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INSTRUMENTATION REQUIREMENTS FOR THE ESF THERMOMECHANICAL EXPERIMENTS[a]

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ABSTRACT

In situ thermomechanical experiments are planned as part of the Yucca Mountain Site Characterization Project that require instruments to measure stress and displacement at temperatures that exceed the typical specifications of existing geotechnical instruments. A high degree of instrument reliability will also be required to satisfy the objectives of the experiments, therefore a study was undertaken to identify areas where improvement in instrument performance was required. A preliminary list of instruments required for the experiments was developed, based on existing test planning and analysis. Projected temperature requirements were compared to specifications of existing instruments to identify instrumentation development needs. Different instrument technologies, not currently employed in geotechnical instrumentation, were reviewed to identify potential improvements of existing designs for the high temperature environment. Technologies with strong potentials to improve instrument performance with relatively high reliability include graphite fiber composite materials, fiber optics, and video imagery.

I. INTRODUCTION

The Yucca Mountain Site Characterization Project (YMSCP), managed by the Nevada Operations Office of the U.S. Department of Energy, is examining the feasibility of siting a potential repository for high-level nuclear waste at Yucca Mountain, which is located on and adjacent to the Nevada Test Site. As part of site characterization, a series of in situ thermomechanical experiments have been planned, which are to be conducted in an Exploratory Studies Facility (ESF).

The specific experiments are described in the Site Characterization Plan (SCP)[1] in Section 8.3.1.15.1.6 (In Situ Thermomechanical Properties Study) and include four types:

- a heated block test
- a canister-scale heater test
- a thermal stress test
- a heated room test.

The thermomechanical experiments are designed to satisfy multiple objectives, including:

- measure the thermal and mechanical properties of the repository host rock in large scale tests
- demonstrate the effects of high temperatures on volumes of rock at the scale of the planned repository openings
- verify fundamental physical model assumptions about the coupled thermal and mechanical behavior of the repository host rock
- provide measured data for comparison with predictive computer analyses, in order to validate coupled thermal-mechanical computer models
- demonstrate the effects of thermal loads on ground support systems that will be required for repository construction.

This paper discusses the test instrumentation to measure temperature, stress, and displacement required for the ESF In Situ Thermomechanical Properties experiments, and identifies existing instrumentation technology with the potential to meet the requirements.

In the current planning, only single tests are planned for each experiment. No contingency for repeating a test currently exists, and no other experiments are planned that can supply the information that is to be provided by the thermomechanical experiments. It is therefore important to obtain accurate results from these experiments. Test instruments must perform with a high degree of reliability.

II. PLANNED THERMOMECHANICAL EXPERIMENTS

The thermomechanical experiments, as a group, are designed to satisfy general objectives. They are to provide accurate measurements in large scale tests to verify that the laboratory values for thermal conductivity, heat capacity, and coefficient of thermal expansion are correct at the rock mass scale. They are also to provide characterization of the deformation modulus, and provide different test cases for evaluation of the performance of computer codes that are to be used to predict excavation performance under heat loads. The

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experiments will provide data at four different scales, in four different geometries and with four different sets of boundary conditions. In order to meet these objectives, accurate measurements of temperature, displacement and stress fields during the tests are needed.

The experiments are designed to heat large volumes of rock to temperatures that simulate projected repository conditions. Current repository criteria limit emplacement borehole temperatures to 275 °C. Within 1 m of the borehole, rock temperature must fall to 200 °C and the emplacement drift wall is limited to 100 °C. To produce temperatures in this range in the thermomechanical experiments with the current designs, local rock temperatures are predicted to range as high as 300-400 °C. Accurate monitoring of the experiments requires exposure of some instruments to these high temperatures.

In the following sections, each of the four experiments is described, its specific objectives are given, and its instrumentation requirements listed. In each experiment, arrays of electric borehole heaters will be used to heat the rock. The thermal environments the instruments will experience were estimated from preliminary analyses by Bauer, Costin and Holland[2] and from prototype experiments [3] in tuff rock.

This paper focuses on the instruments required to satisfy the objectives of the experiments, which make long term measurements of temperature, stress and displacement at high temperature. It is currently planned to measure other parameters; however, it is believed that these measurements can be transient. The instruments to make these measurements will, therefore, not be exposed to elevated temperatures for long periods. Instruments planned but not discussed in this work include neutron probes, piezometers, ultrasonic velocity transducers, moisture sensors and acoustic emission sensors.

