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Report on the Sandia-NEDO Geothermal Drilling R&D Workshop May 26-27, 1999

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Report on the Sandia-NEDO Geothermal Drilling R&D Workshop

May 26-27, 1999

Wyndham Garden Hotel Albuquerque, New Mexico

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Abstract

Representatives from the United States and Japan convened a workshop to exchange information regarding their respective research and development (R&D) programs on geothermal drilling. Sandia National Laboratories and Japan's New Energy and Industrial Technology Development Organization (NEDO) co-sponsored this event. Technical and executive presentations made during the workshop provided an overview of the diverse geothermal drilling research projects and facilities supported by NEDO and by Sandia. In addition, workshop participants discussed potential opportunities for enhanced Sandia/NEDO communication and possibilities for future cooperative R&D efforts. This report documents the workshop agenda and participants, and summarizes the content of the presentations and discussions.

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I. Executive Summary

The Japanese and U. S. governments actively fund separate national research and development (R&D) programs in geothermal drilling technology. In Japan, this work is carried out primarily under the auspices of the New Energy and Industrial Technology Development Organization (NEDO). Much of the Japanese program is conducted or managed for NEDO by the Geothermal Energy Research & Development Co., Inc. (GERD). In the United States, the Department of Energy (DOE) Office of Geothermal Technologies funds R&D by various government, university, and corporate entities. A significant portion of the U.S investment is devoted to work that is accomplished by, or under the direction of, Sandia National Laboratories. In many instances, the same technical problems have been investigated independently in both the United States and Japan, resulting in potentially substantial duplication of effort. Given the limited funding for geothermal drilling research in both countries, such duplication is not prudent. Instead, communication and cooperation in geothermal drilling R&D should be fostered to mutually serve U.S. and Japanese interests.

During a Sandia-sponsored data gathering trip to Japan in June 1996 by Dr. Jim COMBS of Geo Hills Associates and Dr. Sabodh K. Garg of Maxwell Technologies, Inc., NEDO personnel expressed an interest in the possibility of developing joint geothermal drilling R&D projects with the DOE and Sandia. As a result, Sandia submitted annual operating plans to DOE for FY97 and FY98 that recommended funding for a new initiative to identify possible geothermal drilling technology areas where collaboration would benefit both the U.S. and Japan. However, DOE funding limitations in both years precluded any work on this initiative.

Masami HYODO of GERD visited Sandia in February 1999, and discussed the subject of joint drilling R&D with several members of Sandia's Geothermal Research Department. Afterwards, HYODO contacted NEDO regarding the potential for convening a DOE/NEDO workshop on this subject. With the combined primary efforts of Mike PRAIRIE (Sandia) and Yasukuni OKUBO (NEDO), the Sandia/NEDO Geothermal Drilling R&D Workshop was arranged. Sandia subsequently hosted the Workshop on May 26 and 27, 1999, in Albuquerque, New Mexico.

The intent of the workshop was to provide an exchange of information between NEDO and Sandia (see Appendix A for the Agenda) regarding their respective geothermal drilling R&D programs. Presentations made during the workshop were expected to provide an overview of the ongoing geothermal drilling research projects and test facilities supported by Sandia and by NEDO. In addition, the workshop was designed to explore opportunities for informal Sandia/NEDO communications and possibilities for future cooperative geothermal drilling research and development projects; however, by prior understanding no formal commitments were to be made during the workshop.

The workshop included experienced drilling personnel and administrators. A total of seven (7) Japanese and sixteen (16) U.S. individuals participated. A roster of the participants with their contact information is presented in Appendix B. The Japanese delegation included representatives from NEDO, GERD, and Tohoku University. The manager of Sandia's Geothermal Research Department, Sandia technical staff and technicians, a scientist from Brookhaven National Laboratory, and two (2) Sandia consultants represented the U.S.

The Workshop Moderator, Jim COMBS, outlined the purpose, format, and potential outcome of the workshop at the beginning of the first day. Takashi IMANAGA, Director General of NEDO's Geothermal Energy Center, expanded on these topics during a luncheon presentation on the second day. IMANAGA also described administrative details of the funding mechanisms and management for NEDO R&D projects. These details resemble those for DOE-sponsored R&D.

The workshop agenda (see Appendix A) deliberately intermingled Japanese and U.S. presentations. Copies of all viewgraphs and other presentation materials were supplied to each participant.

Opening remarks were made by Takashi IMANAGA, who noted that the interim goal for Japanese geothermal development is to triple the current generating capacity of 500 MW by 2010. Next, Sam VARNADO, the Director of Energy and Critical Infrastructure at Sandia, delivered a welcoming address that focused on the renewable energy program under which geothermal drilling R&D is done at Sandia.

As a prelude to ensuing detailed technical presentations, the next two talks outlined the overall geothermal research programs in, respectively, the U.S. (at Sandia) and Japan. Mike PRAIRIE summarized the Sandia program, briefly introducing the multiple conventional and advanced drilling projects that would be described in later presentations. Yasukuni OKUBO of NEDO then addressed the workshop regarding the status of geothermal development and the role of advanced drilling technology in Japan. He noted that most of the NEDO geothermal drilling research was directed toward deep-seated reservoirs; *i.e.*, reservoirs at depths greater than 2,000 meters. During a discussion session and break following these two overview presentations, the workshop participants noted many similarities between the NEDO and Sandia geothermal drilling R&D programs.

After the break, the presentations focused on specific technical topics. Chip MANSURE and George STALLER covered Sandia's projects on lost-circulation technology, with considerable input during the discussion by the primary field technician, Gary WHITLOW. These projects involve the development of an array of drill-rig instrumentation for circulation detection, a Circulation Monitoring System (CMS), a drillable straddle packer, and advanced materials for lost-circulation treatment. Next, Seiji SAITO of Tohoku University gave a detailed report on the drilling, logging, testing, and completion of two deep, high-temperature wells at the Kakkonda Geothermal Project in northern Honshu.

Following informal technical exchanges during lunch and a formal discussion period moderated by Jim COMBS, Jack WISE opened the afternoon session with a presentation on Sandia's hard-rock drill bit technology program. He described the approach and benefits of Sandia's continuing efforts, dating from the late 1970s, to support bit manufacturers and geothermal operators by developing and testing technology for polycrystalline diamond compact (PDC) cutters and drag bits suitable for hard-rock drilling.

