HT

Operational Amplifier,
Fast-Slewing

Packaging: Hermetic, standard type 741

Applications: High speed with protected inputs

Open Loop Gain, DC, Single Ended: 90 dB typical with no
load

Input Bias Current: ± 1 μ A maximum at 200°C

Input Offset Voltage: ± 14 mV maximum at 175°C

Input Offset Voltage Coefficient: ± 30 μ V/°C typical

Common-Mode Rejection: 90 dB typical

Typical Slew Rate: 120 V/ μ s

Temperature Range: -55° to 200°C

Size, inches: 0.370 dia. x .0185 length

Manufacturer

Micro Networks Corp.

324 Clark Street

Worcester, MA 01606

(617) 852-5400

3.2.2 HYBRID MICROCIRCUITS

Distributor

Technology Marketing Associates, Inc.
325 Dallas NE
Albuquerque, NM 87108
(505) 265-5661
Attn: Jim Costanza, Sales Engineer

MN5700

12-Bit A/D Converter

Packaging: 32-pin DIP
Features: Low power consumption, stable circuitry,
internal reference; no missing codes for 10 bits over
temperature range
Supply Voltage ($\pm V_{CC}$): ± 15 volts
Logic Supply Voltage: 5 to 10 volts
Analog Inputs: 0 to -10 volts, 0 to -20 volts, ± 5 volts,
 ± 10 volts
Conversion Time: 350 μ s maximum
Power Consumption: 455 mW maximum
Temperature Range: -55° to 200°C

High-temperature hybrid microcircuits are also manufactured by the following company:

David Kress
Analog Devices, Inc.
804 Woburn Street
Wilmington, MA 01887
(617) 658-8313

Custom-designed hybrids are manufactured by the following company:

Teledyne Microelectronics
12964 Panama Street
Los Angeles, CA 90066
(213) 822-8229
Attn: John McAulay

3.3 MICROCIRCUITS, COMPONENTS

Passive Devices

- Capacitors -- see CAPACITORS, DISCRETE AND CHIP; CAPACITORS, THICK FILM
- Resistors -- see RESISTORS, DISCRETE; RESISTORS, THICK FILM; RESISTORS, THIN FILM
- Thermistors -- see THERMISTORS

Active Devices

- Diodes -- see DIODES
- Transistors -- see TRANSISTORS, JFET; TRANSISTORS, MOSFET; TRANSISTORS, VMOS

Complex Circuits

- Sockets -- see CIRCUITS, SOCKETS
- Solder -- see CIRCUITS, SOLDER
- Substrates -- see CIRCUITS, SUBSTRATES

Materials -- see ADHESIVES

References 2, 22, 31, 42, 73, and 74, which are listed in the reference section of this sourcebook, contain information relevant to microcircuit components.

3.3.1 MICROCIRCUITS, BONDING WIRE

The following types of bonding wire were tested by Sandia. The bond resistance and pull strengths were measured while the wires were attached to gold thick-film conductors. The characteristics given apply to wires obtained from the Sigmund Cohn Corp., 125 South Columbus Avenue, Mount Vernon, NY 10553.

Aluminum

Bond Resistance, R/R_0 : 3 for 1,000 hours at 300°C

Pull Strength, X/X_0 : Inconclusive

Size: 1 mil

Note: Not recommended for long-term use, i.e., more than 1,000 hours, above 300°C

Aluminum plus 1% Silicon

Bond Resistance, R/R_0 : 3.5 for 1,000 hours
at 300°C

Pull Strength, X/X_0 : 0.5 for 1,000 hours at 300°C

Size: 1 mil, 1% to 3% elongation

Note: Withstands 1,000 hours at 300°C

Aluminum plus 1% Magnesium

Bond Resistance, R/R_0 : 2 for 1,000 hours at 300°C

Pull Strength, X/X_0 : 0.1 for 1,000 hour at 3000°C

Size: 1 mil

3.3.2 MICROCIRCUITS, CONDUCTORS

The following conductors were tested by Sandia.

Manufacturer

Thick Film Systems

324 Palm Avenue

Santa Barbara, CA 93101

(805) 963-7757

3028, A328

Features: Gold, modified fritless conductor; can with-stand 1,000 hours at 300°C

Bond Resistance, R/R_0 : 1.9 at 300°C

Pull Strength, X/X_0 : 0.2 for 1,000 hours at 300°C

Manufacturer

AVX Corp.

98 Cutter Mill Road

Great Neck, NY 11021

(516) 829-8500

3520

Features: Gold, modified fritless conductor; can be used for 1,000 hours at 300°C

Bond Resistance, R/R_0 : 1.4 for 1,000 hours at 300°C

Pull Strength, X/X_0 : 0.28 for 700 hours at 300°C

3.3.2 MICROCIRCUITS, CONDUCTORS

Manufacturer

E. I. Du Pont de Nemours and Co.
Electro Chemicals Department
1007 Market Street
Wilmington, DE 19898
(302) 774-1000

9910

Features: Low-frit, mixed bonded gold ink
Bond Resistance, R/R_0 : 3.2 for 600 hours at 300°C
Pull Strength, X/X_0 : 0.47 for 1,000 hours at 300°C

8653

Features: Gold-platinum ink; no conduction degradation
for 1,000 hours at 300°C or 100 hours at 600°C

9791

Features: Conductor ink for use below 300°C

3.3.2 MICROCIRCUITS, CONDUCTORS

Manufacturer

Cermalloy
Bala Electronics Corp.
Union Hill Industrial Park
West Conshohocken, PA 19428
(215) 825-6050

4121

Features: Fritless gold-platinum conductor; used in temperatures above 300°C for short periods of time

Sheet Resistance: 0.027 Ω/sq

Bond Resistance, R/R_0 : ~ 1 at 300°C

4131

Features: Fritless gold-platinum conductor

Sheet Resistance: 0.085 Ω/sq

Temperature: Tested to 300°C

4398

Features: Gold conductor

Sheet Resistance: 0.0035 Ω/sq

Temperature: Tested to 300°C

3.3.3 MICROCIRCUITS, DIFFUSION BARRIER PADS

Diffusion barrier pads are designed to be used when the aluminum wire bonds are to operate at temperatures $> 275^{\circ}\text{C}$ or for periods > 100 hours. The following bonding techniques were developed by Sandia.

Silicon,
Highly Doped

Size: 5 mil thick x 30 mil x 3 mil

Technique: $1\text{ }\mu\text{m}$ gold and aluminum vapor deposition,
eutectic bond

Nickel, Annealed

Size: 30 mil diameter x 1 mil thick

Technique: $1\text{ }\mu\text{m}$ gold and aluminum vapor deposition per
side, thermocompression bond

Bond Resistance, R/R_0 : 5% for 1,000 hours at 350°C

Pull Strength, X/X_0 : Good retention

Kovar, Annealed

Size: 30 mil diameter x 1 mil thick

Technique: $1\text{ }\mu\text{m}$ gold and aluminum vapor deposition per
side, thermocompression bond

Bond Resistance, R/R_0 : Small increase

Pull Strength, X/X_0 : Good retention

Operation Time: At least 1,000 hours at 350°C

3.3.4 MICROCIRCUITS, LIDS

The following lids were used successfully by Sandia in the construction of microcircuits.

Manufacturer

Semi-Alloys, Inc.

888 South Columbus Avenue

Mount Vernon, NY 10550

(914) 664-2800

Gold and Kovar

Alloy: 88% gold, 12% germanium

3.3.5 MICROCIRCUITS, PACKAGING

Special techniques for the attaching and packaging of microcircuits are necessary when the circuits are to be subjected to high temperatures. Because the techniques are only as good as the materials used, packaging and attaching materials must be capable of withstanding high temperatures. Techniques and materials have been developed that allow the circuit construction to remain intact at 300°C.

The following packaging is used by Sandia in the construction of microcircuits.

Manufacturer

3M Company
Electronic Products Division
3M Center
Saint Paul, MN 55101
(612) 733-1110

Part Number

S372908. A_A

Part Number

S282408. AB

Package Construction: Ceramic with gold-plated Kovar leads

Features: Available in certain standard sizes and with standard numbers of leads

Note: A component of Sandia high-temperature ICs; uses metal lids on a 2-inch by 2-inch substrate

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

Beasom, J. D. "High Temperature Analog Integrated Circuits," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 123.

Commercial integrated circuits have been designed, manufactured, and specified to operate only over the temperature range -55° to 125°C . This range has been satisfactory for the vast majority of military and commercial applications; however, there are some applications such as well logging, engine instrumentation, and industrial controls where higher temperatures are encountered. Users in these areas have been forced to characterize various available parts in search of those which may function adequately at the temperature of their application and then to test out suitable parts from the manufacturers' production. Users have had no assurance that the circuits would be reliable at high temperature nor any that they would continue to find functional parts in future purchases.

Bonn, P. A. and Palmer, D. W. 275°C Thick-Film Hybrid Microcircuitry Fabrication Technology. SAND80-0078. Albuquerque: Sandia National Laboratories, March 1980.

High-temperature electronics is needed for geothermal well logging tools, jet engine monitors, nuclear reactor instruments, and fossil fuel exploration and production systems. This report describes the step-by-step fabrication technology of thick-film hybrids useful for at least 1,000 hours at 275°C . Hybrid technology, qualified to standard military specification, was modified both in materials and fabrication processes to achieve this high-temperature operation. In addition to documenting this Sandia-developed technology, various alternate approaches are described to increase the versatility and applicability of these methods.

Draper, B. L. and Palmer, D. W. "Extension of High-Temperature Electronics," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-2, no 4, December 1979.

See abstract in Section 2.4 Active Devices, Bibliography/Abstracts.

McBrayer, J. D. CMOS Test Chip. SAND78-1390. Albuquerque: Sandia Laboratories, August 1978.

To support an effort to develop high-temperature electronics for geothermal well instrumentation and to develop a complete understanding of radiation effects on CMOS circuits, a CMOS test chip has been designed. This chip will be the test bed for determining the feasibility of CMOS circuitry sustaining 1,000 hours at 300°C . Furthermore, this same chip will be used to understand the latch-up phenomenon and other effects of

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

CMOS circuits under radiation environments. This test chip will be manufactured at Sandia Semiconductor Development Laboratory.

. High-Temperature Complementary Metal Oxide Semiconductors. SAND79-1487. Albuquerque: Sandia Laboratories, October 1979.

Silicon CMOS devices were studied, tested, and evaluated at high temperatures to determine processing, geometric, and operating characteristics and stability parameters. After more than 1,000 hours at 300°C, most devices showed good stability, reliability, and operating characteristics. Processing and geometric parameters were evaluated and optimization steps discussed.

Palmer, D. W. "Hybrid Microcircuitry for 300°C Operation," IEEE Transactions on Parts, Hybrids, and Packaging, vol PHP-13, no 3, September 1977.

Microelectronic instrumentation for geothermal well logging must operate in ambient temperatures up to 300°C for several hundred hours. This study involved an extensive survey of 25° to 300°C operation of resistors, capacitors, conductors, interconnections, and active devices. Three major selection criteria were: (1) part lifetime of at least 1,000 hours at 300°C, (2) minimum change in electrical parameters from 25° to 300°C, and (3) availability to the common circuit builder (no one of a kind). Certain thick-film resistors, capacitors, and conductors were found compatible with such high-temperature operation. In addition, reconstituted mica and aluminum solid electrolytic capacitors were found useful up to 300°C. Simple circuits for geothermal temperature logging tools have been fabricated using these hybrid materials, components, and silicon MOS and JFET devices. Oven tests show satisfactory stability from 25° to 300°C and at least 100-hour circuit operation at 300°C.

and Heckman, R. C. "Extreme Temperature Range Microelectronics," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-1, no 4, December 1978.

Downhole geothermal instrumentation must operate over a large temperature range. The technology and capabilities of room-temperature-to-300°C hybrid and printed-circuit (PC) board electronics that were developed during the last 2 years to meet that need are summarized. To ensure rapid widespread commercialization, this technology was developed, insofar as possible, using commercially available components, devices, and materials. Initial extensive high-temperature characterization revealed that selected thick-film passive components and silicon junction field effect transistors had electrical parameters sufficiently insensitive to temperature change and sufficiently constant in time at high temperatures to form the backbone of this circuitry. Attachment techniques needed to be developed

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

since standard methods failed at high temperatures. Similarly, circuit design innovations were needed because of the restricted list of parts. Voltage regulators, line drivers, voltage comparators, special purpose amplifiers, and multiplexers were constructed and operated over the 25° to 300°C temperature range. Temperature and pressure monitoring instruments using these circuits have been used for downhole measurements in geothermal wells. Methods of fabrication, circuit performance, and the scope of future work are discussed.

. Design and Performance of Geothermal Hybrid Microcircuits. SAND78-1168C. Albuquerque: Sandia Laboratories, September 12, 1978. In Booklet 21 of Proceedings of MIDCON/78 Conference, December 12-14, 1978 (sponsored by IEEE).

Geothermal well logging electronic instrumentation requires carefully chosen materials and layout procedures to ensure hybrid operation from 25° to 300°C for at least 100 hours. Material selection involved thick-film inks, transistor chips, and packaging compounds. Commercial thick-film materials were found which tolerate extreme temperature operation: "plague-free" fritless golds, resistor compositions with temperature coefficients of resistance optimized at 150°C, and high-melting-temperature/low-ion-mobility dielectric inks. Exhaustive semiconductor device surveys indicate the silicon junction field effect devices exhibit a zero temperature coefficient operational bias region from 25° to 300°C and acceptable drift during 1,000 hours at 300°C. Attachment of substrates into hermetic packages is achieved with gold-germanium preforms or low-melting-temperature glaze, and package lids are preform-soldered or welded on in an inert atmosphere. Several layout techniques are used which facilitate assembly and enhance reliability: (1) large rectangular resistor areas enhance stability and extend trimming range, (2) potential resistor bypasses extend the range of trimming, (3) large die pads allow chip replacement, (4) large wire bonding pads permit diffusion barrier attachment, and (5) isolated transistor patterns allow temperature characterization before commitment to the circuit. Using these materials and layout techniques, instruments to measure downhole temperature, pressure, and flow have been developed and tested. Field performance and future directions will also be discussed.

. "Hardening Microcircuits Against 300°C, Yesterday and Tomorrow," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 53.

Although high-temperature electronics had sporadic popularity during the '50s and '60s, a sustained effort on high-temperature microelectronics was not initiated until May 1976, when the effort at Sandia Laboratories began. With each subsequent advance in high-temperature technology, more notice and participation were generated, culminating with today's effort,

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

which involves many industrial and government engineers from researchers to manufacturers. To help coordinate this broad development, it becomes important to document both the history and future direction of Sandia's effort. To that end, this paper will describe the technological approaches that have been taken at Sandia, what the present capabilities are in the lab and field, and where development is leading.

Prince, J. L. et al. "High Temperature Characteristics of Commercial Integrated Circuits," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 115.