A. The Heated Block Experiment

The sides of a block of rock (2m x 2m x 2m) will be isolated from the rock mass by cutting vertical slots in the floor of a drift. Line heaters will be installed outside of two opposing slots, to create a temperature field in the block that is nearly one-dimensional. Flatjacks will be installed in the slots to apply pressure boundary conditions to the faces of the block. The flatjacks can be kept at a constant pressure, and the temperature of the block varied using the line heaters. Later, the flatjacks can be pressure cycled with the block at a constant temperature to determine the modulus of deformation of the rock.

The test instruments currently projected for the heated block experiment are listed in Table 1 along with the maximum temperature the test instrumentation must survive.

Table 1: Heated Block Experiment Instrumentation.

Instrument	Estimated Number of Instruments	Maximum Temperature
Multipoint Borehole Extensometer (MPBX)	4-8	170° C
Borehole Stress Gage	10-20	190°C
Thermocouples	100-200	200° C
Flatjacks	4-16	200° C
Remote Readout Surface Displacement	20-30	140° C
Manual Readout Surface Displacement	10-20	150° C

B. The Canister-Scale Heater Experiment

Two canister-scale borehole heater experiments (CSHEs) are planned. The experiments will be identical, except for the thermomechanical unit of rock in which they will be conducted. It is assumed in this report that the instrumentation requirements for the tests will be identical, and that each experiment will require its own instruments.

The CSHEs are larger scale experiments than the heated block experiment, involving approximately 350 cubic meters of instrumented rock, and will simulate the emplacement of full-scale radioactive waste canisters into boreholes in the repository. Borehole heaters will be used to simulate the thermal output of actual waste canisters, and will demonstrate stability of the emplacement boreholes at high temperatures.

The test instruments required for each of the two experiments, along with the maximum temperature the instruments must survive is given in Table 2.

Table 2: CSHE Instrumentation.

Instrument	Number of Instruments	Maximum Temperature
MPBX - Parallel to Heater (26 ft. length)	3-5	300° C (rods) 50 ° C (Sensors)
MPBX - Transverse to Heater (32 ft. length)	2-4	340° C (Rods) 50 ° C (Sensors)
Borehole Stress Gage	5-10	300°C
Thermocouples	20-50	500° C

C. The Thermal Stress Test

The thermal stress test (TST) will be conducted in a drift or portions of a repository room-scale drift, and will involve approximately 1200 cubic meters of instrumented rock. In this test, a repository-sized drift will be thermally loaded using line heaters along a section of the roof. The specific objectives of this test are to demonstrate the effects of high heat loads on roof support systems and to generate thermal stress induced rock-mass failure. In the initial portion of the test, temperature and stress change are monitored as the instrumented rock heats up to 100 °C. Afterwards, the test includes a thermal overdrive to induce failure of the roof, and therefore yield information on the rock-mass strength.

Although originally not planned for the TST, there exists a strong need to evaluate the effects of elevated temperatures on rock support systems. This will require installation of instrumented rock bolts and instrumentation of shotcrete and other support systems. MPBX gages will be required to measure rock displacements in the roof to correlate with measured support loads.

Table 3 summarizes the instrumentation projected for this test, and the expected thermal environments the instruments must survive.

Table 3: Thermal Stress Test Instrumentation.

Instrument	Number of Instruments	Maximum Temperature
MPBX	2-4	50 ° C (Rods) 40 ° C (Sensors)
Borehole Stress Gage	5-10	200°C
Long Gage Surface Extensometer with Tiltmeters	5-10	200° C
Cross Drift Extensometers	10-20	50 ° C
Thermocouples	200-300	400° C
Rock Bolt Load Cells	10-20	200° C

D. The Heated Room Experiment

The heated room experiment (HRE) examines rock-mass behavior at the largest scale of the ESF thermomechanical experiments. Approximately 3800 cubic meters of rock will be heated and instrumented in this test.