Masami HYODO and Haruya NAKATA, both from GERD, authored the next NEDO presentation, which described the development of drilling and production technologies for deep geothermal resources. HYODO gave the presentation. NEDO's Drilling Technology Program is developing durable, heat-resistant rollercone bits, drilling muds, cement materials, high-temperature/low-speed downhole motors, and a high-temperature MWD (Measurement While

Drilling) system for wells producing geothermal fluids from deep reservoirs. The NEDO Production Technology Program is developing a pressure/temperature/spinner/density (PTSD) logging system, a downhole fluid sampling and chemical monitoring system, a PT monitoring system, a scale monitoring and prevention system, and tracer technology. Most of these drilling and production technologies are also a part of the overall geothermal drilling R&D program at Sandia.

Next, Toshifumi SUGAMA of Brookhaven National Laboratory reviewed ongoing work to develop acid-resistant, high-temperature cements suitable for applications involving CO₂-laden brines.

Allan SATTLER of Sandia then reported on the status of Geothermal Drilling Organization (GDO) projects. Founded in 1982, the GDO is a joint DOE/industry organization that develops and funds near-term technology projects for reducing geothermal drilling and well-maintenance costs. These projects address a wide variety of needs. SATTLER discussed recently completed work on a borehole televIEWer, a retrievable whipstock, rotating head rubbers, and a valve-changing tool. He also discussed ongoing projects dealing with lost circulation, foam cement integrity assessments, insulated drill pipe, percussive mud hammers, deformed casing remediation, steering tools, casing diagnostic instrumentation, and elastomeric casing protectors.

John FINGER described Sandia's slimhole drilling research in the final presentation of the first day. The objective of the Sandia Slimhole Program is to reduce exploration costs, especially up front, by drilling less expensive boreholes to locate and characterize geothermal reservoirs. FINGER indicated that the three components of the Slimhole Program include in-house and contract analysis of slimhole data, cost-shared drilling projects, and the compilation of a *Slimhole Handbook* for the geothermal community.

Technical discussions continued on a person-to-person basis at a Sandia-hosted dinner on the first day of the workshop and at breakfast the following morning. Jim COMBS started the second day of the workshop with a group review of presentations made during the previous afternoon.

In the first formal presentation of the second day, Doug DRUMHELLER discussed Sandia's work on wireless telemetry in a presentation that he co-authored with Steve KNUDSEN. Upcoming work in the acoustic telemetry program area includes field tests of a line-shaft pump alignment system, field testing of a geothermal MWD tool in 2001, telemetry and imaging support for the DWD program, and improvements in passive listening devices for core drilling. Considerable discussion followed this presentation with comparisons being made between acoustic telemetry and mud-pulse data transmission.

Haruya NAKATA and Masami HYODO of GERD prepared the final NEDO technical presentation, which described the development of a high-temperature MWD system and drilling support systems for geothermal wells. NAKATA delivered the talk. This R&D project is progressing consistent with the initial proposal. In particular, all of the MWD system's components have been completed through the prototype stage (by the project team of GERD, Akishima Laboratories and Mitsui Zosen) and field tested. The system components are now being refined and improved for further field testing in wells of opportunity.

Randy NORMANN discussed Sandia's development of high-temperature electronics for geothermal applications in a presentation that he co-authored with Joseph HENFLING. NORMANN noted that Sandia plans to test a HT (high temperature), non-heat-shielded data logger during July or August, 1999, in a geothermal well. Following the presentation, the workshop participants compared Sandia's accomplishments with the NEDO HT MWD system, and discussed the need to share information and insights on fiber optic cables.

In the last formal presentation of the workshop, Mike PRAIRIE described Sandia's Advanced Drilling Technology Program, which features the development of a Diagnostics-While-Drilling (DWD) system. The challenge facing this Program is to support the achievement of DOE strategic goals by reducing the drilling and completion costs of geothermal wells through revolutionary developments in technology. Specific objectives of Sandia's work are to reduce overall drilling costs by at least 25%, and to commercialize a revolutionary DWD system that integrates downhole and surface data. The ultimate desire is to achieve linear cost versus depth for deep wells. The DWD project is a new initiative that is scheduled to run for 6 years with a total funding level, shared by DOE and industry, of \$60 million. In his conclusion, PRAIRIE indicated that the Advanced Drilling Program will crosscut many existing Sandia drilling R&D programs, including acoustic telemetry, high-temperature instrumentation, advanced rig instrumentation, and drill-bit development.

In order to sustain the communication, interactive momentum, and enthusiasm that had been established by the workshop participants, Jim COMBS organized a working lunch for the group to permit the development of a set of "action items." These "action items" would consist of topics of mutual interest presented during the workshop and identified by the group as being important to both the NEDO and Sandia geothermal drilling R&D efforts. To follow up on the workshop, there would be continuing informal interactions between NEDO and Sandia personnel interested in the specific topics. The list of "action items" and the interested NEDO and Sandia personnel are presented in Appendix C.

Informal exchanges regarding these action items will hopefully lead to opportunities for formal cooperation between NEDO and Sandia on drilling research and development projects. If promising opportunities are identified, a mutual research plan will be proposed to NEDO and DOE for joint funding. Cost-shared geothermal drilling projects undertaken by NEDO and Sandia should be reviewed twice yearly, possibly in conjunction with regularly scheduled technical meetings or conferences.

During the afternoon of the second day, the workshop participants visited the MEMS (MicroElectroMechanical Systems) Facility, which is the showcase of Sandia's Intelligent Micromachine Initiative. Afterwards, the Japanese participants and some of the U.S. participants toured the facilities of Sandia's Geothermal Research Department. These facilities included the Lost Circulation and Flow Loop Facility (hosted by Chip MANSURE), the Cutter Wear Test Facility, CWT (hosted by David RAYMOND), the Engineered Lithology Test Facility, ELTF (hosted by George STALLER), and the Orpheus Acoustics Test Site (hosted by Doug DRUMHELLER and Steve KNUDSEN). The workshop ended with much discussion and interaction by all of the participants during a group dinner.