Requirements on active electronic components for the hostile downhole environment of geothermal wells are extreme. One requirement is the ability to function reliably at very high ambient temperatures (up to 325°C) for many tens of hours. The high-temperature functional capability of various discrete silicon components has been established by earlier work, and some information is available on the high-temperature performance of integrated circuits (ICs). System requirements dictate eventual use of IC components. The work described here is directed toward establishing the high-temperature performance and reliability capabilities of diverse IC technologies, particularly those suitable for digital IC fabrication, and toward determining the limiting mechanisms and characteristics of the technologies for high-temperature application. Further work will lead to the generation of design rules, or at least principles, for high-temperature IC design and fabrication.

et al. "Performance of Digital Integrated Circuit Technologies at Very High Temperatures," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-3, no 4. December 1980.

Results of detailed investigations of the performance and reliability of digital bipolar and CMOS integrated circuits over the 25° to 340°C range are reported. Included in these results are both parametric variation information and analysis of the functional failure mechanisms. Although most of the work was done using commercially available circuits (TTL and CMOS) and test chips from commercially compatible processes, some results of experimental simulations of dielectrically isolated CMOS are also discussed. In general, it was found that commercial Schottky clamped TTL and dielectrically isolated, low power Schottky clamped TTL functioned to junction temperatures in excess of 325°C. Standard gold doped TTL functioned only to 250°C, while commercial, isolated I²L functioned to the range of 250° to 275°C. Commercial junction isolated CMOS, buffered and unbuffered, functioned to the range of 280° to 310°C+, depending on the manufacturer. Experimental simulations of simple dielectrically isolated CMOS integrated circuits, fabricated with heavier doping levels than normal, functioned to temperatures in excess of 340°C. High-temperature

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

life testing of experimental, silicon-encapsulated simple TTL and CMOS integrated circuits have shown no obvious life-limiting problems to date. No barrier to reliable functionality of TTL bipolar or CMOS integrated circuits at temperatures in excess of 300°C has been found.

Reagan, M. G. "Commercial Fabrication of 275°C Hybrid Microcircuits," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 65.

Teledyne Philbrick was contracted by Sandia Laboratories in the fourth quarter of 1978. The objective of this contract was to demonstrate the ability to commercially fabricate high-temperature hybrid microcircuits. The contract called for the production of a +15 volt regulator capable of operation to 300°C for a minimum of 100 hours. At that time, Sandia had completed the major portion of the electrical design and had resolved numerous mechanical problems. The challenge that awaited Teledyne Philbrick was to investigate and resolve the remaining mechanical and electrical problems and to identify techniques that would yield the efficient and reliable fabrication of 300°C hybrid microcircuits.

Veneruso, A. F., Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

_____, Palmer, D. W., and Reagan, M. G. "High-Temperature Hybrids for Use Up to 275°C -- Drift and Lifetime," Proceedings of the 1980 International Microelectronics Symposium, October 20-22, 1980. New York: International Society for Hybrid Microelectronics.

This paper reviews the drift and lifetime performance of 275°C hybrid microcircuits that were recently developed by Teledyne Philbrick and Sandia National Laboratories. The specific technology employed is based on temperature-tolerant thick films and discrete silicon JFETs. The results of high-temperature circuit testing are reviewed; component and circuit degradation and failure modes are described and compared to predictions; and, finally, design rules are given to maximize life-times and to minimize performance drift for up to 10,000 hours of operation at 275°C. Although these circuits were developed for instrumenting geothermal boreholes, many other applications for this technology exist in such areas as fossil fuel exploration and production systems, jet engine monitors, and nuclear reactor monitors.

3.4 MICROCIRCUITS, BIBLIOGRAPHY/ABSTRACTS

Vest, R. W. "High Temperature Thick Film Research," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 57.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

Vossen, J. L. "Section V. Refractory Metals," Bibliography on Metallization Materials and Techniques for Silicon Devices: IV. New York: Thin Film Division, American Vacuum Society, September 1978. pp 12-17.

Wiley, J. D., Perepezko, J. H., and Nordman, J. E. High Temperature Metallization System for Solar Cells and Geothermal Probes. SAND80-7167. Albuquerque: Sandia National Laboratories, December 1980.

See abstract in Section 2.4 Active Devices Bibliography/Abstracts.

____ et al. "Amorphous Metallization for High-Temperature Semiconductor Device Applications," High-Temperature Electronics Conference, March 25-27, 1981.

In this paper, we present the initial results of work on a new class of semiconductor metallizations which appear to hold great promise as primary metallizations and diffusion barriers for high-temperature-device applications. These metallizations consist of sputter-deposited films of high-T^g amorphous-metal alloys which (primarily because of the absence of grain boundaries) exhibit exceptionally good corrosion-resistance and low diffusion coefficients. Amorphous films of the alloys Ni-Nb, Ni-Mo, W-Si, and Mo-Si have been deposited on silicon, GaAs, GaP, and various insulating substrates. The films adhere extremely well to the substrates and remain amorphous during thermal cycling to at least 500°C. Rutherford Back-scattering (RBS) and Auger Electron Spectroscopy (AES) measurements indicate atomic diffusivities in the 10⁻¹⁹ cm²/s range at 450°C.

4.0 COMPLEX CIRCUITS AND INSTRUMENTS

References 2, 65, and 75 through 77, which are listed in the reference section of this sourcebook, contain information relevant to power supplies and temperature measurement/transmitting systems. References 22 through 24, 42, 73, and 78 through 81 contain information relevant to complex circuit components.

4.1 POWER SUPPLIES

The following characteristics are taken from manufacturers' specifications. Because of program limitations, no tests were performed on these products by Sandia.

Manufacturer

Venus Scientific Inc.
399 Smith Street
Farmingdale, NY 11735
(516) 293-4100

Model HT-25
DC to DC

Type: Line-regulated converter
Input Voltage: 15 volts
Output Voltage: 1,000 to 2,500 volts
Operation: -40° to 195°C, possibly to 200°C
Temperature Coefficient: $\pm 1\%$ from 20° to 185°C
Pressure: 0 to 1.03 MPa
Packaging: Pressurized liquid/gas, brass housing
Size, inches: 0.88 dia. x 2.40 long over terminals

Manufacturer

HDL Research Lab, Inc.
8381 Westview Drive
Houston, TX 77055
(713) 465-3803
Attn: Mr. J. M. Bradshaw, Representative

Products

Power supplies for 200°C operation and flux gates for
300°C operation

4.2 TEMPERATURE MEASUREMENT/TRANSMITTING SYSTEM

The following characteristics are taken from manufacturers' specifications. Sample quantities of these circuits were tested by Sandia.

Manufacturer

Teledyne Philbrick
Allied Drive at Route 128
Dedham, MA 02026
(617) 329-1600

2700
High-Temperature
Measurement/
Transmitting System

Features: Digital system consisting of four individual hybrid circuit packages combined to serially transmit temperature information

Operating Temperature: 0° to 275°C

Resolution: 0.02 Centigrade degrees

Accuracy (Calibrated): ± 0.5 Centigrade degrees

Thermal Time Constant: 60 seconds

Supply Voltage: +25 to +45 volts

Repeatability Error: < 0.1% for 25 hours at 275°C
following calibration

Output Frequency: 10 kHz at 25°C to 30 kHz at 275°C

Note: Temperature information is transmitted over the line that supplies power to the system. The 2700 is compatible with existing logging techniques and operates on monocables or multiconductor cables. The use of a minimum number of active and passive components minimizes the effects of drifts in electrical properties and improves reliability.

SYSTEM LAYOUT AND INTERCONNECTION DIAGRAM
(TOP VIEW)

4.3 CIRCUITS, COMPONENTS

Passive Devices

Capacitors -- see CAPACITORS, DISCRETE; CAPACITORS, DISCRETE AND CHIP

Resistors -- see RESISTORS, DISCRETE; RESISTORS, CHIP

Thermistors -- see THERMISTORS

Active Devices

Diodes -- see DIODES

Transistors -- see TRANSISTORS, JFET; TRANSISTORS, MOSFET; TRANSISTORS, VMOS

Tubes -- see CERAMIC VACUUM TUBES

4.3.1 CIRCUITS, CIRCUIT BOARDS

Manufacturer

Elite Circuits Incorporated
3443 Tripp Court
San Diego, CA 92121
(714) 455-1665
Attn: Vito D. Elarde, Vice President

Polyimide

Features: Condensation-type printed circuit board made with PM-300 metal alloy circuitry; can be used to 300°C
Source of Data: Manufacturer's specifications

Polyimide

Features: Additive-type printed circuit board with PM-300 metal alloy circuitry; can be used to 250°C
Source of Data: Manufacturer's specifications

Polyimide

Features: Modified polyimide printed circuit board with PM-300 metal alloy circuitry; for 85° to 200°C use
Source of Data: Manufacturer's specifications

Manufacturer

E. I. Du Pont de Nemours and Co.
Electro Chemicals Department
1007 Market Street
Wilmington, DE 19898
(302) 774-1000

Pyralin

Features: Polyimide printed circuit board; survival time > 100 hours at 260°C
Source of Data: Sandia

Manufacturer

Mykroy Ceramics Corp.
Orben Drive
Ledgewood, NJ 07852
(201) 398-7000

4.3.1 CIRCUITS, CIRCUIT BOARDS

1100

Features: Printed circuit board made of glass-bonded mica sheet; material is for continuous usage at 1100°F.

Source of Data: Manufacturer's specifications

4.3.2 CIRCUITS, INTERCONNECTIONS

SYNOPSIS

Many solders and conductor inks have melting points that are below the temperatures found in a geothermal well. At these high temperatures, bonding strengths of the solders and inks deteriorate rapidly, and the metals migrate. Both of these types of materials failures contribute to the degradation of the connections. A search was conducted for solders suitable for use at high temperatures, and solder made from the eutectic combination of gold and germanium was chosen. In tests aimed at identifying suitable conductor inks, thick-film conductor inks made of gold combined with small amounts of other elements show aluminum wire bonding compatibility to 300°C. Methods for bonding aluminum wire and a gold-based conductor have been developed and are described in Sandia publications. Parallel gap welded gold ribbon also was found to be a reliable conductor ink.

4.3.3 CIRCUITS, INTERCONNECTING WIRE

Manufacturer

E. I. Du Pont de Nemours and Co.
Electro Chemicals Department
1007 Market Street
Wilmington, DE 19898
(302) 774-1000
Attn: Cutter Palmer, Representative

Kapton

Features: Solid nickel wire with Kapton (polyimide) coating
Size: To 26 gauge with 0.004-inch Kapton coating
Temperature: For use up to 300°C
Source of Data: Manufacturer's specifications

Manufacturer

Sigmund Cohn Corp.
125 South Columbus Avenue
Mount Vernon, NY 10553
(914) 664-5300

Aluminum plus
1% Silicon
No. 1100
Type 23890-1.20

Size: 1 mil diameter
Elongation: 1.5% to 3%
Tensile Strength: 14 to 16 grams
Temperature: For operation to 275°C
Source of Data: Sandia

The following types of interconnecting wire were tested by System Development Corp.²³

Manufacturer

Gulton Industries, Connector Division
1644 Whitties Avenue
Costa Mesa, CA 92627
(714) 642-0163

4.3.3 CIRCUITS, INTERCONNECTING WIRE

Duroflex I

Features: Insulated solid nickel wire

Size: 22 gauge

Temperature: Sample tested for use up to 1000°F

Manufacturer

Anaconda

Wire and Cable Division

Greenwich Office Park

Greenwich, CN 06830

(203) 622-7000

Nickel

MG-300-20

Features: Mica-tape and glass-braid insulated nickel
wire

Size: 20 gauge

Temperature: Sample tested for 500°C continuous use

Manufacturer

Secon Metals Corp.

7 Intervale Street

White Plains, NY 10606

(914) 949-4757

Features: Ceramic insulated wire

Size: To 5 mil diameters

Temperature: For 300°C usage

Manufacturer

Penntube Plastics

Clifton Heights, PA 19018

(215) 622-2300

Attn: John Walls, Representative

4.3.3 CIRCUITS, INTERCONNECTING WIRE

Insulation

Features: Transparent, heat sealable, chemically inert

Heat Shrink

Size, inches: Wall thickness to a minimum of 0.02

Teflon Tubing

Shrink Ratio: 1.2 to 1

Service Temperature: 204°C maximum

Source of Data: Manufacturer's specifications

4.3.4 CIRCUITS, SOCKETS

The following characteristics are taken from the manufacturer's specifications. Because of program limitations, no tests were performed on these devices by Sandia.

Manufacturer

Textool Products, Dept. 3/M
1410 West Pioneer Drive
Irving, TX 75061
(214) 259-2676

Distributor

Alliance Electronics, Inc.
11728 Linn, NE, Box 13562, Station E
Albuquerque, NM 87123
(505) 292-3360
Attn: Albert Telles, Representative

ZIP DIP II

Socket Body Material: Silicone (300°C)
Contact Material: Beryllium nickel
Plating: Nickel boron
Contact Resistance: < 0.005 Ω
Voltage Breakdown: 2,000 volts

2 and 3 Lead
Rectifier

Socket Body Material: Silicone (300°C)
Contact Material: Beryllium nickel
Plating: Nickel boron
Mounting: Rivet or screw
Configuration: "Top hat stud" or axial lead

Power
Semiconductor

Socket Body Material: Silicone
Contact Material: Beryllium nickel
Mounting: Rivet or screw
Temperature Range: -60° to 350°C
Configuration: 3 leads, 0.200-inch to 0.750-inch pin circle

4.3.4 CIRCUITS, SOCKETS

**Multi-Lead TO-5
Burn-In**

Socket Body Material: Silicone (300°C)
Contact Material: Beryllium nickel
Plating: Nickel boron
Temperature Range: -60° to 300°C

**Multi-Lead TO-5
Burn-In (Flanged)**

Socket Body Material: Silicone (300°C)
Contact Material: Beryllium nickel
Plating: Nickel boron
Temperature Range: -60° to 300°C

Axial Lead

Socket Body Material: Torlon (250°C)
Contact Material: Beryllium nickel
Plating: Nickel boron
Mounting: Printed circuit board or chassis

**Axial or Radial
Lead**

Socket Body Material: Silicone
Contact Material: Beryllium nickel
Plating: Nickel boron
Mounting: Rivet or screw, printed circuit board or chassis
Temperature Range: -60° to 300°C
Connection: Weld or solder
Configuration: Axial or radial lead
Leads Accepted: 0.018-inch to 0.040-inch diameters

4.3.5 CIRCUITS, SOLDER

Manufacturer

Alpha Metals, Inc.
1001 S. Linwood Avenue
Santa Ana, CA 92705
(714) 547-7315

581
Silver-Bearing

Alloy: 97.5% lead, 2.5% silver
Melting Point: 305°C
Source of Data: Manufacturer's specifications

588
Silver-Bearing

Alloy: 97.5% lead, 1.5% silver, 1% tin
Melting Point: 310°C
Note: Temperature cycling can cause cracking.
Source of Data: Sandia tests

1434

Alloy: 72% gold, 20% tin
Melting Point: 779°C
Source of Data: Manufacturer's specifications

Manufacturer

E. I. Du Pont de Nemours and Co.
Electro Chemicals Department
1007 Market Street
Wilmington, DE 19898
(302) 774-1000

8513
Formon

Alloy: 88% gold, 12% germanium
Melting Point: 356°C
Note: Can be used to 300°C
Source of Data: Sandia tests

8529

Product: Flux residue remover
Source of Data: Manufacturer's specifications

4.3.5 CIRCUITS, SOLDER

Manufacturer

Kester Solder Co.
4201 West Wrightwood Avenue
Chicago, IL 60639
(312) 235-1600

588

Alloy: 97.5% lead, 1.5% silver, 1% tin

Melting Point: 310°C

Note: Temperature cycling can cause cracking.