The HRE will be performed in the central drift excavated for the Sequential Drift Mining Experiment (SDME) described in the Excavations Investigations Study Plan.[4]

In the SDME, two parallel instrumentation drifts are excavated approximately 34 m apart. The rock mass between the two drifts is instrumented to monitor its response to the excavation of a central drift parallel to the instrumentation drifts. After completion of the SDME, the central drift will be instrumented and heaters will be installed in the surrounding rock for the HRE. The rock will be heated for up to 40 months to demonstrate drift stability under high heat loads.

In addition to the objectives stated in the SCP, the HRE offers another opportunity of observe the effect of thermal loading on ground supports in a full scale repository drift. The test plan may be expanded to incorporate test sections of typical support systems, including: rock bolts and wire mesh, shotcrete and steel sets.

Table 4 list the currently planned instrumentation and projected operating temperatures.

Table 4: Heated Room Experiment Instrumentation.

Instrument	Number of Instruments	Maximum Temperature
MPBX (Horizontal)	20-30	300° C
MPBX (Vertical)	5-10	150° C
Borehole Stress Gage (Horizontal Orientation)	10-20	300° C
Borehole Stress Gage (Vertical Orientation)	10-20	300° C
Long Gage Surface Extensometer with Tiltmeter	20-30	300° C
Cross Drift Extensometer	20-30	300° C
Thermocouples	100-200	400° C
Rock Bolt Load Cells	20-30	300° C

III. Instrument Specifications and Accuracy

Detailed accuracy requirements for the parameters to be measured in the ESF tests have not been developed. However, guidelines have been developed from other instrumentation studies for nuclear waste disposal experiments[5] and have been adopted in this study for the purpose of evaluating existing instrumentation. The guidelines were developed considering rock materials that include granite, basalt, and generic crystalline or argillaceous rocks and are listed as Table 5. The instrument accuracy requirements were estimates of those needed to obtain material parameters with sufficient accuracy. The accuracy needed for the material parameters was estimated based on requirements for repository design, construction, performance monitoring and other purposes, and on estimates of the values and the ranges of the parameters.

Table 5: Preliminary Instrument accuracy Requirements

Parameter	Proposed Accuracy
Deformation	0.1 mm 0.05 mm (convergence)
Strain	5 microstrain
Stress	0.7 MPa
Temperature	1 -1.5 °C (conduction) 0.1 °C (convection)

IV. Existing Geotechnical Instrumentation

A. Introduction

Activity in the area of development of geotechnical instrumentation for elevated temperature environments was largely suspended in the mid-1980's when the prototype thermomechanical experiments were discontinued. The interest of the various manufacturers in such products is based upon a very limited market, which currently does not include testing associated with nuclear waste disposal.

Commercially available geotechnical instrumentation was reviewed for potential application in the ESF thermomechanical experiments. This review was limited to contacting U.S. manufacturers of main line geotechnical instruments; neither specialty firms nor research and development engineering firms were contacted.

Literature and specification sheets for geotechnical instrumentation were reviewed, and suppliers of primary instruments were contacted directly to establish their background and experience with measurements made at elevated temperature. Literature from suppliers list only their commonly sold products. It is not uncommon to have geotechnical instruments that are modified for specific installations. Ranges, accuracies and operating temperatures of instruments can vary depending on the transducer used.

Instruments with elevated temperature capabilities and actual experience with geotechnical measurements at elevated temperatures were found to be limited. The rock mechanics instrumentation market is in general limited, and currently there is no motive to develop instruments with elevated temperature capabilities. All the suppliers contacted did indicate a willingness to design new equipment or modify existing equipment to meet specific requirements, providing their development costs could be recovered.

B. Summary of Required Instrumentation and Projected Environments

Table 6 lists the instruments required for the thermomechanical experiments by type, giving projected accuracy requirements, the projected temperature they must survive, and the estimated number of instruments needed. On the basis of the expected temperature environment that must be survived, existing instrumentation is divided into the categories of

1. Acceptable - existing instruments meet the temperature requirement and a good data base of experience exists verifying their reliability
2. Questionable - temperature specification for the instrument meets the temperature requirement, but existing operating experience is limited, indicating limited reliability assurance
3. Unacceptable - the instrumentation temperature requirement exceeds the instrument temperature specification

Table 6 indicates that acceptable instruments are available to meet low to medium temperature requirements (up to 170 ° C).