II. Background

The U. S. Department of Energy (DOE) Office of Geothermal Technologies and the New Energy and Industrial Technology Development Organization (NEDO) in Japan have been sponsoring public- and private-sector research and development (R&D) efforts on many, and often the same, aspects of geothermal drilling technology. Much of the work in Japan is conducted or managed for NEDO by the Geothermal Energy Research & Development Co., Inc. (GERD). Similarly, a significant portion of the U.S. investment goes to projects accomplished by, or under the direction of, Sandia National Laboratories (Sandia).

Although common issues are faced in both countries, the respective efforts have not been coordinated or linked, and timing of the emphasis on different elements of the two geothermal drilling R&D programs has not been in phase. NEDO is now supporting work on some of the drilling problems already addressed in past Sandia projects. Similarly, some current research topics being pursued at Sandia have previously been studied under NEDO supervision. Furthermore, several of the same, or related, research directions are now being taken simultaneously in both the U.S. and Japanese geothermal drilling programs. These programs have been, and continue to be, supported by limited funding. This funding could best be leveraged by eliminating, wherever possible, any duplication in effort by means of effective communication and cooperation in geothermal drilling R&D that mutually serves U.S. and Japanese interests.

With sponsorship by Sandia's slimhole R&D program area, Dr. Jim COMBS of Geo Hills Associates and Dr. Sabodh K. Garg of Maxwell Technologies, Inc., made a data gathering trip to Japan in June 1996. During this trip, NEDO personnel expressed an interest in possibly developing joint geothermal drilling R&D projects with DOE and Sandia. In fact, many areas of drilling research are probably appropriate for joint cost-shared efforts by DOE and NEDO. It had become apparent that, as a minimum, there was a need for better communication between the two programs. Improved personal communication could ultimately lead to shared ideas and financial resources for developing new technologies to reduce geothermal drilling costs in the U.S., Japan, and throughout the world.

In its FY97 geothermal annual operating plan, Sandia recommended to DOE that funding should be devoted to a new initiative entitled "Development of Joint DOE-NEDO Drilling Research Project." This project was deferred to FY98 since funds were limited. In FY98, Sandia proposed another new initiative, entitled "NEDO Collaboration," that would promote discussions with NEDO to identify geothermal drilling technology areas where collaboration would benefit both the U.S. and Japan. This project was to be conducted on a very low-level, low-key, exploratory basis; if promising opportunities were identified, a cooperative research plan was to be proposed to DOE for future funding. Once more, funding limitations precluded project initiation.

In February 1999, Masami HYODO of GERD visited Sandia and discussed the subject of joint drilling R&D with several members of Sandia's Geothermal Research Department. After returning to Japan, HYODO contacted NEDO and reported on the possibility of a DOE/NEDO workshop on this subject. With the combined primary efforts of Mike PRAIRIE (Sandia) and Yasukuni OKUBO (NEDO), the Sandia/NEDO Geothermal Drilling R&D Workshop was arranged. Sandia subsequently hosted the Workshop on May 26 and 27, 1999, at the Wyndham Garden Hotel in Albuquerque, New Mexico.

III. The Workshop

III.A Organization

The intent of the workshop was to provide for an exchange of information between NEDO and Sandia regarding their respective geothermal drilling R&D programs. Presentations made during the workshop were expected to provide an overview of the ongoing geothermal drilling research projects and test facilities supported by Sandia and by NEDO. In addition, the workshop was designed to explore opportunities for informal Sandia/NEDO communications and possibilities for future cooperative geothermal drilling research and development projects; however, by prior understanding no formal commitments were to be made during the workshop. The agenda for the workshop, which was followed quite precisely, is duplicated in Appendix A.

The workshop included experienced drilling personnel and administrators. A total of seven (7) Japanese and sixteen (16) U.S. individuals participated. A roster of the participants with their contact information is presented in Appendix B. The Japanese attendees included four individuals from NEDO's Tokyo offices, two individuals from GERD (a private company in Tokyo that carries out many NEDO-sponsored R&D projects), and a professor from Tohoku University in Sendai, Japan. The manager of Sandia's Geothermal Research Department, twelve (12) of his technical staff and technologists, a scientist from Brookhaven National Laboratory, and two (2) Sandia consultants represented the U.S.

The purpose, conduct, and potential outcome of the workshop were outlined at the beginning of the first day by the Workshop Moderator, Jim COMBS, and expanded in detail by Takashi IMANAGA, Director General of NEDO's Geothermal Energy Center, during lunch on the second day. IMANAGA described the administrative details of the funding mechanisms and management of NEDO R&D projects. These details are very similar to those for DOE-sponsored R&D projects.

The workshop agenda (see Appendix A) deliberately intermingled Japanese and U.S. presentations. To facilitate the exchange of information and to document the proceedings, Sandia assembled a 3-ring binder for each workshop participant in which copies of all viewgraphs and other presentation materials were supplied. This was an important aid to the participants since they could efficiently take notes with respect to salient points in the presentations and discussions.

III.B First Day

Opening remarks were made by Takashi IMANAGA, who noted that the interim goal for Japanese geothermal development is to triple the current generating capacity of 500 MW by 2010. Next, Sam VARNADO, the Director of Energy and Critical Infrastructure at Sandia, delivered a welcoming address that focused on the renewable energy program under which geothermal drilling R&D is done at Sandia. Varnado reviewed historical contributions made by Sandia to geothermal drilling technology (e.g., PDC drag bits; high-temperature muds; electronics and downhole tools), and indicated that the current annual budget for geothermal R&D at Sandia exceeds \$5M.

As a prelude to ensuing detailed technical presentations, the next two talks outlined the overall geothermal research programs in, respectively, the U.S. (at Sandia) and Japan. Mike PRAIRIE summarized the Sandia program in his presentation entitled "Overview of DOE (SNL) Geothermal Drilling R&D Program." He pointed out that as much as 50% of the cost of most geothermal power projects is due to the drilling and completion of production and injection wells. Therefore, the mission of the DOE-sponsored Sandia geothermal R&D program is to reduce drilling costs. Sandia's efforts are divided between the Conventional Drilling and Advanced Drilling Programs. PRAIRIE's presentation focused on the Conventional Drilling Program, which aims at reducing geothermal well costs by 25% or more through targeted incremental technology improvements that are rapidly deployed in commercial products. PRAIRIE indicated that the Conventional Drilling Program consists of seven (7) separate technology areas. These areas are Lost Circulation, Hard-Rock Drill Bit Technology, High-Temperature Instrumentation, Wireless Telemetry, Slimhole Drilling Technology, GDO Projects, and System Studies. He noted that individual presentations in all of the technology areas except System Studies would be made by Sandia staff members during the Workshop. PRAIRIE made the point that Sandia's geothermal drilling technology development program features R&D projects that typically have Sandia personnel working jointly with individuals from the drilling industry, universities, other national laboratories, and/or geothermal operators.