Source of Data: Sandia tests

4.3.6 CIRCUITS, SUBSTRATES

Manufacturers

Coors Porcelain Co.

600 9th Street

Golden, CO 80401

(303) 279-6565

Materials Research Corp.

Orangeburg, NY 10962

(914) 359-4200

American Lava Co. of 3M

Cherokee Boulevard and Manufacturers Road

Chattanooga, TN 37405

(615) 755-5400

Alumina Ceramic

Features: For use in thick-film hybrid circuits; no degradation over time at 300°C; formulation temperature $\approx 1400^\circ$ to 1900°C

Source of Data: Sandia

4.4 COMPLEX CIRCUITS AND INSTRUMENTS, BIBLIOGRAPHY/ABSTRACTS

Beasom, J. D. "High Temperature Analog Integrated Circuits," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 123.

See abstract in Section 3.4 Microcircuits Bibliography/Abstracts.

EerNisse, E. P., McConnell, T. D., and Veneruso, A. F. Development of a High Resolution Downhole Pressure Instrument for High Temperature Applications. SAND78-1550. Albuquerque: Sandia Laboratories, March 8, 1979. In Proceedings of Lawrence Berkeley Laboratory International Well Testing Symposium, October 25, 1978.

As part of the Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy, high-resolution, quartz-crystal-based, downhole pressure instruments are being developed. Under a joint no-cost contract, Sandia and Paroscientific, Inc., of Redmond, Washington, are working to upgrade a Paroscientific transducer for operation at 275°C. In addition, Sandia Laboratories has been investigating various design configurations and fabrication techniques for high-temperature quartz resonators and their associated electronic circuits. The goal of these efforts is to achieve a resolution of 0.01 psi in a 0 to 7,000 psi range and in temperatures up to 275°C. The progress and plans for this project will be reviewed, and hardware samples will be displayed.

Palmer, D. W. and Ganyard, F. P. "Aluminum Wire to Thick-Film Connections for High-Temperature Operation," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-1, no 3, September 1978.

Hybrid microcircuits in geothermal instrumentation must operate from room temperature to 300°C. Bond failure occurred during operation of initial geothermal circuits due to intermetallic growth at the aluminum wire-to-gold conductor interface. To remedy this problem, two wire bonding techniques have been qualified in high-temperature aging tests: (1) ultrasonic bonding of aluminum wire directly to modified fritless gold conductor inks (Du Pont 9910, AVX 3520, and TFS A328) and (2) insertion of a 1-mil diffusion barrier pad between the thick film and the aluminum wire. Both systems allow 100 to 1,000 hours operation at 300°C. Three alloys of wire were tested: pure aluminum, aluminum with 1 percent silicon, and aluminum with 1 percent magnesium. The degradation rates differed greatly, with pure aluminum being the least tolerant to temperature aging and wire with 1 percent silicon faring best. Because thick-film surfaces tend to be harder than thin-film surfaces, hardened aluminum wire (elongation 0.5 percent) formed bonds with less pad deformation and, consequently, with higher pull strengths than standard bonding wire (elongation 1 to 3 percent). Comparison of wire bonds aged at three temperatures (250°, 300°, 350°),

4.4 COMPLEX CIRCUITS AND INSTRUMENTS, BIBLIOGRAPHY/ABSTRACTS

and 350°C) demonstrated several orders of magnitude spread in degradation rates; for 1,000-hour bond lifetime, 300°C was found to be about the highest allowed operational temperature for direct bonding to gold. Disks of kovar and nickel of 1-mil thickness and 30 mils diameter were used as diffusion barriers between the gold and aluminum. Evaporated on one side of each disk was a 1- μ m gold thin film for thermocompression bonding to the thick film; the other side received an evaporated aluminum film for wire bonding. Aging for 1,000 hours up to 350°C produced no increase in bond resistance for any of the three wire alloys tested. Some decrease in pull strength with time was noticed but was attributed to annealing of the wire.

Prince, et al. "High Temperature Characteristics of Commercial Integrated Circuits," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 115.

See abstract in Section 3.4 Microcircuits, Bibliography/Abstracts.

_____, "Performance of Digital Integrated Circuit Technologies at Very High Temperatures," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol CHMT-3, no 4, December 1980.

See abstract in Section 3.4 Microcircuits, Bibliography/Abstracts.

Traeger, R. K., Varnado, S. G., and Veneruso, A. F. Continental Drilling in Thermal Regimes: Drilling In-Situ Diagnostics and Sampling. SAND80-2164A. Albuquerque: Sandia National Laboratories, September 16, 1980. In Proceedings of Fall Meeting, American Geophysical Union, December 8-12, 1980.

The current status of drilling technology, in-situ diagnostics, and formation/fluid sampling is reviewed in context to the Continental Scientific Drilling Program. A hypothetical, 7 km deep scientific drill hole is used to identify required technological developments, potential research problems imposed by drilling or field hardware, and major cost factors. Gas wells to 9 km in depth with maximum temperatures of 200° to 225°C have been drilled at costs of \$5 million to \$40 million. Conventional logging instruments have been used to 150°C, with dewared instrumentation used to 220°C. New commercial technology will be available for logging to temperatures of 225°C, and advanced instrumentation studies are expected to provide downhole capabilities to 300°C. Coring and in-situ fluid sampling have been limited to low temperatures and pressures of 0.5 to 1.5 kbar. Technology developments are needed in drilling, instrumentation, and sampling for temperatures exceeding 300° to 350°C. Since developments

4.4 COMPLEX CIRCUITS AND INSTRUMENTS, BIBLIOGRAPHY/ABSTRACTS

will be site specific (temperature, pressure, geology, environment), location of the proposed hole and extensive geological, geophysical, and geochemical studies are needed to focus hardware development.

Veneruso, A. F. High Temperature Instrumentation. SAND77-1895J. Albuquerque: Sandia Laboratories, (date not available). In Proceedings of Invitational Well-Testing Symposium, October 19, 1977.

Methods for obtaining geothermal borehole measurements and making appropriate interpretations are limited at present by technical deficiencies in that logging tools developed for the oil and gas industry rarely encounter temperatures above 150°C. Also, most of the available logging tools, cables, and seals are rated to only 180°C, whereas, in geothermal wells, temperatures frequently range up to 350°C. The Geothermal Logging Development Program being conducted by Sandia Laboratories for DOE's Division of Geothermal Energy is reviewed. This program is an industry-based effort to develop and apply the high-temperature instrumentation which is needed by the wireline logging industry to serve a rapidly expanding geothermal market. In order to satisfy critical existing needs, the near-term goal is to develop instrumentation for use at or above 275°C in pressures up to 48.3 MPa (7,000 psi) by the end of FY80. The long-term goal is for operation up to 350°C and 138 MPa (20,000 psi) by the end of FY82. To meet these goals, existing hardware will be upgraded and new components will be developed and evaluated in critically needed prototype tools such as the temperature, flow rate, and high-resolution downhole pressure sondes.

and Stoller, H. M. High Temperature Instrumentation for Geothermal Applications. SAND78-0668C. Albuquerque: Sandia Laboratories, March 1978. In Transactions of Geothermal Resources Council Annual Meeting (July 1978), vol 2. p 679.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities (~ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program being conducted by Sandia National Laboratories for the Department of Energy, Division of Geothermal Energy is an industry-based effort to develop and apply the high-temperature instrumentation needed to make geothermal borehole measurements. The near-term goal is to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi); subsequent goals are to extend the capabilities to 350°C and 138 MPa (20,000 psi). Working closely with geothermal producers, logging service companies are conducting R&D to correct technical deficiencies so the companies may adequately serve the growing geothermal market. The basic impediments they face involve special technologies which are not normally required in their trade and for which there are

4.4 COMPLEX CIRCUITS AND INSTRUMENTS, BIBLIOGRAPHY/ABSTRACTS

insufficient incentives for the companies to develop. These technologies are precisely those which are being developed by this program; components development activities are directed toward stimulating industries' own inventions and field applications of geothermal logging instruments having improved reliability, appropriate size, reasonable cost, and performance versatility which encompasses not only geothermal but conventional petroleum and hot, deep natural gas logging as well. Tools to be upgraded and/or developed include temperature, flow rate, high-resolution downhole pressure, caliper, and fracture mapping sondes.

_____, Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

White, K. R. Solid State 275°C Geothermal Temperature Tool. SAND78-1037. Albuquerque: Sandia Laboratories, July 1979.

Development of geothermal energy sources requires accurate and interpretable data describing the temperature and other characteristics of the fluid column in a geothermal borehole. Temperatures in these fluids are known to approach 275°C in many geothermal boreholes. This report discusses the advantages and disadvantages of two types of previously available instruments for measuring the borehole temperature profile: (1) analog temperature tools, which are primarily a sensor connected to a long logging cable, where the sensor's output is an analog of the temperature in the borehole, and (2) digital temperature tools, which consist of a sensor and an analog-to-digital converter connected to the logging cable.

5.0 TRANSDUCERS, ELECTRICAL AND MECHANICAL

5.1 SYNOPSIS

The sensors reviewed in this section include types that measure temperature, pressure, and fluid velocity. Sensors, the first functional stage of transducers, were considered in a study of geothermal transducer techniques⁹⁰ that was performed by the Measurement Analysis Corp. under subcontract to Sandia. The results of this study are presented in this sourcebook as are the names of representative manufacturers. According to the study, all three types of sensors need further development in order for them to operate reliably at 300°C. This conclusion can also be generalized to include most types of sensors not mentioned here. Although some of the temperature limitations are inherent in the sensor technique and hardware used, the limitations of the transducer's electronics must also be considered. The results described in the study apply to the sensor only and not to the entire system because a sensor with the associated system electronics may exhibit additional degraded performance at the temperatures given.

Tables 8 through 16 list various commercial types of temperature, pressure, flow, and fluid-density transducers that have demonstrated high-temperature performance.

For more complete information, the user should refer to other studies and manufacturers' literature and to sources listed in Subsection 5.3 Transducers, Electrical and Mechanical, Bibliography/Abstracts. References 2, 50, and 82 through 90, which are listed in the reference section of this sourcebook, contain information relevant to transducers.

Table 8

Performance Comparison of Geothermal Process Temperature Sensors^{2,90}

Performance Parameter	Resistance Temperature Detectors	Thermistors	Thermocouples	Bimetallic Thermometer	Thermochemical and Physical Melt Indicators	Bulb-Bourdon Tube, Thermal Fluid Filled
Temperature range	-260° to 900°C	-100° to 400°C	-270° to 2000°C	-60° to 450°C	38° to 1649°C labels (38° to 600°C)	0° to 340°C
Accuracy	0.01% (< 0.1°C)	1%	0.1%	1% (0.5% available)	1% (0.3% available)	1%
Sensitivity (signal level)	Good: +0.5%/°C (< 0.1 V/°C with bridge)	High: -5%/°C, -0.5% linearized (< 0.5 V/°C with bridge)	Very low, 1%/°C (< 0.02 mV/°C)	Depends on dial size, etc.	NA	0.5% of full scale
Linearity	Excellent: 1%	Poor: 10% to 20% Linearized: 2%	Poor: 10% to 25%	1%	NA	1%
Stability	Excellent	Poor	Excellent	Good	NA	Fair
Interchangeability	Excellent	Good	Poor	NA	NA	NA
Size	Medium: $\geq 1/8$ in. dia. by $> 1/4$ in. long	Very small	Small	1 to 5 in. dial, stem dia. $> 1/8$ in.	Typically $> 1/8$ in.	Very large
Time constant	0.2 to 10 s	0.05 to 10 s	0.1 to 4 s	10 to 30 s	1 s	Long
Cost	\$25 to \$1,000	\$2 to \$300	\$1 to \$50		\$.50 to \$7	High
Comments	Best overall	Narrow span (typically < 150°C)	Requires reference temperature junction	Can be configured w/maximum registering dial. Used in Kuster 'bomb' type high-temp. logging tool (span limited ~ 200°C)	None	Used in GRC 'bomb' type high-temp. logging tool (span limited ~ 150°C). Kuster also makes a system rated for 260°C.