At temperatures above 150° C, several existing instruments are questionable. Vibrating wire stress meters (VWS) are available in both single axis and biaxial models with temperature specifications of 200° C, however, there is little operating data at high temperature to judge their reliability. Performance of the single axis VWS has been effected by emplacement parameters that make its calibration difficult.

At temperatures above 200° C, instruments are not available for load, stress and displacement measurements. In the MPBX gages, rod elongations are excessive, even with super Invar rods. Graphite fiber composite rods are being used and have lower thermal expansion. However, rod decomposition may occur in the non-specialized composite rods at temperatures in excess of 200° C. No stress gages are available with specifications above 200° C. The surface extensometers require tiltmeters, and no tiltmeters are available for elevated temperatures. Rock bolt load cells are also not available at elevated temperatures.

Many instruments are used in unique configurations or conditions, and it is therefore difficult to verify the accuracy of a field measurement. This is particularly true for the high temperature thermomechanical experiments. With the limited data available on high temperature field testing, several of the instruments have been classified as questionable with regard to accuracy. In general, if the instrument cannot meet temperature criteria, it can not meet the accuracy criteria at temperature.

As illustrated in Table 6, most of the identified high temperature requirements cannot be met with existing instrumentation. To assure performance at the high end of the temperature range, the development of new instruments, the modification of existing instruments, or the incorporation of

Table 6: Preliminary List of Instrumentation Required for the In Situ Thermomechanical Experiments.

Instrument	Estimated Accuracy Required	Maximum Temperature Predicted	Number Required	Temperature Criteria are Met	Accuracy Criteria are Met
MPBX	0.1 mm	50° C (rod) 40 °C (Sensor)	2-4	Yes	Yes
MPBX	0.1 mm	170° C (rod) 40 ° C (Sensor)	9-18	Yes	Yes
MPBX	0.1 mm	300° C (rod) 40 ° C (Sensor)	5-9	No	No
MPBX	0.1 mm	340° C (rod) 300 °C (Sensor)	20-30	No	No
Long Gage Surface Extensometer	0.1 mm	50° C	20-03	Yes	Yes
Long Gage Surface Extensometer	0.1 mm	300 ° C	25-40	No	No
Cross Drift Extensometer	0.1 mm	40° C	10-20	Yes	Yes
Cross Drift Extensometer	0.1 mm	300 °C	20-30	Questionable	Questionable
Tape Extensometer	0.1 mm	50° C	10-20	Yes	No
Borehole Stress Gage	0.7 MPa	200°C	15-30	Questionable	Questionable
Borehole Stress Gage	0.7 MPa	300°C	20-50	No	No
Thermocouple	1° C	1000° C	400-800	Yes	Yes
Flatjacks	NA	200° C	4-16	Yes	NA
Instrumented Rock Bolts	10% Full Scale	200°C	10-20	No	No
Instrumented Rock Bolts	10% Full Scale	300°C	20-30	No	No

enhanced components into existing instruments, will be required. However, many of the components needed for the modifications appear to be available as standard products outside of the geotechnical field.

The area of stress measurement at elevated temperature requires the most improvement. Rigid inclusion stress gages based upon vibrating wire transducers currently meet some of the temperature criteria and it is possible that their operating capabilities may be extended successfully to the high end of the temperature range required by the ESF thermomechanical experiments. However, the lack of operating experience suggests that other approaches should be investigated and utilized, in order to provide redundancy.

Displacement measuring instruments have performed successfully in moderate temperature environments, but their performance may be enhanced by the use of low thermal expansion materials like graphite composites. Enhanced transducer performance is also necessary to reach the high end of the temperature range required by the thermomechanical experiments, and appears to be available in the form of high temperature linear variable differential transformers (LVDTs), fiber optic transducers, laser extensometers and video imagery systems.

V. Technologies with Potential for High Temperature Application

A. Introduction

New instrument components and other technology with potential to enhance instrument performance at elevated temperatures are discussed below. Several criteria were used to evaluate the suitability of new technology or component instruments for use in high temperature instrumentation:

- existing geotechnical instrument designs and measurement principles should be emphasized, with retrofitting of different technology or components to enhance performance
- applications of different technology with proven performance in other technical areas of instrumentation were sought, rather than the development of new measuring systems
- new technology or new components should result in the same level, or preferable an increase in the reliability of the resulting instrumentation.