Yasukuni OKUBO presented the second overview, entitled "Stagnant Geothermal Development We Face and the Role of Advanced Drilling Technology in Japan." He summarized the NEDO program, and noted that most of the NEDO geothermal drilling research was directed toward deep reservoirs; *i.e.*, reservoirs at depths greater than 2,000 meters. In his talk, OKUBO covered six (6) separate topics: the potential of geothermal energy in Japan, current status of geothermal development in Japan, bottlenecks, breakthrough points, improvements required for deviated directional drilling, and impacts of deviated directional drilling. The past nationwide assessments of geothermal energy in Japan have been divided into resources outside national parks, inside national parks, and inside deep (>2000 m) reservoirs. The total potential resource base for Japan is estimated to be 64,500 MW/30yrs. The geothermal generating capacity of Japan is presently 544 MW, and the Japanese interim goal is to reach a capacity of 1,500 MW by 2010.

OKUBO pointed out that the main bottlenecks to attaining the 2010 goal are constraints arising from the locations of geothermal reservoirs, uncertainties in sustainability of the reservoirs, difficulties with exploration and drilling in complex geologies, and resultant high costs of geothermal electricity relative to other sources. Nuclear reactors, coal, petroleum, and natural gas currently supply 90% of Japan's overall energy requirement. In order to increase the geothermal electrical capacity of Japan, OKUBO stated that advances in deviated directional drilling must be made. These advances are anticipated on the basis of improvements in the following categories: high-temperature instrumentation, torque-drag analysis technology, and high-temperature downhole technologies (*e.g.*, MWD; LWD = Logging While Drilling; SWD = Seismics While Drilling; and, low-speed mud motors). On the basis of R&D breakthroughs in these categories, deviated directional drilling will provide effective land use and fewer constraints on drilling locations, enhance drilling performance in complex geologies, and reduce geothermal drilling costs. Cost reductions will be realized by implementing high-quality survey technology to detect fracture systems and by improving control technology for well/reservoir operations. During the discussion, OKUBO indicated that the two major problems encountered while drilling geothermal wells in Japan are lost circulation and hole collapse; however, these topics were not specifically addressed in his presentation.

During the question and answer sessions and continuing during the break following these two summary presentations, the workshop participants noted and discussed the many similarities between the NEDO and Sandia geothermal drilling R&D programs. It was apparent that the workshop would be a success in terms of communication and interaction among the participants. After the break, the presentations focused on specific technical topics.

Chip MANSURE and George STALLER of Sandia gave the next presentation, "Lost Circulation Technology," with considerable input during the discussion by the primary field technician, Gary WHITLOW. The Sandia Lost Circulation Technology Program is divided into two focus areas with two projects apiece. One of the focus areas is dedicated to lost circulation detection and characterization. The two projects in this area involve work on advanced drill-rig instrumentation and on a Circulation Monitoring System (CMS). The objective of the advanced drill-rig instrumentation project is to develop sensitive and practical meters for accurate real-time detection of lost circulation, fluid influx, loss of pump efficiency, washouts, stuck drill pipe, gas/steam kicks, *etc.* The CMS project aims to develop an expert system for transfer to the geothermal industry; this system will analyze drilling circulation conditions using input from the advanced drill-rig instrumentation. The speakers noted that considerable progress has been made with the development of the flow meters and the accompanying expert system.

The other focus area is devoted to lost-circulation treatment and has two active projects: development of a Drillable Straddle Packer (DSP) and evaluation of advanced Lost Circulation Materials (LCMs). The objective of the DSP project is to produce a low-cost drillable packer for cost-effective treatment of lost circulation. The LCM project is investigating the use of chemical grouts, such as polyurethane foams, instead of cement for some plugging applications. The speakers reported that considerable progress has been made on both of the lost-circulation treatment projects.

Seiji SAITO of Tohoku University delivered the next NEDO presentation, which was entitled "Experience From a 3.7 km Deep, 500°C Drilling, Kakkonda, Japan." This was a detailed report on the drilling, logging, testing, and completion of the WD-1 and WD-1A wells at the Kakkonda Geothermal Project in northern Honshu. NEDO funded this project for a duration of eight years (1992-1999) in an attempt to delineate a possible deep geothermal reservoir beneath the presently utilized shallow reservoir that supports the Kakkonda I (50 MW) and Kakkonda II (30 MW) power plants.

Drilling technology studies associated with the Kakkonda deep-drilling project had two primary objectives. The first objective was to evaluate existing technologies under the high-temperature, hard-rock conditions at Kakkonda. These technologies included bits, positive displacement motors, MWD, mud-cooling devices, and bottomhole assembly (BHA) cooling methods while running in the hole. The second objective was to obtain useful drilling data. The original well plan featured a total depth of 4,000 m and an expected maximum formation temperature of 400°C. In actuality, the WD-1A was completed to a depth of 3,729 m and encountered a peak formation temperature of 500°C. The top-drive system used during this project allowed continuous mud pumping while each additional stand of drill pipe was added; this arrangement proved very effective for prolonging bit life. During drilling, a total of eleven (11) correction runs were made with the downhole motor using MWD.

In the past several years, this very important NEDO-sponsored geothermal research project has provided data for several tens of technical papers that have been published in the geothermal literature. Discussion of the current talk gave Sandia staff an opportunity to introduce the results from very recent field experiments using insulated drill pipe. Developed through a Sandia-sponsored GDO project, this insulated pipe yielded much cooler bottomhole temperatures, compared to conventional drill pipe, while circulating at two different flow rates in a well at the Salton Sea Geothermal Field in the Imperial Valley of southern California.

The first day's luncheon proved to be another intense discussion session between Japanese and U.S. participants interspersed at each of the tables. After lunch, a half-hour session of summary comments and additional questions and discussion pertaining to the morning presentations was moderated by Jim COMBS.