Note: NA = data not available

Table 9

Manufacturers of Temperature Sensors^{2,90}

Manufacturer/Supplier	Sensor Types				
	Electrical Sensing			Passive Indicating	
	Resistance Temperature Detectors	Thermistors	Thermocouples	Maximum Indicating Sensors	Bimetallic Stem Thermometers
ARI Industries	X		X		
Barber-Coleman Co.	X	X	X		
Big Three Industries				X Thermochemical	
BLH Electronics	X		X		
Brooklin Thermometer				X Glass/bimetallic	
Celeasco Transducer Products	X	X	X		
C. S. Gordon Co.			X		
Fenwal Electronics		X			
Fischer & Porter Co.	X		X		
Foxboro Co.	X		X		
Hi-Cal Engineering	X		X		
ITT-Barton	X				
Markel Co.				X Thermochemical	
Matthey Bishop, Inc.	X				
Minco Products, Inc.	X		X		
Omega Engineering	X	X	X		
Rosemont, Inc.	X				
Semco, Inc.	X		X		
Spectro Systems, Inc.				X Metal pellets	
Sybron-Taylor Corp.	X		X	X Glass	X
Thermometrics, Inc.		X			
Victory Engineering		X			
W. Wahl Corp.	X	X	X	X Thermochemical and bimetallic dial	X
Weed Instrument Co.	X				
W. H. Keseler Co., Inc.				X Glass	
Weston Instruments					X
Yellow Springs Instruments	X	X			

5.1 SYNOPSIS

Table 10

Temperature Transducer Manufacturers⁹⁰

<u>Name</u>	<u>Location</u>	<u>Telephone No.</u>
ARi Industries	Franklin Park, IL	(312) 671-0511
Barber-Coleman	Rockford, IL	(815) 968-6833
Barton-ITT	Monterey Park, CA	(213) 961-2547
Big Three Industries	S. Plainfield, NJ	(201) 757-8300
BLH Electronics	Waltham, MA	(617) 890-6700
Brooklin Thermometer	Farmingdale, NY	(516) 694-7610
Celesco Transducer Products	Canoga Park, CA	(213) 884-6860
C. S. Gordon Co.	Richmond, IL	(815) 678-2211
Fenwal Electronics	Framingham, MA	(617) 872-8841
Fischer & Porter Co.	Warminster, PA	(215) 674-6000
Foxboro Co.	Foxboro, MA	(617) 543-8750
Hi-Cal Engineering	Santa Fe Springs, CA	(213) 698-7785
Markel Co.	Chicago, IL	(312) 826-1700
Matthey Bishop, Inc.	Malvern, PA	(215) 648-8000
Minco Products, Inc.	Minneapolis, MN	(612) 571-3121
Omega Engineering, Inc.	Stamford, CT	(203) 359-1660
Rosemont, Inc.	Minneapolis, MN	(612) 941-5560
Semco, Inc.	N. Hollywood, CA	(213) 982-1400
Spectro Systems, Inc.	Springfield, VA	(703) 321-9240
Sybron-Taylor Corp., Consumer Industrial Products Div.	Arden, NC	(704) 684-8111
Thermometrics, Inc.	Edison, NJ	(201) 287-2870
Victory Engineering	Springfield, NJ	(201) 379-5900
W. Wahl Corp.	Los Angeles, CA	(213) 641-6931
Weed Instrument Co.	Elgin, TX	(512) 285-3411
W. H. Keseler Company, Inc.	Westbury, NY	(516) 334-4063
Weston Instruments	Newark, NY	
Yellow Springs Instruments	Yellow Springs, OH	(513) 767-7241

5.1 SYNOPSIS

Table 11

Performance Comparison of Some Commercial Pressure Transducers^{2,90}

No.	Manufacturer and Model	Sensor Technique	Overall Accuracy % FS	Resolution % FS	Stability and Drift	Max. °F	Coefficient	Maximum Pressure Range (psia)	Size in.	Comments
1	Hewlett-Packard, 2811B	Diaphragm with oscillating quartz crystal	0.025%	Infinite (0.01 psi, typ.)	0.01%/yr	300	—	11,000	1-7/16 dia. by 40 long	Accepted standard for precision downhole oil/gas well testing; temp. correction to $\pm 1^\circ\text{C}$ recorded.
2	Mensor, Digital quartz manometer	Fused quartz helical bourdon tube w/optical sensor and electronic nulling	< 0.2%	0.0005%	0 at 3 mo (0.01%/yr)	122	0.0004%/°C	1,000	11 by 10 by 8-1/2	System temp. control/compensation to $\pm 0.2^\circ\text{C}$ to achieve performance quoted; also makes unit like No. 3 below.
3	Heise (Dresser), Digiquartz	C bourdon tube and servo-force balance	0.05%	0.005%	NA	125	Very small, 0.1% FS over range	10,000	4-3/8 by 6 by 16	Sperry-Sun sells for use with their "tube" pressure transmission system.
4	Paroscientific, Digiquartz	Bellows linked to vibrating quartz bar	0.1%	< 0.1%	0.1%/yr	225	0.004%/°F	5,000	1-3/20 dia. by 3-1/4 long	High-temp. at pressure (530°F at 10,000 psi) unit currently under joint development with SNL; will have high-temp. electronics.
5	Sundstrand Data Controls, Inc. (developmental)	Bellow linked via quartz structure w/force-balance and capacitor feedback	0.11%	0.004%	0.1%/yr (?)	176	NA	500	1-5/8 dia. by 2 long	Mfr. claims higher pressure (5K to 10K) unit is developable; basic sensor capable of higher temperature.
6	Setra Systems, 204/205	Diaphragm w/capacitor plate displacement	0.11%	< 0.1%	0.05%/yr (?)	250	0.004%/°F	10,000	1-3/4 dia. by 2 long	Basic sensor w/o integral electronics capable of much higher temperature.
7A	Heise (Dresser), #CHM16	C bourdon tube linked to dial and potentiometer	0.1%	0.01%	0.02%/yr	125	0	10,000	17-3/8 dia. by 3-1/4 long	16 in. by 660 dial readout, electrical output also provided; can operate up to 250°F w/external compensation.
7B	Mensor, 2792									
8	Robinson-Halpern, 144	Helical bourdon tube linked to differential transformer	0.15%	< 0.01%	NA	165	0.1%/°F	10,000	6 by 6 by 4-1/4	—
9	Bell & Howell, CEC-1000	Diaphragm w/thin-film strain gage (sputtered)	< 0.2%	< 0.05%	0.1%/yr	600+	0.005%/°F	10,000	1 dia. by 2-1/2 long	Mfr. claims higher accuracy and temp. performance available.
10	Bell & Howell, CEC-4-361	Diaphragm w/unbonded wire strain gage	0.25%	< 0.05%	0.5%/yr	700	0.1%/°F	5,000	1-1/4 dia. by 2-1/2 long	Fragile and slow temp. response time (mfr. feels thin film will replace).
11	Kaman Sciences, KP-1911	Diaphragm with eddy current variable impedance coil	1%	0.1%	NA	1000	0.1%/°F	5,000	5/8 dia. by 1-1/2 long	—
12	Sparton Southwest, 890 RT	C bourdon tube with wire potentiometer	1%	0.3%	NA	600+	0.1%/°F	10,000	1 dia. by 2-1/2 long	—
13	Celeasco, P2	Diaphragm w/variable reluctance transducer	1%	0.1%	0.5%/yr	250	0.2%/°F	10,000	1-1/4 dia. by 3-3/8 long	Mfr. has built high-temp. (600°F) unit w/derated accuracy (~ 1-1/2%).
14	Data Instruments, MPA 1000	Diaphragm w/bonded semiconductor strain gage	0.25%	< 0.05%	0.5%/yr	250	0.001%/°F	5,000	1-1/4 dia. by 2-1/2 long	—
15	Vernitech	C bourdon tube with film potentiometer	0.7%	0.05%	0.5%/yr	185	0.01%/°F	10,000	2-1/2 dia. by 2 long	—

Note: FS = full scale
SNL = Sandia National Laboratories

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Table 12

Pressure Transducer Manufacturers⁹⁰

<u>Name</u>	<u>Location</u>	<u>Telephone No.</u>
Barton-ITT	Monterey Park, CA	(213) 961-2547
Bell & Howell, CEC Division	Pasadena, CA	(213) 796-9381
BLH Electronics	Waltham, MA	(617) 890-6700
Bourns Inc./Instrumentation Division	Riverside, CA	(714) 781-5148
Celeco Transducer Products	Canoga Park, CA	(213) 884-6860
Cognition, Inc.	Mountain View, CA	(415) 969-8300
Data Instruments, Inc.	Lexington, MA	(617) 861-7450
Fischer & Porter Co.	Warminster, PA	(215) 674-6000
Foxboro Co.	Foxboro, MA	(617) 543-8750
Gulton-Servonic/Instrumentation Division	Costa Mesa, CA	(714) 642-2400
Heise, Industrial Valve and Instrument Division, Dresser Industries	New Town, CT	(203) 426-4406
Hewlett-Packard	Palo Alto, CA	(415) 856-1501
Kaman Sciences Corp.	Colorado Springs, CO	(303) 599-1500
Mensor Instruments	San Marcos, TX	(512) 392-6091
Paroscientific, Inc.	Redmond, WA	(206) 883-8700
Precise Sensors	Monrovia, CA	(213) 358-4578
Robinson-Halpern Co.	Plymouth Meeting, PA	(215) 825-9200
Rosemont, Inc.	Minneapolis, MN	(612) 941-5560
Schaevitz Engineering	Pennsauken, NJ	(609) 662-8000
Sensor-Metrics, Inc.	Van Nuys, CA	(213) 988-6076
Setra Systems, Inc.	Natick, MA	(617) 655-4645
Sparton Southwest, Inc.	Albuquerque, NM	(505) 898-1150
Sunstrand Data Controls, Inc.	Redmond, VA	(206) 885-3711
Sybron-Taylor Corp., Process Control Division	Rochester, NY	(716) 235-5000
Teledyne Taber	N. Tonawanda, NY	(716) 694-4000
Validyne Engineering Corp.	Northridge, CA	(213) 886-8488
Viatran Corp.	Grand Island, NY	(716) 773-5148
Vernitech	Deer Park, Long Island, NY	(516) 586-5100

Table 13

Performance Summary Comparison of Single-Phase Flowmeters^{2,90}

Type of Meter	Flow Range FPS	Accuracy % FS ^a	Resolution % FS ^a	Fluid State	Response Time seconds	Current Temp. Limit °F	Max. Pipe Size ^b Inline (spool) Insertion, in.	Pressure Drop psi	Sealing/ Abrasion Suscep- tibility	Dynamic Range	Potential for Downhole Geothermal Logging	Potential for Geothermal Process Plant	Comments
Acoustic travel travel time	0.02 to 100	< 1%	< 0.5%	Liquid	< 4	~ 500	12/120 (clamp-on)	No obstruction	Low, none for clamp-on	1,000:1	Good	Good to excellent	--
Acoustic Doppler	0.3 to 80	< 2%	< 1%	Liquid	< 4	~ 500	/36 (clamp-on)	No obstruction	None for clamp-on	500:1	Good to excellent	Fair to good	Can be designed to work in 2-4 flow; requires measurement or calibration for acoustic vel-C; only clamp-on type currently available.
Magnetic	1 to 30	1%	< 1%	Liquid	< 2	360	48/180	No obstruction	Low	~ 100:1	Fair to poor	Fair to good	Pressure limited to ~ 300 psi; requires nonconductive liner.
Fixed obstruction head, orifice or venturi	0.1 to 30, liquid; 10 to 300, vapor	~ 2%	< 1%	Liquid or vapor	< 2	> 750	> 48	0.5 to 40	High	< 4:1	Poor	Fair	--
Movable obstruction/variable orifice head	0.5 to 20	1% to 2%	~ 0.1%	Liquid or vapor	< 2	> 750	16/-	2 to 20	High	~ 100:1	Poor	Fair	Unidirectional only.
Pressure head, Pitot type	< 1 to > 30, liquid; > 250, vapor	~ 1% of value	~ 0.1%	Liquid or vapor		> 750	> 48	0.5 to 5	High	< 4:1	Fair to poor	Fair to good	--
Drag body	0.3 to 15	1%	~ 0.1%	Liquid	< 1	> 750	48	< 1	High	~ 10:1	Fair to poor	Fair	--
Turbine	0.5 to 50, liquid; 2 to 250, vapor	< 1%	< 0.1%	Liquid or vapor	< 1	> 750	14/48	< 5	High	10:1 100:1	Fair	Fair	--
Thermal anemometer	0.03 to 30, liquid; 10 to 250, vapor; (Np > 10 ⁴)	~ 1%	< 1%	Liquid or vapor	< 1	300	/any size	<< 1	High	> 100:1	Poor	Fair (film type only)	Temp. limit can be raised; fragile.
Vortex	1 to 20, liquid; 10 to 250, vapor	0.5%	< 0.1%	Liquid or vapor	< 1	< 750	48/108	< 6	High	> 100:1	Poor	Good to excellent	Unidirectional; subject to scaling.

^aFS = full scale^bDepends on Flow Range (see Column 2)

Table 14

Identified Manufacturers for Single-Phase Process Line Flowmeters^{2,90}

Manufacturer	Acoustic		Pressure Head							Thermal Anemometers
	Travel Time	Doppler	Magnetic	Fixed Obstruction	Pressure Probe	Drag Body	Variable Orifice	Turbine	Vortex	
Baird Controls		X								
Badger Meter, Inc.	X									
Barton-ITT								X		
Bennett Gervase, Inc.							X			
Brooks Instrument			X				X	X	X	
Controlotron Corp.	X									
Dieterich Standard Corp.					X					
Disa Electronics										X
Dupont Co., Instruments	X									
Eastech Incorporated									X	
Electronic Flow-Meters								X		
Engineering Measurements Co.								X		
Fisher & Porter Co.			X	X			X	X		
Flow-Dyne Engr., Inc.				X						
Flow Technology, Inc.								X		
Foxboro Co.			X	X		X		X	X	
Fox Valve Devel. Co., Inc.				X						
Hersey Products, Inc.		X								
J-Tech Associates									X	
Leeds & Northrop		X								
Mapco, Inc.	X									
Polysonics, Inc.		X								
Ramapo Instrument Corp., Inc.						X				
R. M. Nikkel Co.								X		
Sybron-Taylor Corp.			X							
Tech Tube Corp.				X						

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Table 15

Single-Phase Flow Transducer Manufacturers⁹⁰

<u>Name</u>	<u>Location</u>	<u>Telephone No.</u>
Badger Meter, Inc.	Tulsa, OK	(918) 584-4471
Baird Controls, Inc.	Naperville, IL	(312) 355-3040
Barton-ITT	Monterey Park, CA	(213) 961-2547
Bennett Gervase, Inc. (Gil-Flow Sensor)	Muskegan, MI	(616) 739-9421
Brooks Instrument (Emerson Electric)	Hatfield, PA	(215) 368-2000
Controlotron Corp.	Long Island, NY	(516) 249-4400
Dieterich Standard Corp. (Annubar Flow Sensor)	Boulder, CO	(303) 449-9000
Disa Electronics	Franklin Lakes, NJ	(201) 891-9460
Dupont Co., Instrument Products	Monrovia, CA	(213) 357-2111
Eastech Incorporated	S. Plainfield, NJ	(201) 561-1000
Electronic Flo-Meters, Inc.	Dallas, TX	(214) 349-1982
Engineering Measurement Co.	Boulder, CO	(303) 447-0550
Fischer & Porter Co.	Warminster, PA	(215) 674-6000
Flow Dyne Engineering, Inc.	Fort Worth, TX	(817) 732-2858
Flow Technology, Inc.	Phoenix, AR	(602) 268-8776
Foxboro Co.	Foxboro, MA	(617) 543-8750
Fox Valve Development Co., Inc.	E. Hanover, NH	(201) 887-7474
Hersey Products, Inc.	Spartanburg, SC	(803) 578-3800
J-Tech Associates	Cedar Rapids, IA	(319) 366-7511
Leeds & Northrop	North Wales, PA	(215) 643-2000
Mapco, Inc.	Tulsa, OK	(918) 584-4471
Polysonics, Inc. (Tech/Sonics)	Houston, TX	(713) 623-2134
Ramapo Instrument Corp., Inc.	Montville, NJ	(201) 263-8800
R. M. Nikkel Co.	Foster City, CA	(415) 573-0511
Sybron-Taylor Corp., Process Controls Div.	Rochester, NY	(716) 235-5000
Tech Tube Corp.	Houston, TX	(713) 623-0638

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Table 16

Fluid-Density Transducer Manufacturers ⁹⁰

<u>Name</u>	<u>Location</u>	<u>Telephone No.</u>
Agar Instrumentation, Inc.	Houston, TX	(713) 461-2427
Automation Products, Inc.	Houston, TX	(713) 869-1485
Barton-ITT	Monterey Park, CA	(213) 961-2547
Halliburton	Duncan, OK	(405) 251-3081
Micro-Motion, Inc.	Boulder, CO	(303) 499-6400
Ramsey Engineering Co., Texas Nuclear Div.	Austin, TX	(512) 836-0801

5.2 TRANSDUCERS

The following characteristics are taken from manufacturers' specifications. Due to program limitations, Sandia did not test these devices.