Instrument development should move in the direction of increased inherent reliability. Measurement systems should be as simple as possible to assure long term performance. The concept of inherent reliability is illustrated by the thermocouple, whose application in prototype thermomechanical experiments has been very successful. This inherent reliability resulted in very few failures in previous high temperature experiments.[3,7,8,9]

Several components and technologies were identified that have strong potentials to meet the evaluation criteria and that require minimum development effort. These are discussed in the following sections and include:

- high temperature LVDT displacement sensors
- graphite fiber composite materials with low thermal expansion
- fiber optic sensors
- light based remote sensing of convergence
- high resolution video imagery with digital processing.
- stress gages incorporating flatjacks

Existing instrumentation for measuring temperature has the capability to perform at the required temperatures and, therefore, instrumentation for measuring temperature is not discussed below.

B. High Temperature LVDTs

LVDT transducers that have an operating temperature over 600° C are available. These transducers have several high temperature applications including monitoring aircraft control structures near jet engine exhausts, nuclear reactor applications, and determining roller position in hot strip and slabbing mills, and are available as off-the-shelf items. The manufacturer of these LVDTs indicated that information on reliability and performance may be available from several users.

These LVDT transducers are manufactured in standard sizes and with full scale displacement ranges compatible with off-the-shelf MPBX instruments. They could also form the basis of the custom designed surface extensometers and wire convergence gages that are required in the ESF thermomechanical experiments. Stress gages that are based upon rock displacement measurements might also be modified by incorporating the high temperature LVDTs.

C. Graphite Fiber Composite Materials

The use of graphite fiber composite materials which have very low thermal expansion has the potential to reduce temperature induced deformations of instrument housings and components. Fiber composite materials can be engineered with very low thermal expansion and are currently employed in high technology applications where minimization of thermally induced deformation is critical. For example, the structure for the corrective optics for the Hubble Space Telescope is being designed with graphite fiber composites.

The use of graphite fiber composite rods has the potential of greatly reducing the temperature dependence of MPBXs. Currently two manufacturers use graphite composite rods in their high temperature extensometers. Application of MPBXs with graphite composite rods was reported[5] for monitoring steam assisted drainage of tar sands. Instruments were required to withstand 200° C, however results were not described in detail. The manufacturer indicated that the rods currently employed are standard commercial blanks used primarily for the manufacture of fishing rods. It is suspected that the rods would decompose at the upper end of the ESF test temperature range and that specialized rods will be required to meet the requirements of the ESF experiments.

D. Fiber Optic Sensors

Fiber optic sensors have considerable potential in elevated temperature environments. The sensor basis has inherent reliability, similar to the reliability of thermocouples. They are available with high temperature capabilities (glass fiber with stainless steel sheathing is rated at 430° C). The sensor probe components (glass fiber, glass optics) are small and easily mounted. The sensor can be remotely mounted (up to 100 m)[10] from the electronic components, which can then be located in a controlled environment. The electronic components (based upon LED light sources and photodiode cells) have very long life times. Because they can be resistant to ionizing radiation, they have the potential for use in long term monitoring of waste emplacement areas for performance confirmation.

Fiber optic sensors are currently being used to measure most physical properties, including displacement, strain, temperature and pressure.[10] A prototype single axis, rigid inclusion stressmeter using a fiber optic transducer to replace the vibrating wire transducer, was tested by Soil and Rock Instrumentation for the Salt Project[6] and showed very small thermal drift.

Fiber optic sensors include intensity modulated transducers, phase modulated sensors and remote monitoring of instruments. Intensity modulated transducers measure displacements by measuring the change in light intensity that results from movement of a fiber optic probe. Phase modulated sensors use inferometric techniques to measure the output of transducers. These techniques utilize phase shifting of the source light to measure small movements with a sensitivity of up to 10^{-13} meters and may be applied where very high sensitivity is required. Application of a phase modulated fiber optic sensor for measuring earth pressure was reported by Homuth.[11] Results demonstrated a resolution of approximately 10 lbs for sensors buried at depths between 5 and 8 feet. The same sensor was used to measure the weight of a man and the weight of a 100,000 lb M60 tank, indicating a very large range.