Jack WISE gave the first Sandia presentation of the afternoon session, entitled "Hard-Rock Drill Bit Technology." Sandia began working in the late 1970s with bit manufacturers and geothermal operators to design and test PDC drag bits in hard-rock formations. Sandia identified and corrected design deficiencies, developed basic bit design principles, and was instrumental in opening broad international market opportunities (annual sales exceeding \$200 million) for PDC bits. In an early part of the discussion, it was noted that the Sandia hard-rock drill bit program has concentrated on improving drag bits whereas the NEDO program has concentrated on improving rollercone bits. The primary objectives of the Sandia Hard-Rock Drill Bit Technology Program are to double both the rate of penetration (ROP) and bit life in high-temperature, hard-rock drilling.

The Sandia approach has been to work with drill-bit companies and researchers to improve drag-bit performance in harder rocks through computer modeling, materials research, and laboratory testing. Two important laboratory facilities at Sandia are the Linear Cutter Test Facility (LCTF) and the Cutter Wear Test Facility (C WTF). The C WTF has recently been renamed as the Hard-Rock Drilling Facility (HRDF). The LCTF and C WTF were included in the tour conducted during the second afternoon of the workshop. The nine (9) specific projects discussed as part of the bit technology program were: Drill Bit Technology Assessment, PDC Bit Field Testing, Self-Induced PDC Bit Vibrations, Mudjet-Augmented PDC Bits, PDC Claw-Cutter Optimization, Track-Set Drill Bit Optimization, Explosively-Compacted Drag Cutters, Bi-Center PDC Bits, and PDC Bit Modeling. WISE concluded his presentation with the following comment: "The Sandia hard-rock drill bit program continues to effectively promote the advancement of drilling technology by fostering national-laboratory/industry/university cooperation in promising R&D activities."

Masami HYODO and Haruya NAKATA, both from GERD, authored the next NEDO presentation, "Development of Drilling and Production Technology for Deep-Seated Geothermal Resources." HYODO gave the presentation, which described both the Drilling Technology Program and the Production Technology Program.

The NEDO Drilling Technology Program focuses on the development of durable, heat-resistant rollercone bits, drilling muds, cement materials, high-temperature/low-speed downhole motors, and a high-temperature MWD system for the drilling and completion of wells to produce geothermal fluids from deep-seated reservoirs. The objective of the bit project is to commercialize rollercone bits that can be used at temperatures up to 250°C for 30 hours while

drilling, and that can survive temperatures up to 350°C for 6 hours without circulation. In the NEDO program, drilling-mud compositions are sought which maintain their properties for 3 days while subjected to 350°C formation temperatures. Cement materials are being developed that have a low specific gravity (1.35) and that exhibit a high compressive strength (70 kgf/cm²) after 7 days at a formation temperature of 350°C. Because of the limited availability of surface drilling locations and the resultant need for deviated drilling in Japan, the fourth Drilling Technology project is dedicated to the improvement of high-temperature, low-speed downhole mud motors. HYODO reported that advances are being made in all areas of the Drilling Technology Program, and indicated that NAKATA would present a specific update on the MWD project during the second day of the workshop.

The NEDO Production Technology Program is concerned with the development of a pressure, temperature, spinner, and density (PTSD) logging system, a downhole fluid sampler (chemical monitoring system), a PT monitoring system, a scale monitoring and prevention system, and tracer technology. A memory-type PTSD logging tool has been developed by NEDO that can withstand formation temperatures up to 400°C for 6 hours. Data obtained in the Kakkonda WD-1A well was presented and discussed. Unfortunately, the density-logging tool has a Cs-137 source that, under current regulations, could not be run in most geothermal wells in the U.S. The NEDO sampler can be used to obtain one-liter specimens of fluid at temperatures up to 400°C; it is triggered on the basis of elapsed memory time. NEDO's PT monitoring system will track pressure and temperature (up to 400°C) for long periods of time. It uses capillary tubing to detect bottomhole pressure, and an optical fiber to measure the borehole temperature distribution.

The scale technology project focuses on (1) analysis of scale deposit mechanisms for silica, CaSO₄ and clay minerals, and (2) methods for scale prevention and removal. This project addresses the scales associated with the four separate problem areas encountered in a geothermal power project: production wells, surface conversion equipment, injection wells, and reservoir (after injection).

HYODO also mentioned studies on several materials that are suitable as fluid tracers, two-phase tracers, and gas tracers for reservoir temperatures up to 350°C.

Following the presentation by HYODO, a lively discussion ensued regarding the use of fiber optic cables for the measurement of subsurface temperature distributions. Because of time constraints, the formal discussion was cut short.

Next, HYODO made an additional presentation describing a very robust and user-friendly Data Base System for Lost Circulation that has been developed with NEDO funding. The database for this system includes information from 340 wells in 50 areas, summarizing 4,706 lost-circulation treatments. Even though the data base system is programmed in Japanese, Sandia personnel expressed great interest in converting the computer software to English for use by geothermal operators in the U.S.

Immediately following the afternoon break, Toshifumi SUGAMA of Brookhaven National Laboratory gave his presentation entitled "Acid-Resistant, High-Temperature Cements." SUGAMA pointed out that the quality of the cementing phase of a geothermal well completion often establishes the life expectancy of the well. Improperly designed cement jobs can result in blowouts and casing corrosion or collapse. In addition to the need for cements that, upon curing,

yield the necessary physical, mechanical and chemical characteristics, their slurry precursors must have rheological properties that permit placement in high-temperature environments. With DOE funding, scientists at Brookhaven National Laboratory have been working for more than fifteen years to develop acid-resistant, high-temperature cements to be used in geothermal wells. Their research has indicated that materials formed by acid-base reactions between calcium aluminate compounds and phosphate-containing solutions mixed with lightweight fillers (*e.g.*, hollow aluminosilicate microspheres) can produce pumpable slurries with specific gravity as low as ~1.1. These slurries yield high-strength, low-permeability, and CO₂-resistant cements when cured in hydrothermal environments. SUGAMA and coworkers have developed several formulations that exhibit low rates of carbonation. Laboratory characterization has basically been completed and engineering scale-up is essentially done. Validation of the cement formulations will be based on the results of a number of thoroughly documented field tests on wells being drilled and completed in high-temperature reservoirs containing CO₂-laden geothermal brines.