Manufacturer

William Wahl Corp.
Temp-Plate Division
12908 Panama Street
Los Angeles, CA 90066
(213) 822-6144

Miniature Temperature
Recorder Model 410

Size, inches: 3/16 diameter by 1/100 thick
Accuracy: $\pm 1\%$ from 43.3 to 260°C
Features: Indicator window turns black when exposed to
critical temperature; self-adhesive backing

Manufacturer

Panex Corp.
5860 Ranchester Drive
Houston, TX 77036
(713) 777-9141
Attn: Leroy Delatorre

High-Temperature/
High-Resolution
Capacitor-type
Pressure Gauge

Experimental gauge under development for well-logging
applications

Manufacturer

Geophysical Research Corp.
136 Mohawk Boulevard
Tulsa, OK 74106
(918) 583-7511
Attn: Calvin Vogt

5.2 TRANSDUCERS

High-Temperature
Capacitor-Type
Pressure Gauge

Experimental gauge under development for well-logging applications.

5.3 TRANSDUCERS, ELECTRICAL AND MECHANICAL, BIBLIOGRAPHY/ABSTRACTS

EerNisse, E. P. and McConnell, T. D. "Quartz Resonator Pressure Transducer for Geothermal Well Logging," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 209.

Sandia National Laboratories is developing a quartz resonator pressure transducer for geothermal well logging applications. The resulting pressure tool will be designed for use in wells at up to 275°C (527°F) and pressure up to 52 MPa (7,500 psi).

Heard, F. E. Upgrading the Acoustic Borehole Televiwer for Geothermal Fracture Mapping. SAND80-1279J. Albuquerque: Sandia National Laboratories, May 1980. In Transactions of the Geothermal Resources Council Annual Meeting (September 1980), vol 4. p 341.

The importance of fracture characterization in geothermal logging has long been recognized. The acoustic borehole televiwer is probably the single most useful tool for determining location, orientation, and characterization of fractures. However, since the televiwer was developed for low-temperature oil and gas exploration, it has not been capable of reliable operation at geothermal temperatures. This paper reviews the theory of operation of the acoustic televiwer, identifies the problems associated with its operation at both high and low temperatures, and reviews a program to upgrade the tool. Major results of the program have been (1) a high-temperature acoustic transducer, (2) an improved acoustic window, (3) more reliable electronics, and (4) the elimination of troublesome slip rings.

Koehler, D. R. Quartz Resonator Pressure Gauges: Temperature Performance. SAND81-0130. Albuquerque: Sandia National Laboratories, September 1981.

The force-frequency effect in quartz resonators has in the past been utilized as a transducer mechanism in various realizations and, in particular, successfully commercialized as a pressure transducer. More recently the need for a very precise (0.01 psi pressure uncertainty at 10,000 psi) pressure transducer to operate at high temperatures (275°-300°C) in geothermal environments has necessitated further development efforts directed to improve performance. The incorporation of the rotated X-cut into a pressure transducer, similar to the Hewlett-Packard design, represents one such development effort at Sandia National Laboratories. The present report characterizes the pressure-temperature performance of the AT- and rotated X-cut resonators and the Hewlett-Packard sensor where the experimental data in the pressure-temperature domain are available. Given a 10,000 psi pressure ambient, if temperature instabilities or inaccuracies are of the order of $\pm 0.05^\circ\text{C}$, there results associated pressure uncertainties of the order of ± 0.4 psi for any of these

5.3 TRANSDUCERS, ELECTRICAL AND MECHANICAL, BIBLIOGRAPHY/ABSTRACTS

designs. One concludes that cuts with reduced temperature coefficients for the force-frequency effect, or other resonator designs that minimize this temperature dependence, are therefore necessary to achieve the above-mentioned goal of 0.01 psi uncertainty. Development of a slotted-resonator design is just being started at Sandia with the goal of investigating whether the required fifty-fold improvement factor can be attained.

McConnell, T. D. Pressure Instrumentation for Geothermal Borehole Measurements. SAND80-1282C. Albuquerque: Sandia National Laboratories, May 1980. In Transactions of the Geothermal Resources Council Annual Meeting (September 1980), vol 4. p 365.

Accurate geothermal logging requires pressure measurements and resolutions down to 0.01 psi in environments of up to 275°C and 15,000 psi. This paper examines the characteristics of several basic types of pressure transducers and compares the characteristics to the logging requirements. Specific deficiencies are identified such as thermal stability and resolution limitations; R&D activities and results correcting these deficiencies are discussed.

Major, B. H. "Upgrading Mechanical Tools Survey Clocks," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 231.

Development of the earth's high-temperature geo-energy resources is dependent on sufficient well logging to obtain the characterization of essential physical and chemical properties of the well. Methods for obtaining this information are limited at present by technical deficiencies in that the logging tools in current use were developed for the oil and gas industry. Such instruments rarely encounter temperatures above 150°C, whereas gas wells frequently reach 180°C, and some geothermal wells reach 350°C. The Amerada-type subsurface recording gauges have been the staple instruments of the oil and gas industry for several years. The same instruments are currently in use by the growing geothermal industry. However, at elevated temperatures, significant reductions in reliability and tool life have been reported. A primary concern of the Amerada-type instrument is its survey clock, which often fails in well logging at high temperature. Much test time and labor is lost as a result of a single failure of the clock mechanism. Currently, increased reliability is sought by either restricting the log to three hours or by utilizing two gauges connected in tandem to ensure at least one successful log. However, because of the large number of Amerada-type instruments currently in use by industry, it would be best to upgrade them for high-temperature reliability. This should be accomplished with a minimum of redesign and rework.

5.3 TRANSDUCERS, ELECTRICAL AND MECHANICAL, BIBLIOGRAPHY/ABSTRACTS

and Witten, C. L. Upgrading Amerada-Type Survey Clocks for High-Temperature Geothermal Service. SAND80-0046. Albuquerque: Sandia National Laboratories, June 1980. In Transactions of the Geothermal Resources Council Annual Meeting (September 1980), vol 4. p 361.

The Amerada-type subsurface recording gauges have been used by the oil and gas industry for many years. These mechanical logging instruments are currently used by the growing geothermal industry. As the gauges were designed for service in low-temperature oil and gas wells, a significant number of failures are occurring at elevated geothermal temperatures. The spring-driven mechanical survey clocks appear to be the primary cause of the failures. The clock mechanisms tend to stop or lock up when exposed to temperatures as high as 300°C. This paper summarizes a project that was undertaken to upgrade the survey clocks to 300°C capability. The major problems causing clock failure were identified and corrected by straightforward design and modifications together with special lubrication of the moving parts. Several clocks so modified performed reliably, both during laboratory oven tests and during field tests that were performed in actual geothermal wells at temperatures up to 330°C.

Veneruso, A. F. and McConnell, T. D. "Pressure Measurements in Low Permeability Formations," Proceedings for the Third Invitational Well Testing Symposium, March 26-28, 1980. Berkeley: Lawrence Berkeley Laboratory, 1980.

This paper examines the performance requirements and identifies candidate hardware implementations for pressure instrumentation that is needed to provide well test data in low-permeability formations. Low permeability values are typically defined to be less than 1 μ D and are usually encountered in hard rock formations, such as granite, that are of interest in hot dry rock geothermal, deep exploration drilling, and fluid waste disposal. Groundwater flow in these "tight" formations has been shown to be dominated by flow-through fractures rather than through the formation's intrinsic permeability. In these cases, we cannot use Darcy's law or the usual dimensionless coefficients to estimate the expected scale factors and dynamic responses necessary to properly select and set up the wellbore pressure instrument. This paper shows that the expected instrument responses can be estimated using some recent work by Wang, Narashimhan, and Witherspoon. This paper further describes the minimum electronic capability that the downhole pressure instrument must have in order to provide the required measurement resolution, dynamic range, and transient response. Three specific hardware implementations are presented based on the following transducers: a quartz resonator, a capacitance gauge, and a resistance strain gauge.

, Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

5.3 TRANSDUCERS, ELECTRICAL AND MECHANICAL, BIBLIOGRAPHY/ABSTRACTS

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

_____. "Geothermal Production Logging Tools -- Components, Prototype Field Testing and Commercialization." Paper given at the Society of Petroleum Engineers 55th Annual Technical Conference and Exhibition, September 21-24, 1980.

This paper demonstrates that commercial components and prototype designs are now available to build geothermal production logging tools for operation to 275°C. Prototype temperature, pressure, and flow tools have been built and successfully field tested to 275°C. The design, fabrication, and field operation of these instruments are presented along with a list of commercial sources for the components and circuits employed.

Wonn, J. D. "New Acoustic Sensor Materials for a Geothermal Borehole Televierer," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 219.

The borehole televierer (BHTV) is a well logging tool originally developed and used for fracture mapping and characterization in petroleum wells. A geothermal workshop report issued in 1975 identified the need for upgrading the environmental tolerance of the BHTV to permit logging under near-term DOE goal conditions of 275°C (527°F), 7,000 psi, and in the corrosive geothermal fluid. Presently, commercial versions of the BHTV have a maximum advertised temperature rating of 150°C (302°F) and are not designed for exposure to highly corrosive fluids.

6.0 CABLES AND CABLEHEADS

6.1 SYNOPSIS

Cables and cableheads have been grouped into one section because they collectively provide the electromechanical coupling of the uphole control and data acquisition electronics to the downhole sensing and electronics package. The mechanical integrity of the cable-head-sonde system is essential to preventing excessive downtime due to sonde flooding through the head-sonde interface or, even worse, lost cable in the hole. Thus, the choice of which metals to use is highly dependent on the hostile environment the metals will be subjected to. For highly corrosive, hot geothermal wells, the high-grade stainless steel products and other noncorrosive alloys should be used.⁴⁸

In addition, electrical insulators in cables must be resistant to the chemical environments in geothermal wells. The material used must retain its electrical resistivity and strength under these conditions. Also, conductors within the cable are commonly protected with corrosion-resistant coatings such as nickel. The severe temperatures, pressures, and chemicals encountered in geothermal wells call for cost and performance tradeoffs to achieve an economical, reliable system.

Metal-sheathed cables are under development that promise longer life at higher temperatures than conventional, contrahelically armor-wired, polymer-insulated wireline cables. Although mechanically stiffer, metal-sheathed cables have the advantage that they isolate the electrical insulator from the corrosive fluid environment. Hence, there is a greater choice of insulation materials; even porous materials, such as magnesium oxide powder, may be used (see Halpen Engineering data, Section 6.2 Cables).

Experimental fibre optic cables have been disappointing in their high-temperature wellbore performance. Besides being extremely difficult to manufacture, they exhibit high signal loss under wellbore pressure due to microbending of the fibres'

6.1 SYNOPSIS

polymeric coating or buffer. Also, quartz fibres rapidly fail by stress cracking in the presence of even minute amounts of water.⁹⁰

References 2, 36, 48, and 91 through 99, which are listed in the reference section of this sourcebook, contain information relevant to cables and cableheads.

6.2 CABLES

The following characteristics are taken from manufacturers' specifications. No tests were performed on these products by Sandia because of program limitations.

Manufacturer

Insulated Wire, Inc.
McArthur Airport, P.O. Box 577
Ronkonkoma, NY 11779
(516) 981-7424

Distributor

Lenert Company
Box 2184, 1420 Hutchins
Houston, TX 77001
(713) 225-1465

One Conductor, PTFE Insulated

Features: Shielded and jacketed cable; conductor and shield are silver-plated OFHC copper, manufactured for 200°C operation.

Conductor Sizes: 18 to 30 AWG

Capacitance: 34 to 142 pF/ft

Voltage Ratings: 750, 1,800, 3,000 VDC

Weight: 4.2 to 14.5 lb/m

Two Conductors, PTFE Insulated

Features: Shielded and jacketed cable; conductor and shield are silver-plated OFHC copper, manufactured for 200°C operation.

Conductor Sizes: 18 to 30 AWG

Voltage Ratings: 750, 1,800, 3,000 VDC

Weight: 6.3 to 29.5 lb/m

Three Conductors, PTFE Insulated

Features: Shielded and jacketed cable; conductor and shield are silver-plated OFHC copper, manufactured for 200°C operation.

Conductor Sizes: 18 to 30 AWG

Voltage Ratings: 750, 1,800, 3,000 VDC

Weight: 7.4 to 38.2 lb/m

6.2 CABLES

Four Conductors, PTFE Insulated

Features: Shielded and jacketed cable; conductor and shield are silver-plated OFHC copper, manufactured for 200°C operation.

Conductor Sizes: 18 to 30 AWG

Voltage Ratings: 750, 1,800, 3,000 VDC

Weight: 9.2 to 47.8 lb/m

Seven Conductors, PTFE Insulated

Features: Shielded and jacketed cable; conductor and shield are silver-plated OFHC copper, manufactured for 200°C operation.

Conductor Sizes: 22 to 30 AWG

Voltage Ratings: 750, 1,800, 3,000 VDC

Weight: 11.8 to 41.3 lb/m

Note: Insulated Wire, Inc., also makes their cable conductors in nickel-plated copper for 260°C operation. Free samples are furnished upon request.

Manufacturer

The Rochester Corp.
P.O. Box 312
Culpeper, VA 22701
(703) 825-2111

Stock Cable Line

Conductor Sizes: 14 to 24 AWG

Conductor Material: Copper

Number of Conductors: 1 to 7

Breaking Strength: 1,000 to 17,000 lb

Insulators: Tefzel®, FEP, PFA, and TFE Teflons®

Armors: GIPS, MP-35, 304SS

*Registered trade name of E. I. Du Pont de Nemours and Co.