Remote monitoring of mechanically reading instruments may be performed by fitting a fiber with an optic fixed to focus on the face of a gage (displacement, pressure, etc.). At a remote location, a reading device is attached to the fiber, and the gage reading noted. In this approach, a suite of instruments could be manually read on a regular schedule, using a single reading device. This approach would be acceptable for the very slow changes in measured parameters anticipated in the thermomechanical experiments. Alternatively, the gages could be monitored by video equipment connected to each fiber optic.

E. Remote Distance Measuring

Light-based systems could be developed to measure drift convergence. Light based systems to measure surface displacements have been employed to measure convergence of underground openings in salt mines[12] with a reported accuracy of 7 mm.

A tunnel profiling system is available from Amberg Measuring Technique Ltd. that has a reported accuracy of 5 mm. This type of measuring system can potentially be made more accurate by installing the profiler on a rigid fixed track so that repeated measurements would be taken from the same precise location to generate a series of profiles during one of the experiments to determine convergence.

Drift convergence has been measured using photographic techniques.[13] In this technique, reflector points are fixed around the perimeter of the drift in a cross-section normal to the camera axis. Photographs taken from a fixed point, with a fixed scale in the photo, can be used to calculate the absolute and relative motion of the reflector points. The reported accuracy was 0.0025 m.

F. High Resolution Video Imagery with Digital Processing

Video filming of surfaces can be used to monitor displacement. Fixed pins or reference points could be attached to the rock surface and base line measurements made with mechanical gages. Displacements of the reference points and fixed scales for calibration would then be recorded by video camera during the experiment. Manipulation of the digital image can be accomplished using various commercially available software systems, which allow image enhancement, definition of fixed points and measurement of distances, angles, and areas, using graphical interfaces.

Video systems can also be coupled to fiber optics which would allow remote imagery of boreholes or of convergence gages. Such a system could be used to measure fracture displacements inside the heated block experiment. Images of fractures intersecting borehole walls could be digitized at various applied pressures. Proper orientations of two fibers would allow measurement resolution of shear and normal displacements.

Using fiber optics, video images of the motion of extensometer rods could be made at close range. This could eliminate the need for any type of gage on the reference head. The length of rod extending out of the reference head would be measured by pixel mapping. The pixel calibration would be established with respect to a reference scale machined directly on the rod.

G. Stress Gages Incorporating Flatjacks

A relatively new stress change gage is available through two manufacturers that appears to meet requirements for accuracy and that will operate at elevated temperatures. This gage is described by Keller and Lowry,[14] and application of a similar instrument is discussed by Kessels.[15]

The operating principle of both gages is based upon the use of small, thin, high pressure flatjacks grouted into boreholes. The applied normal stress acting on the flatjack is determined by noting the fluid pressure at which the flatjack opens. The measurement is temperature insensitive because the pressurization is transient and is a direct measurement of the applied load.

The gage discussed by Kessels[15] is denoted as the AWID Flat Jack. Multiple measurements were made, using three different gages, over a period of 7 months, in a salt pillar loaded with large flatjacks. The measurements agreed with the applied load to within 4%. When used in a borehole heater test at the Asse salt mine in Germany, good gage performance was indicated at temperatures in the range of 250-300° C.

The gage manufactured by Science and Engineering Associates, Inc.[14] is denoted as the CALIP gage, for calibration in place. The CALIP instrument uses a ytterbium stress gage to measure stress continuously. The fluid pressure to the flatjack, when greater than the applied load, represents a direct measurement of stress to the yttrium gage, and therefore allows for calibration of the instrument at any time after installation. Additionally, as in the Kessel gage, the pressure which causes separation of the flatjack represents a direct measurement of the applied load.

VI. CONCLUSIONS

Current designs for the ESF thermomechanical experiments require displacement, stress and temperature instrumentation with capabilities of operating at temperatures between 200-350 °C. Review of available geotechnical instrumentation indicates that the projected operating temperatures exceed existing instrument specifications, and that modifications are needed to extend their operational temperature range. Modifications of existing instrument designs by incorporating different technology with proven applications in other technical fields appears to be a feasible approach toward developing reliable instruments. Technologies with the potential to extend the operating temperature range of the required instrumentation are

- graphite fiber composite materials
- fiber optics
- video imagery
- remote distance measuring instruments

Modification of instrumentation should be directed towards simplification of the measuring systems and increasing reliability

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