Next, Allan SATTLER of Sandia provided a detailed review of "Geothermal Drilling Organization (GDO) Projects." The Geothermal Drilling Organization (GDO) was founded in 1982. It is a joint DOE/industry organization that funds and develops near-term technology projects for reducing geothermal drilling and well-maintenance costs. Sandia administers DOE funds to assist industry-critical, cost-shared projects, and provides development support for each GDO project. SATTLER pointed out that projects usually considered by the GDO are those where the basic research and development have already been completed, and all that remains before possible commercialization are applications development and field testing. In fact, the primary objective of the GDO is to reduce geothermal drilling and well-maintenance costs by developing and commercializing new tools, materials, and techniques via cost-shared projects between Sandia and the geothermal industry.

Recently completed GDO projects described by SATTLER include a high-temperature borehole televIEWer, high-temperature rotating head rubbers, a retrievable whipstock, and a high-temperature/high-pressure valve-changing tool. SATTLER reviewed ongoing GDO projects in some detail. These projects include technology for stemming lost circulation, foam cement integrity log interpretation, insulated drill pipe, percussive mud hammers for geothermal drilling, deformed casing remediation, high-temperature steering tools, diagnostic instrumentation for casing in geothermal wells, and elastomeric casing protectors. For each of the ongoing GDO projects, SATTLER presented FY98 and FY99 objectives and results, FY2000 plans, and actual and/or anticipated achievements associated with the completion of each project.

John FINGER of Sandia discussed "Slimhole Drilling Research" in the final presentation of the first day. The objective of the Sandia Slimhole Program is to reduce exploration costs, especially up front, by drilling less expensive boreholes to locate and characterize geothermal reservoirs. According to FINGER, the three components of the Slimhole Program include in-house and contract analysis of slimhole data, cost-shared drilling projects, and the compilation of a *Slimhole Handbook* for the geothermal community.

FINGER indicated that the results of the slimhole program to date are (1) demonstration of the lower cost associated with the drilling, logging, testing, and completion of slimholes, (2) correlation of injectivity and productivity indices between slimholes and large-diameter production wells so that data obtained from slimholes can be used to predict the discharge characteristics of production wells, and (3) the development of new drilling technology including

a core-tube data logger, flow instrumentation, rig database system, and a latch detector. The *Slimhole Handbook* (published as report SAND99-1976) is a compilation of experience in the planning, designing, drilling, logging, testing, and completion of slimholes for geothermal exploration and reservoir assessment. According to FINGER, the future direction of the Sandia Slimhole Program will concentrate on promotion of small-scale/off-grid, or distributed, geothermal power facilities using slimholes to provide the energy. Drilling, completion, and discharge characteristics of slimholes, as well as small-scale geothermal power module technology, have been demonstrated, but not for long-term operations. The potential co-location of small towns and villages with geothermal resources, *i.e.*, market/resource maps, is incomplete and should be completed. Finally, FINGER recommended that there should be several long-term demonstration projects, with thorough documentation, of the viability and economic validity of small-scale geothermal power modules energized by slimholes.

The first day of the workshop concluded with a New Mexican dinner at the Gardunos of Mexico Restaurant & Cantina on Academy Road. Technical discussions continued on a person-to-person basis throughout the meal, furthering the desired exchange of information between the NEDO and Sandia participants.

III.C Second Morning

After a continental breakfast with informal discussions on the second morning of the workshop, the participants contributed to a formal discussion of presentations made the previous afternoon. The Workshop Moderator, Jim COMBS, terminated this activity in order to comply with the schedule.

Doug DRUMHELLER of Sandia gave the first presentation of the second day, "Wireless Telemetry," which he co-authored with Steve KNUDSEN. Tasks of common interest in most geothermal drilling include directional drilling of deviated wells, fracture detection, multi-lateral completions, and Seismics-While-Drilling (SWD). Effective downhole communication can be a key element in accomplishing these tasks. For example, acoustic telemetry can be used to transmit downhole measurements of temperature, pressure, gas influx, gamma flux, electrical resistivity, flow rate, well dimensions and well direction.

DRUMHELLER indicated that one of the primary objectives of the acoustic telemetry program is to develop a geothermal drilling tool that can establish a communications link between the drill bit and the surface. A tool of this type could reduce drilling costs by initially transmitting information about annular fluid levels during loss of circulation. It could also serve as a prototype communications system for advanced drilling and navigation technology. The anticipated geothermal drilling tool will have the following features: operation at 200°C and survival at 300°C, depth range of at least 2,500 m, encapsulation in a 12-cm drill collar, and a data rate of 1 baud initially, with a potential 30-baud rate. Progress to date on the geothermal drilling tool includes the completion of the mechanical component design and the placement of orders for the piezoceramic transducer elements and power amplifier.

One of the recurring problems in the production of fluids from moderate-temperature reservoirs is the misalignment of line-shaft pumps in geothermal wells and the resultant lost production and costs of replacing the damaged multistage pump. DRUMHELLER has developed a Line-Shaft Alignment Monitor that consists of an accelerometer and whistle placed at opposite ends of the

shaft. After successful bench tests of a prototype, a patent has been awarded, and Sandia is now waiting for field-test opportunities.

Upcoming tasks for the acoustic telemetry program at Sandia include field testing of a geothermal MWD tool in 2001, development of repeater technology, telemetry and imaging-systems support for the Diagnostics-While-Drilling (DWD) project, support for scientific SWD efforts, and improvement of passive listening devices for core drilling. Upon completion of DRUMHELLER's presentation, there was considerable discussion with comparisons made between acoustic telemetry and mud-pulse data transmission.

Masami HYODO and Haruya NAKATA, both from GERD, authored the final NEDO presentation, "Development of High-Temperature MWD Systems and Drilling Support Systems for Geothermal Wells." The talk was given by NAKATA. Geothermal well drilling in Japan faces several challenges. Drilling is typically done in complicated geological formations that have hard, fractured rock and lost-circulation zones at high temperatures and pressures. Furthermore, there is limited developable surface area in the vicinity of geothermal reservoirs found in the national parks and in mountainous areas. Consequently, improvements in drilling efficiency and accuracy are necessary to decrease drilling costs. Based on the analysis of considerable data from geothermal wells in Japan, NAKATA noted that the primary requirement for improved drilling is the accurate measurement of certain key parameters while drilling. These parameters include the inclination and azimuth of the borehole, as well as the temperature and pressure at the bottom of the borehole. To meet the identified requirement, a NEDO program was initiated to produce a high-temperature MWD system using data transmission by mud pulse.