6.2 CABLES

Manufacturer

U.S. Steel Corp., Oilwell Division
2001 North Lamar Street
Dallas, TX 75202
(214) 670-1511
Attn: Earl R. Karges, Representative

1K18XD
One Conductor,
TFE Insulated

Features: Covered with galvanized steel
armor for 288° to 316°C use
Conductor Size: 20 AWG
DC Conductor Resistance: 10.3 Ω /Mft
Capacitance: 44.7 pF/ft
Voltage Rating: 1,000 Vrms
Weight (Air): 64 lb/Mft
Breaking Load: 3,500 lb

1L18RD, 1G20RD,
1N22RD, 1N32ND
One Conductor,
PFA Insulated

Features: Covered with galvanized steel
armor for 260° to 288°C use
Conductor Sizes: 14, 18, 20 AWG
DC Conductor Resistance: 2.52 to 10.3 Ω /Mft
Capacitance: 44.4 to 57.2 pF/ft
Voltage Rating: 1,000 Vrms
Weight (Air): 64 to 194 lb/Mft
Breaking Load: 3,600 to 10,300 lb

7H42RD
Seven Conductors,
PFA Insulated

Features: Covered with galvanized steel armor for
260° to 288°C use
Conductor Size: 20 AWG
Capacitance: 50.5 pF/ft
Voltage Rating: 1,000 Vrms
Weight (Air): 320 lb/Mft
Breaking Load: 16,800 lb

6.2 CABLES

7J46RF
Seven Conductors,
PFA Insulated

Features: Covered with galvanized steel armor for
232° to 260°C use
Conductor Size: 20 AWG
DC Conductor Resistance: 11.1 Ω /Mft
Capacitance: 57.4 pF/ft
Voltage Rating: 1,000 Vrms
Weight (Air): 324 lb/Mft
Breaking Load: 17,000 lb

Manufacturer

Vector Cable
555 Industrial Road
Sugar Land, TX 77478
(713) 494-9196
Attn: Cliff Wagoner, Representative

1-20TFE
One Conductor,
TFE Insulated

Features: Covered with a 10 x 16 MP-35 armor for
316°C use. (See subsection Cables, Armor for
specifications for MP-35.)
Conductor Size: 20 AWG
DC Conductor Resistance: 11.5 Ω /Kft maximum
Insulation Resistance: 1,500 M Ω /Kft-min
Capacitance: 45 pF/ft
Voltage Rating: 600 Vrms
Weight (Air): 89 lb/Kft

7-42 PFA
Seven Conductors,
PFA and TFE Insulated

Features: Covered with 18 x 18 GIPS armor for 288°C use
Conductor Size: 20 AWG
DC Conductor Resistance: 11.0 Ω /Kft maximum
Insulation Resistance: 1,000 M Ω /Kft-min
Capacitance: 65 pF/ft
Voltage Rating: 600 Vrms
Weight (Air): 325 lb/Kft

6.2 CABLES

Ten Conductor PFA

Features: Double GIPS armor; one 50-ohm coax and nine 19-AWG conductors insulated with PFA for 277°C use
DC Conductor Resistance: 20 AWG--10.4 Ω /Kft; 19 AWG--7.9 Ω /Kft
Insulation Resistance: 1,000 M Ω /Kft at 20°C
Voltage Ratings: Coax--1,000 Vrms; 19-AWG conductor--600 Vrms
Weight (Air): 584 lb/Kft

Eleven Conductor FEP

Features: 24 x 24 GIPS armor cable; 1 modified RG-179 coax and 10 24-AWG conductors insulated with FEP Teflon® rated at 232°C
DC Conductor Resistance, Maximum: 28 AWG--80 Ω /Kft; 24 AWG--26 Ω /Kft; braid--9.4 Ω /Kft
Insulation Resistance: 500 M Ω /Kft
Voltage Rating: 250 Vrms
Weight (Air): 220 lb/Kft

Manufacturer

Custom Cable Co.
5310 Glenmont Drive
Houston, TX 77081
(713) 666-6301

Custom-Built Cables

Manufactured to specifications of wire content, insulation, jacket, binding, shielding, armoring, and other characteristics, depending on application

Manufacturer

Halpen Engineering, Inc.
1051 Clinton St.
Buffalo, NY 14206
(716) 856-3185
Attn: Arthur Halpenny, President

6.2 CABLES

Metal-Sheathed Insulated Cable

Features: One or two conductors; mineral insulation;
covered with a stainless steel 304L sheath

Note: Halpen is also producing a single-conductor cable
for 350°C use for Sandia.

Manufacturer

LaBarge, Inc.
LaBarge Wire and Cable Division
2851 Alton Avenue
Irvine, CA 92705
(714) 549-0300

Custom-Built Cables

Manufactured for use in environments with chemical,
polymer, or insulation problems

6.2.1 CABLES, ARMORS

The following characteristics are taken from W. E. Garne of The Rochester Corp.

Galvanized Improved
Flow Steel (GIPS)

Tensile Strength: 270,000 psi
Cost, \$/lb (1979): .50
Resistivity: 20.1 $\mu\Omega/\text{cm}$
H₂S Resistance: Poor
Chloride Resistance: Fair

MP-35

Tensile Strength: 290,000 psi
Cost, \$/lb (1979): 50.00
Resistivity: 101 $\mu\Omega/\text{cm}$
H₂S Resistance: Excellent
Chloride Resistance: Excellent

304SS

Tensile Strength: 280,000 psi
Cost, \$/lb (1979): 2.50
Resistivity: 72 $\mu\Omega/\text{cm}$
H₂S Resistance: Fair
Chloride Resistance: Variable

6.2.2 CABLES, CONDUCTORS

For cost efficiency and corrosion protection, silver- or nickel-coated, stranded, copper electrical conductors rated to 275°C are recommended.

6.2.3 CABLES, FILLER COMPOUNDS AND BINDERS

Insulation materials such as Teflon® PFA and Teflon® TFE are often used, as are polyimide tape, glass tape, and glass twine. TFE comes in different forms, such as tape, braid, and matrix filler. TFE appears suitable for use up to 315°C, while PFA is good to about 260°C. Unfortunately, TFE must be sintered in place and, unlike PFA, is not extrudable.

6.2.4 CABLES, ELECTRICAL INSULATION

Tefzel®

Melting Point: 270°C
Dielectric Constant: 2.6
Dissipation Factor at 1 MHz: 0.005
Cost, \$/lb (1979): 10.00
Performance: Good deformation resistance at 500°F,
excellent chemical resistance, good processibility

Teflon® FEP

Melting Point: 275°C
Dielectric Constant: 2.1
Dissipation Factor at 1 MHz: 0.0007
Cost, \$/lb (1979): 7.50
Performance: Poor deformation resistance at 500°F,
excellent chemical resistance, good processibility

Teflon® PFA

Melting Point: 300°C
Dielectric Constant: 2.1
Dissipation Factor at 1 MHz: 0.0004
Cost, \$/lb (1979): 15.00
Performance: Good deformation resistance at 500°F,
excellent chemical resistance, good processibility

Teflon® TFE

Melting Point: 327°C
Dielectric Constant: 2.1
Dissipation Factor at 1 MHz: 0.0002
Cost, \$/lb (1979): 9.00
Performance: Fair deformation resistance at 500°F,
excellent chemical resistivity, needs special equipment
for processing

6.2.5 CABLES, CABLE TESTING FACILITIES

The following information is taken from L. C. Rose of Aerospace Research Corp.

Manufacturer

Aerospace Research Corp.
5450 Jae Valley Road, S.E.
Roanoke, VA 24014
(703) 342-2961

The test system is intended for testing multi- or monoconductor cables in a hostile environment. A short segment, approximately 3 feet of the cable, can be tested at a number of different combinations of pressure, temperature, and tension while immersed in fluid. Several corrosive fluids can be used in this system including hydrogen sulfide.

The following information is taken from W. Kerr of Wayne Kerr and Associates, Inc.

Manufacturer

Wayne Kerr and Associates, Inc.
10503 Rockley Rd, Suite 107
Houston, TX 77099
(713) 495-9740

This program can test cable samples in high-temperature, high-pressure environments and at tension loads to simulate downhole geothermal wellbore conditions. The electrical characteristics measured are DC resistance, DC insulation resistance, capacitance, impedance, TDR, and attenuation.

6.2.5 CABLES, CABLE TESTING FACILITIES

The following information is taken from P. T. Gibson of Tension Member Technology.

Manufacturer

Tension Member Technology
15161 Golden West Circle
Westminster, CA 92683
(714) 898-5641
Attn: Philip T. Gibson, Representative

The company performs a number of tensile tests on cables, including bending fatigue tests and tension fatigue tests.

6.3 CABLEHEADS

The following information was supplied by Sandia.

Manufacturer

Gearhart-Owen Industries, Inc.

1100 Everman Rd., Box 1936

Fort Worth, TX 76101

(817) 293-1300

This company manufactures high-temperature, high-pressure, corrosion-resistant, custom-made cableheads.

6.4 CABLES AND CABLEHEADS, BIBLIOGRAPHY/ABSTRACTS

Coquat, J. A. Cablehead Assembly for Hostile Environment Well Logging. SAND79-1396A. Albuquerque: Sandia Laboratories, July 1979. In Transactions of the Geothermal Resources Council Annual Meeting (September 1979), vol 3. p 133.

One of the most challenging problems in geothermal logging is to develop a cablehead that interconnects the wireline cable to the downhole instrument so that the system will successfully operate in a geothermal well. A high-temperature (275°C), corrosion-resistant logging cablehead for use with single-conductor cables is described. The head has demonstrated the ability to solve electrical communications problems (leakage resistance) generally associated with the cable-to-sonde interface while logging hostile environment geothermal wells.

. "Monoconductor Cables and Cableheads," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 79.

A significant problem in the overall task of high-temperature instrumentation for geothermal logging is a reliable, low-noise interconnect system between the up-hole (cool) electronics and the downhole (hot) electronics. A project to develop such a single-conductor-based interconnect system is discussed including successes to date, on-going work, and plans for the near future. The project is logically divided into two major areas: the cablehead and the cable itself. A high-temperature (275°C), corrosion-resistant head developed with Gearhart Owen Industries, Inc. (GOI) has demonstrated the ability to solve electrical communications problems (leakage resistance) generally associated with the cable-to-sonde interface while logging hostile environment geothermal wells. A commercial Teflon® TFE insulated cable has been purchased from the Vector Cable Company and has been successfully used to 300°C in a geothermal field test and laboratory tested to its rated specification of 315°C for 9 hours. A 2-year program to develop and test a long-term, high-temperature, and high-reliability cable based on nonconventional logging cable technologies has begun. A two-fold goal has been determined: (1) to fabricate a production logging cable for continuous application for at least 1 year and (2) to produce a highly reliable logging cable capable of extended repeated use.

Rose, L. C. "Hostile Environment Test System for Logging Cables," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 101.

6.4 CABLES AND CABLEHEADS, BIBLIOGRAPHY/ABSTRACTS

A hostile environment test system for well logging cables has been developed by Aerospace Research Corporation. The system is capable of subjecting a short section (approximately 3 ft) of either multi- or single-conductor cable to various combinations of pressure, temperature, and tension while submerged in various fluids such as water, sodium chloride solution, or the liquid portion of drilling mud. A system for using a hydrogen sulfide solution has been installed and tested at ambient temperature and pressure.

Veneruso, A. F., Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

7.0 PACKAGE MATERIALS AND COMPONENTS

7.1 ADHESIVES

7.1.1 SYNOPSIS

The construction of downhole instrumentation requires the use of high-temperature adhesives. These are materials that are commonly used in microcircuit packaging and in mechanical applications. For microcircuit applications, conductive and nonconductive adhesives are available. Some adhesives are specially made to withstand geothermal temperatures. Others perform well at these temperatures even though they are not so rated.

References 31, 36, and 100, which are listed in the reference section of this sourcebook, contain information relevant to adhesives.

7.1.2 ADHESIVES

The following characteristics are taken from manufacturers' specifications. Because of program limitations, Sandia did not test these materials.

<u>Manufacturer</u>	
	Ablestik Adhesive Co. 833 West 182nd Street Gardena, CA 90248 (213) 532-9341
ABLEBOND 70-1	Conductive epoxy with a 25-m Ω change at 300°C with long-term use
ABLEBOND 70-2	Nonconductive adhesive tested for 200 hours at 300°C with a 5-kg force applied
ABLEBOND 71-1	Silver-filled conductive epoxy for continuous use at 350°C and intermittent use at 500°C Volume Resistivity: 0.0001 Ω -cm at 350°C
ABLEFILM 506	Glass fabric, flexible epoxy for bonding materials with mismatched coefficients of expansion; for continuous usage at 150°C Volume Resistivity: 8.7×10^{13} Ω /cm
ABLEFILM ECF 506	Same usage as 506; silver-filled, conductive epoxy; for continuous operation at 150°C Electrical Resistance: 0.005 Ω
ABLEBOND 71-2	High-temperature epoxy

7.1.2 ADHESIVES

Manufacturer

E. I. Du Pont de Nemours and Co.

Electro Chemicals Department

1007 Market Street

Wilmington, DE 19898

(302) 774-1000

8254

Thick-film sealing glass for 275°C use

Manufacturer

Epoxy Technology, Inc.

14 Fortune Drive

P.O. Box 567

Billerica, MA 01821

(617) 667-3805

Epotek H20E

Silver conductive adhesive used for high-temperature applications

Manufacturer

Hysol Division

Dexter Corp.

15051 East Don Julian Road

Industry, CA 91746

(213) 968-6511

EA6

Adhesive used in temperatures up to 275°C

7.2 ELASTOMERS

7.2.1 SYNOPSIS

Elastomeric materials are widely used as seals in geothermal applications, such as in O-rings, cableheads, wire insulators, and packers. Elastomers are usually easy to install and tolerant of irregular surfaces. The main disadvantages of elastomers are due primarily to their reversible loss of mechanical properties and to their permanent degrading under the influence of the high temperatures and adverse chemical constituents in the downhole environment. Mechanical properties, such as the tensile strength modulus, change markedly with temperatures exceeding 200°C. The consequence of these problems is that the seal may mechanically set, that is, lose elasticity, and no longer function as a seal. Table 17 gives data on the deterioration of mechanical and thermomechanical properties of some uncoated elastomers that were exposed to brine at 275°C and 5,000 psi for 24 hours.

Table 18 summarizes the steam resistance of various fluoroelastomers and hydrocarbon-type elastomers at 260°C. Throughout the testing, steam pressures were autogeneous. The exposure time was 100 hours, which does not include the 14-hour heat-up and cool-down time periods for the test vessel. Both peroxide- and bisphenol-cured fluoroelastomers were evaluated. It is clear that the peroxide-cured formulations were superior with respect to steam resistance. However, the best stability was exhibited by an EPDM (ethylene propylene diene monomer) formulation made by L'Garde.¹⁰⁵ This formulation was also cured using peroxides.

The thermochemical stability and sealing capability of several commercial O-rings were determined in order to select stable O-rings for use in geothermal logging tool cableheads. Thermochemical stability was determined by measuring the changes that occurred in the mechanical properties and glass transition temperature of the O-ring before and after exposure to geothermal brine at 275°C and 4,900 psi for a period of 24 hours. The brine was obtained from the Salton Sea basin Mesa Well No. 6-1 and contained no hydrogen sulfide. The sealing capability was determined using a two-part fixture that simulated the cablehead of a geothermal logging sonde. The results obtained are summarized in Table 19. In this table, the elastomers are listed in order of their observed stability in brine. It is evident

7.2.1 SYNOPSIS

from these data that a good correlation exists between sealing capability and the extent of thermochemical degradation that occurred.

References 2, 48, and 101 through 111, which are listed in the reference section of this sourcebook, contain information relevant to elastomers.