The major components of the MWD system under development are a downhole sonde and a surface-based data processing and analysis system. Specifications for the MWD sonde include an outer diameter of 5 cm or less, a maximum working temperature of 200°C, and a maximum working pressure of 1,000 kg/cm² (14.2 kpsi). The sonde is designed to operate 50 hours on battery power and has an expected data transmission rate of 1 bit every 15 seconds (*i.e.*, 0.07 baud). A prototype downhole unit was built and successfully tested in 1998, and additional improvements and upgrades of the sonde are now being made. The Directional Drilling Control Support System (DDCSS) is an important component of the MWD Data Analysis system on the rig floor. The DDCSS has three separate modules: a well-trajectory planning system, a well-trajectory visualization system, and a well-trajectory prediction system. Desktop computer images generated by these modules can be plotted as 2-dimensional (2-D) plane views, 3-D bird's-eye views, or cylindrical views. The MWD Data Analysis System also incorporates a Formation Evaluation Support System that tracks and assesses downhole formation temperature and lost-circulation parameters.

NEDO's MWD drilling R&D project is progressing as planned. NAKATA indicated that all of the system components have been completed and field tested through the prototype stage by the project team of GERD, Akishima Laboratories, and Mitsui Zosen. The system components are now being refined and improved for further field testing in wells of opportunity.

Randy NORMANN of Sandia gave the next presentation, entitled "High-Temperature Electronics for Geothermal Applications," which he authored jointly with Joseph HENFLING. The growing demand for high-temperature (HT) electronics that exceed military specifications (mil-spec) was described. To meet this demand, NORMANN pointed out that a new level of

commercially available HT SOI (Silicon-On-Insulator) electronics is being developed. The SOI devices are rated for almost twice the mil-spec temperature range above 0°C. For example, Honeywell and Allied Signal offer new SOI devices rated at 225°C with most operating up to 300°C. Fortunately for the geothermal industry, which represents a very limited market, the aircraft industry is seeking new HT engine controllers. HT electronics, as an enabling technology, could affect all aspects of the geothermal industry.

The benefits of HT electronics are easily recognized for logging tools. With the availability of HT components, the cost of future logging tools will be reduced since heat-shield dewars, which cost from \$6,000 to \$16,000, can be eliminated. HT electronics will extend the time that a logging device can be left in the well (heat shields only provide for 6 to 12 hours of operation), and they will reduce component lot testing by tool builders.

Sandia is currently advancing drilling applications for HT electronics technology by (1) developing a simple unshielded downhole data logger for 300°C, (2) developing new HT batteries for 180 to 300°C operation, and (3) developing HT, long-life fiber optics for downhole sensing and communications. On the basis of Sandia's involvement with industry, NORMANN anticipates quick commercialization of HT electronics for geothermal use. He noted that memory tools previously developed by Sandia in conjunction with industry partners can be retrofitted with HT electronics. Sandia staff members are also working on new efforts with Boeing and Honeywell to develop a HT MWD system. Advantages envisioned for a new HT MWD/DWD system include a greatly simplified downhole instrument and significantly increased baud rates for data transmission that allow new measurements and an improved user interface.

In conclusion, NORMANN indicated that the HT electronics industry is rapidly developing new products. Sandia is actively assisting the HT industry by informing them of geothermal needs and requirements, by working on new HT geothermal applications, and by reporting HT component test results to the drilling service industry. Finally, NORMANN noted that Sandia plans to test a HT non-heat-shielded data logger during July or August, 1999, in a geothermal well. Following the presentation, there was considerable discussion by the participants about comparisons with the NEDO HT MWD system and the need to share information and insight on the development of fiber optic cables.

Mike PRAIRIE of Sandia delivered the last formal presentation of the workshop, entitled "Advanced Drilling Technology --Diagnostics-While-Drilling." The challenge for the Sandia Advanced Drilling Technology Program is to reduce the cost of drilling and completion of geothermal wells through revolutionary developments in technology. PRAIRIE pointed out that advanced drilling technology will be necessary to meet the DOE strategic goals of providing geothermal power to 7 million U.S. homes by 2010 and providing 10% of the U.S. energy needs after 2010. The Sandia program goals are to reduce drilling costs by at least 25%, and to commercialize a revolutionary systems approach to drilling based on integrated downhole and surface data, the so-called Diagnostics-While-Drilling (DWD) system. The ultimate desire is to achieve linear cost versus depth for deep wells.

DWD will revolutionize drilling by providing a feedback system for real-time control and optimization during the drilling of wells to access geothermal and deep hydrocarbon resources. In other words, the DWD will enable new approaches to drilling that feature surface-controllable downhole tools, enhanced underbalanced drilling, acquisition of detailed data on drilling and the

downhole environment, sophisticated Logging-While-Drilling (LWD) systems, and downhole diagnostics on bit wear and cutter temperatures. PRAIRIE noted that DWD is a new initiative of the Sandia Geothermal Drilling R&D Program. This initiative is planned to run for 6 years in four phases with a total funding level of \$60 million, shared in roughly equal proportions by DOE and industry. Phase 1 will entail completion of a program plan and the formation of a consortium with program review by DOE, industry and university participants. Phase 2 will provide for the assembly of a prototype DWD system and demonstration of the benefits with proof-of-concept tests. During Phase 3, Sandia will develop basic systems needed for cost-effective DWD in the geothermal and oil and gas industries. The Phase 3 activities will include software and sensor development and testing, as well as assessments of the relative merits of different telemetry systems, *e.g.*, acoustic versus fiber optic. In Phase 4, Sandia and its industry and university partners will continue research, development, and field testing on enhanced DWD tools. In conclusion, PRAIRIE indicated that the Advanced Drilling Program will crosscut many of the existing Sandia drilling R&D programs including acoustic telemetry, high-temperature instrumentation, advanced rig instrumentation, and drill-bit development.

III.D Conclusions

Because of the extended question and answer sessions after each of the morning presentations on the second day, the Workshop Moderator, Jim COMBS, suggested a “working lunch” for the agenda. All agreed. In order to sustain the communication, interactive momentum, and enthusiasm that had been generated during the past day and a half by the workshop participants, COMBS further suggested that the group develop a set of “action items.” These “action items” would consist of topics of mutual interest presented during the workshop and identified by the group as being important to both the NEDO and Sandia geothermal drilling R&D efforts. To follow up on the workshop, there would be continuing informal interactions between NEDO and Sandia personnel interested in the specific topics. The list of “action items” and the interested NEDO and Sandia personnel are presented in Appendix C.