7.2.2 ELASTOMERS LISTING

Table 17

Degradation of Uncoated Elastomers¹⁰²

Elastomer Designation	Elastomer Type	Change in Tensile Strength %	Change in Elongation, %	Change in Tg* °C	Seal Efficiency Test
Kalrez 1050	Perfluoroelastomer	-24	-6	0	Pass
3074		No test	No test	0	Pass
E692-75	Ethylene propylene diene monomer (EPDM)	-70	+23	0	Pass
E540-80	Ethylene propylene copolymer (EPR)	-62	+30	+2	Pass
V752-7	Fluoroelastomer (peroxide cured)	-52	-68	+2	Pass
V709-90	Fluoroelastomer (bisphenol cured)	Too brittle to obtain tensile properties		+12	Fail
V747-75	Fluoroelastomer (bisphenol cured)	Too brittle to obtain tensile properties		> +140	Fail
N552-90	Nitrile rubber	Too brittle to obtain tensile properties		+69	Fail
S609-70	Silicone	Too brittle to obtain tensile properties		> +100	Fail
L449-70	Fluorosilicone	Too brittle to obtain tensile properties		> +100	Fail

Note: All of these elastomers were tested in geothermal brine for 24 hours at 275°C and 5,000 psi.

*

Tg = glass transition temperature

Table 18
Steam Stability of Elastomers¹⁰³

Elastomer Designation	Elastomer Type	Source	Control		Aged		Comparison		Comments
			Tensile Str., psi	Elong. %	Tensile Str., psi	Elong. %	Δ Tensile Str., %	Δ Elong. %	
267 EPDM	Hydrocarbon	L'Garde	1,395	70.2	1,261	60.2	-9	-14.9	--
266 EPDM/FKM blend	Hydrocarbon/fluoroelastomer	L'Garde	1,596	111	1,410	71.2	-11	-36.7	--
291 Propylene/PTFE	Hydrocarbon/fluoroelastomer	L'Garde	2,321	170	1,799	87.4	-22	-48	--
255 FKM	Fluoroelastomer	L'Garde	2,312	121	1,376	135	-40	+11.6	Peroxide cure
GH FKM	Fluoroelastomer	Du Pont formula	1,301	172	364	45	-72	-74	Peroxide cure
E60C FKM	Fluoroelastomer	Du Pont formula	864	145	Broke	Broke	Broke	Broke	Bisphenol cure
914-80	Fluoroelastomer	BOP seal manufacturer	882	148	Broke	Broke	Broke	Broke	Bisphenol cure

Table 19

Summary of Thermochemical Stability
and Sealing Tests Performed on Elastomers
by Industry^{103,105,106,107,108,109,110}

Source of Samples	Elastomer Designation	Elastomer Type	Test Description	Test Conditions	Comments	References
L'Garde	267 EPDM	Hydrocarbon	Tensile property change	Synthetic brine for 22 h at 260°C	Data on durometer (hardness) and extrusion also available	L'Garde literature
L'Garde	255 FKM	Fluoroelastomer	Tensile property change	Synthetic brine for 22 h at 260°C	Data on durometer (hardness) and extrusion also available	L'Garde literature
L'Garde	266 EPDM/FKM	Hydrocarbon/fluoroelastomer	Tensile property change	Synthetic brine for 22 h at 260°C	Data on durometer (hardness) and extrusion also available	L'Garde literature
L'Garde	291 Propylene-TFE	Hydrocarbon/fluoroelastomer	Tensile property change	Synthetic brine for 22 h at 260°C	Data on durometer (hardness) and extrusion also available	L'Garde literature
L'Garde	255 FKM	Fluoroelastomer	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
Parker	V709-90 FKM	Fluoroelastomer (bisphenol cured)	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
Parker	V747-75 FKM	Fluoroelastomer (bisphenol cured)	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
L'Garde	267 EPDM	Hydrocarbon	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
Parker	E692-75 EPDM	Hydrocarbon	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature

Table 19 (Continued)

Summary of Thermochemical Stability
and Sealing Tests Performed on Elastomers
by Industry^{103,105,106,107,108,109,110}

Source of Samples	Elastomer Designation	Elastomer Type	Test Description	Test Conditions	Comments	References
L'Garde	266 EPDM/FKM	Hydrocarbon/fluoroelastomer	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
L'Garde	291 Propylene-TFE	Hydrocarbon/fluoroelastomer	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
Du Pont	Kalrez 3074	Perfluoroelastomer	Simulated seal tests	Synthetic brine at 260°C under differential pressure between 2,100 and 4,100 psi	Tested to a maximum of 22 h or until failure	L'Garde literature
Utex	RD-215	Hydrocarbon	Tensile property change	Geothermal brine for 100 h at 500°F and 1,200 psi	Data on durometer (hardness) and volume change also available	Utex literature
Utex	RD-216	Hydrocarbon	Tensile property change	Geothermal brine for 100 h at 500°F and 1,200 psi	Data on durometer (hardness) and volume change also available	Utex literature
Utex	RD-217	Hydrocarbon	Tensile property change	Geothermal brine for 100 h at 500°F and 1,200 psi	Data on durometer (hardness) and volume change also available	Utex literature
Du Pont	Viton 10	Fluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Viton 10K	Fluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Viton 10G	Fluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Kalrez 3050	Perfluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature

Table 19 (Concluded)

Summary of Thermochemical Stability
and Sealing Tests Performed on Elastomers
by Industry^{103,105,106,107,108,109,110}

Source of Samples	Elastomer Designation	Elastomer Type	Test Description	Test Conditions	Comments	References
Du Pont	Kalrez 3065	Perfluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Asahi	Atlas 150H	Fluoroelastomer	Tensile property change	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Viton 10	Fluoroelastomer	Crosslink densities	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Viton 10K	Fluoroelastomer	Crosslink densities	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Kalrez 3050	Perfluoroelastomer	Crosslink densities	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Du Pont	Kalrez 3065	Perfluoroelastomer	Crosslink densities	3 synthetic solutions for periods up to 60 h at 252°C	Data taken at 260°C	JPL literature
Unknown	HAC ketone fluoroelastomer (purified)	Fluoroelastomer	Hydrolytic stability	Water at 235°C for 45 h	Visual results	Hughes literature
Unknown	Polyphenylene sulfide	Aromatic sulfide	Hydrolytic stability	Water at 275°C for 72 h	Visual results	Hughes literature
Du Pont	Kalrez	Perfluoroelastomer	Hydrolytic stability	Water at 275°C for 72 h	Visual results	Hughes literature
Union Carbide	Carborane-siloxane rubber	Siloxane	Hydrolytic stability	Water at 275°C for 72 h	Visual results	Hughes literature
Union Carbide	HAC amide fluoroelastomer, solid	Fluoroelastomer	Hydrolytic stability	Water at 275°C for 72 h	Visual results	Hughes literature
Union Carbide	Silicone rubber, 50 Shore	Silicone	Hydrolytic stability	Water at 235°C and 400 psi	Visual results	Hughes literature

Note: JPL = Jet Propulsion Laboratory

7.3 LUBRICANTS

7.3.1 SYNOPSIS

Lubricants used for downhole tools are available in various forms, such as grease, oil, and dry film. Like other materials used in geothermal instrumentation, lubricants show a degradation in their properties at high temperatures. Also, care must be taken in their use because, at high temperatures, they may react in unexpected ways with the environment and with other materials used in the tools.

Tables 20 and 21 list the approximate maximum operational temperatures of the lubricants as determined by testing or manufacturers' specifications. These limiting temperatures are approximate and may be more accurately determined with further testing.

References 50 and 112 through 114, which are listed in the reference section of this sourcebook, contain information relevant to lubricants.

Table 20

High-Temperature Lubricants

Product	Manufacturer	Lubricant Type	Maximum Temperature, °C	Comments
AF-419C	Gulf	Silicone grease	290	Poor load capability and does not mix well with additives.
APG-90	Lubriplate	Petroleum grease	200	--
High Temp	Lubriplate	Petroleum grease	260	--
LS-1850	Graphite Products	Anti-seize compound	260	Possible use to 430°C; oil base with MoS ₂ .
Molykote 321R	Dow Corning	Dry film	430	Coefficient of friction (0.1).
Molykote 710G	Dow Corning	Silicone oil and 5% graphite	260	Possible use to 370°C with decreased load capability.
SS-21	Oil Center Research	Dry film	290	Poor load capability; Teflon® base.
Lubribond A	Electrofilm	Solid film	--	--
Santovac 5	Kurt J. Lesker	Synthetic fluid	275	No decomposition.
Santovac 6	Kurt J. Lesker	Synthetic fluid	275	--
Krytox 143AD	Du Pont	Fluorinated oil	275	Sandia tested.
Jet Oil II	Mobil	Synthetic fluid	275	Sandia tested.
44 Grease	Dow Corning	Silicone grease	200	Poor load capability and does not mix well with additives.
Brayco 812	Bray Oil	Lubricating fluid	275	Good for ball bearings.
Brayco 815Z	Bray Oil	Synthetic fluid	260	--
1200-2	Lubriplate	Petroleum grease	230	--
930-AA	Lubriplate	Petroleum grease	200	--
550	Dow Corning	Silicone fluid	315	--

7.3.2 LUBRICANTS LISTING

Table 21

Lubricant Manufacturer/Distributor List

<u>Name</u>	<u>Location</u>	<u>Telephone</u>
Bray Oil Company	1925 N. Marianna Ave. El Monte, CA 90032	(213) 575-1212
E. I. Du Pont de Nemours and Co.	Petroleum Chemicals Div. 1007 Market St. Wilmington, DE 19898	(302) 774-1000
Electrofilm, Inc.	7116 Laurel Canyon Blvd. North Hollywood, CA 91605 (address not verified)	(213) 875-1000 (not verified)
Kurt J. Lesker Company for Dow Corning and Santovac Products	5635 Horning Road Pittsburgh, PA 15236	(800) 245-1656 (412) 655-9500

7.4 METALS

7.4.1 SYNOPSIS

The corrosion of metals in the downhole environment is a major problem that is caused by ions such as chloride, hydrogen, and sulfide. Whether they are present singly or together, these ions are very corrosive. In choosing a metal to be used in a geothermal well, tradeoffs between price and performance should be considered, and, in most cases, it is advisable to consult an expert.

This section contains a partial list of commercial alloys that can be used successfully in certain severe environments. These alloys and the environments in which they were tested were selected by the Radian Corp., which also performed the testing for the DOE.⁴⁸ Chloride was the primary corrosive tested. However, hydrogen as a corrosive requires special attention because hydrogen loading can occur to metals downhole. When hydrogen-loaded metals are returned to surface conditions of pressure and temperature, the metals may exhibit stress corrosion cracking at a later time.

It is important to note that the tested alloys are only a sample of prospective candidates; there are many others having potential geothermal use that are not included in this list.

References 2, 48, and 115, which are listed in the reference section of this sourcebook, contain information relevant to metals.

7.4.2 METALS

The following information was taken from D. W. DeBerry, P. F. Ellis, and C. C. Thomas of Radian Corp.⁴⁸

Radian Corp. information shows that the following materials met the company's geothermal corrosion performance criteria satisfactorily:

- Inconel 625
- Hastelloy C-276
- Allegheny Ludlum 6X, 29-4, 20-4-2
- TZM
- AISI 310
- TiCode 12
- Ti-0.2Pd

The tests were performed in 155,000-ppm chloride at 232°C. To meet Radian's criteria, the uniform corrosion was required to be less than 12 µm/yr. Performance was observed for the following characteristics: resistance to pitting, crevice corrosion, stress corrosion cracking, intergranular corrosion, and good weld resistance.

The test results indicate that TiCode 12 may be used up to 300°C; Ti-0.2Pd, to 310°C; and AISI, from 310° to 430°C in a chloride environment.

Chemicals other than chloride may be present in geothermal wells. For example, H₂S₄ and other corrosives are particular to each drilling site, and these substances may cause problems other than those tested for under the conditions discussed previously.

7.5 INSULATORS, DEWARS, AND COOLERS

References 2, 51, and 116 through 119, which are listed in the reference section of this sourcebook, contain information relevant to insulators.

Woodward-Clyde Consultants⁵¹ investigated the following insulator materials:

<u>Type</u>	<u>k at 315°C, W/m°C</u>
Asbestos Fibers	0.073 to 0.095
Calcium Silicate	0.073 to 0.088
Diatomaceous Silica	0.068 to 0.118
Cellular Glass	0.109
Glass Fibers	0.059
Mineral Fiber	0.065 to 0.097
Expanded Perlite	0.077
Silica/Alumina Fibers	0.051 to 0.087

The following characteristics are taken from L. B. Thompson of Vacuum Barrier Corp.

<u>Manufacturer</u>	Vacuum Barrier Corp. 5 Barton Lane Woburn, MA 01801 (617) 933-3570 Attn: Lewis B. Thompson, Representative
Insulating Package	Insulation: Evacuated aluminum layers with glass fiber
Cylindrical Dewar	spacers
Flask	External Temperature, Maximum: 600°F Length: Up to 12 feet Diameter: 1/2 inch to 5 inches

7.5 INSULATORS, DEWARS, AND COOLERS

The following characteristics are taken from manufacturers' specifications. Sandia performed no tests on these devices because of program limitations.

Manufacturer

Southland Cryogenics
1821 North Broadway
Carrollton, TX 75006
Attn: Steve Brothman
(214) 242-7551

Dewars

Product: High-temperature dewars built to cost requirements
Sizes: Standard sizes in stock
Temperature Range: Typically up to 260°C

Manufacturer

Borg-Warner Thermoelectrics
Borg-Warner Corp.
3570 North Avondale Avenue
Chicago, IL 60618
(312) 588-5120

950 Series

Thermoelectric Cooler.

Temperature Range: Up to 200°C; for operation below 150°C, contact Borg-Warner engineers.

Maximum Temperature Differential, ΔT : 150°C at $Q_c = 0$

Maximum Heat Pumped by Module, Q_c : 5 to 51 watts for
 $\Delta T = 0$

Maximum Current: 6 amps

Maximum Voltage: 1.5 to 15 volts

Nominal Resistance: 0.15 to 1.20 Ω

Size, inches: 0.38 x 0.38 x 0.15 to 1.20 x 1.20 x 0.15

7.6 PACKAGE MATERIALS AND COMPONENTS, BIBLIOGRAPHY/ABSTRACTS

Arnold, C., Coquat, J. A., and Baker, L. E. Evaluation of Seals for a Geothermal Logging Tool. SAND78-0423C. Albuquerque: Sandia Laboratories, March 1978. In Transactions of the Geothermal Resources Council Annual Meeting (July 1978), vol 2. p 17.

The seal efficiency and environmental resistance of various elastomeric O-rings and a metallic joint that were immersed in geothermal brine and in water at elevated temperatures and pressures were determined. A leakproof seal was maintained with a stainless steel Conoseal-joint for 100 hours in water and 24 hours in geothermal brine at 275°C and 34.5 MPa (5,000 psi). Only very small quantities of moisture penetrated O-ring seals made from Kalrez, a perfluoroelastomer, ethylene/propylene rubber, and a Parylene C-coated Viton O-ring. All other rubber seals failed catastrophically.

_____ and Coquat, J. A. "Degradation of Elastomers in Geothermal Brine at Elevated Temperatures and Pressures," Abstracts of Papers of the American Chemical Society, vol 1979. American Chemical Society, April 1979. p 132.

Elastomeric seals are required in logging tools for geothermal sondes to protect the internal electronic circuitry from moisture as the tool is lowered into a borehole. The stability of five generic classes of elastomers toward geothermal brine at 275°C/5,000 psig for 24 hours was determined in order to identify those elastomers which could be used for such purposes. The five classes of rubbers evaluated were perfluoro-elastomers, fluoroelastomers, hydrocarbons, nitriles, and silicones. Stability was determined by visual examination and by measuring the changes that occurred in the tensile properties of the rubber as a result of exposure. In addition, changes in the glass transition temperature of the elastomer were determined. The highest stability was noted for a perfluoroelastomer that contained both asbestos and carbon black fillers. Even so, this elastomer suffered a 24% loss in its tensile strength as a result of exposure. The least stable elastomer was the silicone; this elastomer underwent hydrolytic reversion with complete loss of physical integrity. The nitrile rubber also exhibited rather poor stability; the glass transition temperature of this elastomer increased markedly, and the rubber became so brittle that tensile properties could not be determined. Intermediate stability was noted for the fluoroelastomers and hydrocarbon types. The observed property changes can be rationalized by postulating structural changes on a molecular level which involve both chain scission and cross-linking. Infrared analysis of the pyrolysis products of the fluoroelastomer suggests that dehydrofluorination of the backbone is also one of the degradation reactions.

DeLafosse, P. H., Tibbitts, G. A., and Green, S. J. Evaluation of High Temperature Lubricants for Downhole Motors in Geothermal Applications. SAND79-7085C. Albuquerque: Sandia Laboratories, December 1979. In Transactions of the Geothermal Resources Council Annual Meeting (September 1979), vol 3. p 149.

7.6 PACKAGE MATERIALS AND COMPONENTS, BIBLIOGRAPHY/ABSTRACTS

A bearing-seal package is being developed for use with downhole motors and turbines for drilling geothermal wells. The lubricant will be sealed in the bearing section, which will allow the bearings to operate directly in the lubricant. The development of the bearing-seal package involves the improvement of high-temperature seals and lubricants. Candidate high-temperature lubricants were tested in the high-temperature lubricant tester under elevated temperatures and pressures. A list of candidate high-temperature lubricants, a description of the lubricant test program, and the lubricant test results are presented.

Douglass, D. L. "Factors Influencing the Selection of Corrosion-Resistant Alloys for High-Temperature, Downhole Applications," High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. eds A. F. Veneruso, R. S. Simpson, and C. Arnold. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980. p 143.

The environment existing downhole for both petroleum and geothermal systems is highly corrosive and generally contains oxygen, sulfur, and chlorine, among other species. These three elements are particularly corrosive, either singly or in combination. Basically, the problem is designing against the troublesome effect of corrosive agents. The most important consideration in selecting an alloy for a particular application is to define the environment in terms of gas or liquid composition, temperature, and pressure. This task may be difficult, if not impossible, to do. However, if we assume that the environment can be determined, there are numerous factors that determine which alloy might survive for the desired lifetime. For example, if the system is liquid rather than gaseous, careful thought must be given to localized corrosion as well as to general corrosion. Such phenomena as pitting, waterline corrosion, stress corrosion cracking (SCC), intergranular corrosion, etc., must be considered. These phenomena might mitigate against using an alloy whose general corrosion rate is more than adequate. Likewise, gaseous systems require different alloys, depending on the gas composition. Each case must be considered individually; it is dangerous to make generalizations. This paper will discuss some of the factors involved in the various forms of corrosion and show the rationale involved in selecting the right material for a given application.

Hendrickson, R. R. and Winzenried, R. W. "Development and Testing of Seals and Lubricants for Geothermal Rock Bits" (SAND number not available). Albuquerque: Sandia National Laboratories. In Transactions of the Geothermal Resources Council Annual Meeting (September 1980), vol 4. p 293.

The paper describes the successful development and evaluation of seals and lubricants for journal-type rock bits for use in geothermal reservoirs. Elastomeric compounds which sealed effectively to temperatures of 288°C (550°F) and mechanical seals for reservoir temperatures over 288°C (550°F)

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are presented. Newly developed lubricants which meet both the compatibility and lubrication requirements are described. Several seals and lubricants are recommended for high-temperature laboratory drilling and field geothermal drilling tests in roller-cone bits.

Itoh, T., Miyairi, M., and Kimura, K. "The High-Temperature Well Logging System for Geothermal Well." Paper presented at a meeting of the Society of Professional Well Log Analysts (SWLA). Available from Central Technical Laboratory, Japan Petroleum Exploration Co. Ltd., 3190-1 Hane-Musashima, Hamura-machi, Nishitama, 190-11 Tokyo, Japan.

Veneruso, A. F., Simpson, R. S., and Arnold, C., eds. High Temperature Electronics and Instrumentation Seminar Proceedings, December 3-4, 1979. SAND80-0834C. Albuquerque: Sandia National Laboratories, May 1980.

See abstract in Section 1.5 Passive Devices, Bibliography/Abstracts.

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Tom Anderson
IMCO Services
P.O. Box 22605
Houston, Texas 77027

Alvaro Arbelaez
R. F. Smith Corporation
1145 Amelia Drive
Long Beach, California 90807

Frank Barrier
Tri-State Oil Tool Industries, Inc.
P.O. Box 5757
Bossier City, Louisiana 71111

William R. Berry
Occidental Exploration and Production
Company
5000 Stockdale Highway
Bakersfield, California 93309

W. E. Bingman
Shell Oil Company
Two Shell Plaza
P.O. Box 2099
Houston, Texas 77001

Bruce A. Blackman
Halliburton Services
Duncan, Oklahoma 73533

J. Bresee
U.S. Department of Energy
Division of Geothermal Energy
Mail Station 3344
12th and Penn, N.W.
Federal Building
Washington, D.C. 20461

R. A. Broding
Amoco Production Company
Research Center
Box 591
Tulsa, Oklahoma 74102

Jan Brown
Schlumberger Doll Research
P.O. Box 307
Ridgefield, Connecticut 06877

John Byrne
Chevron Oil Field Research Company
P.O. Box 446
La Habra, California 90631

Roger L. Cadenhead
Gearhart Industries
P.O. Box 1936
Fort Worth, Texas 76101

Tom Campbell
Campbell Consulting
9542 Russell Street
La Habra, California 90631

C. Carwile
U.S. Department of Energy
Division of Geothermal Energy
Mail Station 3344
12th and Penn, N.W.
Federal Building
Washington, D.C. 20461

Stan Coombs
Pacific Resources Management
727 W. Seventh Street, Suite 937
Los Angeles, California 90017

Joseph De Lorenzo
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

D. C. Dening
General Electric Company
Electronics Laboratory EP 3109
P.O. Box 4840
Syracuse, New York 13221

Bert Dennis
P.O. Box 1663, Mail Stop 980
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

L. Diamond
Dyna-Drill
P.O. Box C-10576
Irvine, California 92713

Carl Dodge
Halliburton Company
Welex Division
P.O. Box 42800
Houston, Texas 77042

Ing. Bernardo Dominguez
Comision Federal de Electricidad de
Mexico
P.O. Box 248
Calexico, California 92231

R. A. Downing
Institute of Geological Sciences
Maclean Building
Wallingford, Oxfordshire, England

Dick Dunlap
Aminoil USA, Inc.
P.O. Box 11279
Santa Rosa, California 95406

Lyman Edwards
Dresser Industries, Inc.
601 Jefferson/Dresser Tower
P.O. Box 6504
Houston, Texas 77005

Errol EerNisse
Quartex, Incorporated
1020 West Atherton Drive
Building C-202
Salt Lake City, Utah 84107

O. Eknayan
Institute for Solid-State Electronics
Department of Electrical Engineering
Texas A&M University
College Station, Texas 77843

Peter F. Ellis
Radian Corporation
8500 Shoal Creek Boulevard
Austin, Texas 78758

Paul Engelder
Scientific Drilling
18011 Mitchell South
Irvine, California 92714

G. C. Ferrara
ENEL/Geothermal Research Center
Piazza B. Sassoferato, 14
I-56100 Pisa, ITALY

J. Fontenot
NL Petroleum Services
P.O. Box 1473
Houston, Texas 77001

Professor M. Friedman
Dept. of Geology
Texas A&M University
College Station, Texas 77843

Howard Gordon
Teledata Research
20 Hurricane Street
Marina Del Rey, California 90291

W. Gravley
Mobil Research and Development
Corporation
Field Research Laboratory
P.O. Box 900
Dallas, Texas 75221

André Guimard
Flopetrol
B.P. 592
77005 Melun Cedex, France

Ralph Haenel
Niedersächsisches Landesamt
für Bodenforshung
Stilleweg 2
D-3000 Hannover, Germany

M. Hanif
Teleco
2081 South Main Street
Middletown, Connecticut 06457

Alan M. Hirshberg
Schlumberger Well Services
5000 Gulf Freeway
Houston, Texas 77023

Bob Hoard
Phillips Petroleum Company
71-C PRC
Bartlesville, Oklahoma 74004

Gus Hoehn
Mobil R&D Corporation
3600 Duncanville Road
Dallas, Texas 75211

Earl Hoff
Phillips Petroleum Company
Geothermal Operations Headquarters
655 East 4500 South
Salt Lake City, Utah 84107

Toshinobu Itoh
Japan Petroleum Exploration Co. Ltd.
Technical Laboratory
3190-1 Hane-Musashima, Hamura-machi
Nishitama, Tokyo
190-11 Japan

Ray Jurgens
Jet Propulsion Laboratory
Mail Stop 238-420
4800 Oak Grove Drive
Pasadena, California 91109

W. Scott Keys
U.S. Geological Survey
Building 25, MS-403
Denver Federal Building
Denver, Colorado 80225

J. Kingsolver
Smith Tool Company
P.O. Box C-19511
Irvine, California 92713

E. D. Knight
Custom Electronic, Inc.
Browne Street
Oneonta, New York 13820

Dr. George A. Kolstad
Mail Stop J309
U.S. Department of Energy
Office of Basic Energy Science
Washington, DC 20585

David Kress
Analog Devices, Inc.
804 Woburn Street
Willington, Massachusetts 01801

Jack Kusters
Hewlett-Packard
5301 Stevens Creek Boulevard
Santa Clara, California 95050

Michael D. Lamers
Measurement Analysis Corporation
23852 Madison Street
Torrance, California 90505

J. W. Langford
Dresser Industries, Inc.
P.O. Box 24647
Dallas, Texas 75224

Ray LaSala RA-244
U.S. Department of Energy
Division of Geothermal Energy
MS 3344 Federal Building
12th & Pennsylvania, NW
Washington, DC 20461

Donald R. Lindsay
Occidental Geothermal, Inc.
5000 Stockdale Highway
Bakersfield, California 93309

Bob McElwrath
United Wireline
1603 S. Union Avenue
Bakersfield, California 93309

Cliff McFarland
U.S. Department of Energy
Division of Geothermal Energy
MS 3344 Federal Building
12th & Pennsylvania, NW
Washington, DC 20461

Bob Macy
Sunoco Energy Development Co.
12700 Park Central Place
Suite 1500
Box 9
Dallas, Texas 78251

H. E. Mallory
Loffland Brothers Company
P.O. Box 2847
Tulsa, Oklahoma 74101

Bob Mayer
Gearhart Owen Wireline Services
P.O. Box 1483
Dallas, Texas 75221

Joseph F. Petko
Dresser Atlas, Suite 3079
P.O. Box 6504
Houston, Texas 77005

G. Polk
NL Petroleum Services
City Centre Building, Suite 365W
6400 Uptown Boulevard
Albuquerque, New Mexico 87110

D. E. Pyle
Union Geothermal Division
Union Oil Company of California
Union Oil Center
Los Angeles, California 90017

Paul Quinlivan
Geothermal Energy Nz Ltd.
P.O. Box 37231
Auckland 1, New Zealand

Louis J. Ragonese
Electronic Laboratory
General Electric Company
Electronics Park, Bldg. 3
Syracuse, New York 13221

Leonard Raymond
Department of Electrical Engineering
University of Arizona
Tucson, Arizona 85721

Richard Reich
Teledyne Philbrick
Allied Drive at Route 128
Dedham, Massachusetts 02026

Gordon Richardson
Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts 02140

J. C. Rowley
Los Alamos National Laboratory
Mail Stop 570
Los Alamos, New Mexico 87545

W. D. Rumbaugh
Otis
P.O. Box 34380
Dallas, Texas 75243

Howard Schaible
Rochester Corporation
5725 Hartsdale Drive
Houston, Texas 77035

Ron Schroeder
The Berkeley Group
P.O. Box 777
Berkeley, California 94701

Dick Simpson
University of Houston
Department of Electrical Engineering
Houston, Texas 77004

Paul Sinclair
Schlumberger Well Services
5000 Gulf Freeway
Houston, Texas 77023

Al Skellie
Schlumberger Well Services
5000 Gulf Freeway
Houston, Texas 77023

Dick Slater
Micropac Industries, Inc.
905 East Walnut Street
Garland, Texas 75040

D. Smith
Halliburton
Drawer 1413
Duncan, Oklahoma 73533

Dan Stalmack
Chevron Research
Box 411
La Habra, California 90631

Peter Syms
Ministry of Works and Development
Wairakei
Private Bag
TAUPO
New Zealand, Taupo 48221

Clay Tatom
Burr-Brown, Inc.
International Industrial Park
P.O. Box 11400
Tucson, Arizona 85734

Bernard Thierree
Geoservices
7, rue Newton
93150 Le Blanc-Mesnil, France

Pierre Ungemach
Commission of the European Communities
Directorate General Research, Science &
Education
200, rue de la Loi
B-1049 Brussels, Belgium

Sam Varnado
NL Petroleum Services
P.O. Box 1473
Houston, Texas 77001

Joe Vincent, Director
Research and Development
Smith Tool
P.O. Box C-19511
Irvine, California 92713

Calvin O. Vogt
Geophysical Research Corp.
136 Mohawk Boulevard
Tulsa, Oklahoma 74106

T. Warren
Amoco Production Company
Research Center
P.O. Box 591
Tulsa, Oklahoma 74102

Bill Wilson
Dresser Atlas
P.O. Box 1407
Houston, Texas 77001

Joe Zemanek
Mobil R&D Corporation
3600 Duncanville Road
Dallas, Texas 75211

2145 P. A. Bonn
2145 D. W. Palmer
2151 R. C. Heckman
2151 B. L. Draper
4000 T. F. Foster
4200 G. Yonas
4300 R. L. Peurifoy, Jr.
4400 A. W. Snyder
4500 E. H. Beckner
4700 J. H. Scott

4710 G. E. Brandvold
4720 D. G. Schueler
4740 R. K. Traeger
4741 J. R. Kelsey (40)
4743 H. C. Hardee
4746 B. Granoff
4747 P. J. Hommert
4748 B. E. Bader
4750 V. L. Dugan
4751 J. R. Tillerson
4754 A. F. Veneruso
4756 H. M. Dodd
5133 R. J. Chaffin
5500 O. E. Jones
5811 C. Arnold
8266 E. A. Aas
3141 L. J. Erickson (5)
3151 W. L. Garner (3)