Hopefully, these informal interactions during the next few years will lead to opportunities for formal cooperation between NEDO and Sandia on drilling research and development projects that are jointly funded and conducted. If promising opportunities are identified, a joint research plan will be proposed to NEDO and DOE for possible future funding. Joint cost-shared geothermal drilling R&D projects ultimately undertaken by NEDO and Sandia should be reviewed twice yearly. Such reviews could be accomplished during geothermal technical meetings in Japan, during the International Geothermal Association World Geothermal Congress (held every five years), or during specific sessions convened in association with the Geothermal Resources Council (GRC) Annual Meeting or the annual Stanford Geothermal Reservoir Engineering Workshop.

III.E Sandia Tours

During the afternoon of the second day, the workshop participants visited the MEMS (MicroElectroMechanical Systems) Facility, which is the showcase of Sandia's Intelligent Micromachine Initiative. Afterwards, the Japanese participants and some of the U.S. participants toured the facilities of Sandia's Geothermal Research Department. The tour included the Lost Circulation and Flow Loop Facility (hosted by Chip MASURE), the Cutter Wear Test Facility, CWTF (hosted by David RAYMOND), the Engineered-Lithology Test Facility, ELTF (hosted

by George STALLER), and the Orpheus Acoustics Test Site (hosted by Doug DRUMHELLER and Steve KNUDSEN.) The workshop ended with much discussion and interaction by all of the participants during dinner at the Seagull Street Restaurant on Academy Road.

Appendix A: Workshop Agenda

May 26, 1999

08:30-09:00 Continental Breakfast

09:00-09:15 Introductions and Workshop Format - Jim Combs

09:15-09:30 Welcome - Sam Varnado

09:30-09:45 Overview DOE (SNL) Geothermal Drilling R&D Program - Mike Prairie

09:45-10:30 Stagnant Geothermal Development We Face and the Role of Advanced Drilling Technology in Japan - Yasukuni Okubo

10:30-10:45 Break

10:45-11:30 Lost Circulation Technology - George Staller and Chip Mansure

11:30-12:15 Experience From a 3.7 km Deep, 500°C Drilling, Kakkonda, Japan - Seiji Saito

12:15-13:00 Lunch with Discussions - All Participants

13:00-13:30 Summary and Discussion of Morning Presentations - Jim Combs, Moderator

13:30-14:15 Hard-Rock Drill Bit Technology - Jack Wise

14:15-15:00 Development of Drilling and Production Technology for Deep-Seated Geothermal Resources - Masami Hyodo and Haruya Nakata

15:00-15:15 Break

15:15-16:00 Acid-Resistant, High-Temperature Cements - Toshifumi Sugama

16:00-16:45 Geothermal Drilling Organization (GDO) Projects - Allan Sattler

16:45-17:30 Slimhole Drilling Research - John Finger

17:30-18:30 Free Time - All Participants

18:30-20:30 Dinner with Discussions - All Participants (Gardunos of Mexico Restaurant & Cantina, Academy Road)

Appendix A: Workshop Agenda (continued)

May 27, 1999

08:00-08:30 Continental Breakfast

08:30-09:00 Summary and Discussion of Previous Afternoon Presentations - Jim Combs, Moderator

09:00-09:45 Acoustic Telemetry - Doug Drumheller

09:45-10:30 Development of High Temperature MWD Systems and Drilling Support Systems for Geothermal Wells - Masami Hyodo and Haruya Nakata

10:30-10:45 Break

10:45-11:30 High-Temperature Electronics for Geothermal Applications - Randy Normann

11:30-12:00 Advanced Drilling Technology — Diagnostics-While-Drilling - Mike Prairie

12:00-12:30 Action Items for Joint Geothermal Drilling R&D - Jim Combs, Moderator

12:30-13:30 Lunch with Discussions - All Participants

13:30-14:00 Travel to Sandia for Tours

14:00-14:45 Tour of MEMS Facility at Sandia - Japanese Guests & Interested Participants

14:45-15:00 Travel to Sandia Geothermal Drilling Facilities and Brief Break

15:00-17:30 Tour of Sandia Geothermal Drilling Facilities - All Participants
 Lost Circulation and Flow Loop - Host: Chip Mansure
 Cutter Wear Lab - Host: Dave Raymond
 Engineered Lithology Test Facility - Host: George Staller
 Orpheus Acoustics Test Site - Host: Steve Knudsen

17:30-18:30 Free Time - All Participants

18:30-20:30 Dinner with Discussions - All Participants (Seagull Street Restaurant, Academy Road)

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Appendix C: Workshop “Action Items”

1. COSTING MODEL SOFTWARE & ACTUAL COSTS OF WELLS

Interested Individuals: LIVESAY and NAKATA

2. LOST CIRCULATION TECHNOLOGY

Interested Individuals: STALLER, SUGAMA and SAITO

3. HIGH-TEMPERATURE LOGGING & DOWNHOLE INSTRUMENTATION

Interested Individuals: NORMANN, COMBS, and NAKATA

4. HIGH-TEMPERATURE, ACID-RESISTANT CEMENTING TECHNOLOGY

Interested Individuals: SUGAMA and HYODO

5. SLIMHOLE TECHNOLOGY & OFF-GRID, SMALL-SCALE POWER PLANTS

Interested Individuals: FINGER, COMBS, NAKATA and WADA

6. GEOTHERMAL MWD SYSTEMS & SOFTWARE

Interested Individuals: DRUMHELLER, LIVESAY and HYODO

7. HARD ROCK, HIGH-TEMPERATURE DRILL BITS (PDC & Rollercone)

Interested Individuals: WISE and WADA

8. HIGH-TEMPERATURE ELECTRONICS & BARE DOWNHOLE TOOLS

Interested Individuals: NORMANN, COMBS, NAKATA and WADA

9. DIAGNOSTICS-WHILE-DRILLING

Interested Individuals: PRAIRIE and WADA

10. JOINT FIELD TESTING EXPERIENCE

Interested Individuals: PRAIRIE, COMBS, NAKATA and WADA

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