Application of SUSTERA high-{$T_c$} SQUIDs at and under the ground

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SUSTERA is the mutual aid organization (nonprofit organization) in which members conduct collaborative research on the sensing technology based on HTS-SQUIDs.

Initial members:
+ Fujitsu Ltd.
+ The Chugoku Electric Power Co., Inc.
+ MINDECO
+ ISTEC (until June, 2016)

Products: HTS-SQUID chip (module), compact cryostat
HTS SQUIDs with multilayer structure and ramp-edge JJs (2007~)

**Features**
- Integrated circuit structure with several oxide layers
- High-angle GB is eliminated from JJs and coils

**Advantages**
- Stable operation at 77 K
- Easy to fabricate multi-channel array sensor
- Robust against application of magnetic field
- High field sensitivity approaching LTS SQUIDs
Magnetometer with multi-turn input coil

Josephson junction
Base electrode (Washer)
Counter electrode
Input coil
Superconducting contact

Pickup coil

15 mm

2.2 mm

13.5 mm

5 µm

100 µm
Field noise spectra in Earth’s magnetic field

Magnetometer with multi-turn input coil

10 fT/Hz\(^{1/2}\)
SQUITEM-III system
for exploration of metal resources

- 15 kg
- 10.6 kg
- 2.5 kg
- 60 cm

# Compact design
# Vacuum maintenance free
# Keep LN₂ for 17 h
# > x 10 higher slew rate
 (> x 20 higher S/N)

Commissioned by JOGMEC

Slew rate = 10.5 mT/s


IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017. Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.
SQUITEM-III system
for exploration of metal resources

Commissioned by JOGMEC

15 kg
SQUID Magnetometer (by ISTEC)

10.6 kg
Receiver (by MINDECO)

2.5 kg

60 cm
# Compact design
# Vacuum maintenance free
# Keep LN₂ for 17 h
# > x 10 higher slew rate
(> x 20 higher S/N)

Actual exploration in Peru
Commissioned projects at SUSTERA

- Development of advanced bio-sensing technology using HTS-SQUID (JST S-innovation program; FY2009～)

- Development of highly-sensitive magnetic NDE for deterioration evaluation and maintenance of infrastructure (JST SIP program; FY2014～)

- Development of next-generation SQUITEM system (JOGMEC project; FY2010～FY2012, FY2014～FY2016)

- Development of SQUITEM system for exploration of geothermal reservoir (JOGMEC project; FY2016～)

- Development of long-distance EM logging system using SQUID sensors (JOGMEC project; FY2012～)
Highly-sensitive magnetic nondestructive evaluation for deterioration evaluation and maintenance of infrastructure

R&D Leader: Prof. Keiji Tsukada (Okayama University)

Member: K. Tsukada (Okayama Univ.)
K. Tanabe (SUSTERA)
T. Furukawa (JAPEIC)
T. Sasayama (Kyushu Univ.)

compact NDE system with MR sensor
highly-sensitive NDE system using SQUIDs
simulation, pulse ECT method with MR sensor
inverse problem

Supporting Member: Mitsui Engineering & Shipbuilding Co., Ltd.
Chugoku Electric Power Co., Inc.

Cross-ministerial SIP (Strategic Innovation Promotion Program) FY2014-2018
operated by Council for Science, Technology and Innovation, Cabinet Office

“Technology for maintenance, renewal, management of infrastructure” program

700,000 bridges, 100,000 tunnels many of them older than 50 years
huge maintenance cost has to be saved by technologies

44 R&D subjects (NDE techniques, materials, robotics, ICT, asset management)
supported by JST and NEDO
Highly-sensitive magnetic nondestructive evaluation for deterioration evaluation and maintenance of infrastructure

Target of NDE system with HTS-SQUIDs: Steel deck plate

Fatigue crack usually starts along a welding line inside a rib, and finally penetrates to the top surface of the deck plate.

An electromagnetic inspection technique is expected to detect fatigue cracks through an asphalt pavement.

By using HTS-SQUIDs with high sensitivity even at low frequencies, detection of non-through cracks as early-stage diagnosis is expected.
Issue of eddy current testing (ECT) of ferromagnetic material (ex. steel)

+ Distortion of eddy current flow around a crack changes the secondary field distribution which is detected by a sensor.

+ For the case of a ferromagnetic material, high permeability makes skin depth \( \delta = (2/\mu \sigma \omega)^{1/2} \) very short.

+ Leaked flux through a test object and a magnetic field generated by a magnetization also link to the sensor.

+ Permeability changes generally have a much greater effect on eddy current response than conductivity variations [1] and would make crack detection difficult.

[SQUID-ECT method using low frequency excitation may be advantageous.]

Trial fabricated SQUID-ECT system

Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.
Test steel plate with simulated crack (slit)

Steel plate (SM490A) 0.7 m x 1.0 m x 6 mm

- Non-through crack (Backside)
  - Length 50 mm
  - Width 1 mm
  - Depth 4 mm (2/3 of plate thickness)

- Penetrated crack
  - Length 50 mm
  - Width 1 mm
  - Depth 6 mm

Scan lines (8 lines with 30 mm interval)

Averaging every 2 mm of moving using encoder signal

2D contour map
NDE results

- Quadrupole pattern from penetrated crack is observed in Re data at both 20 and 160 Hz.
- Due to a longer δ, quadrupole pattern from backside crack can be observed in 20 Hz Re data.
- Re and Im components have different origins (flux leakage, eddy current).
- Background signal due to magnetization is reduced by decreasing the excitation frequency.
NDE system using a cart for field test
Development of long-distance EM logging system - Application to oil field -

Schematic of enhanced oil recovery (EOR) technology utilizing CO₂

Combination of electromagnetic (EM) method with seismography and gravity survey could significantly improve monitoring of CO₂ EOR.

Expected increments of oil production by CO₂ EOR

Resistivity difference

B. Kirkendall, J. Roberts 2004
Lawrence Livermore National Lab.
Development of long-range EM logging system
- Application to oil field -

- Insufficient sensitivity of conventional induction coil sensor → short distance
- Owing to high sensitivity of SQUID even at low frequencies

EM in steel-cased wells with the distance > 1000 m expected

Technical challenges:
- Analysis technique to compensate influence of steel casing
- High-power transmitter & injection coil
- HTS-SQUID receiver (magnetometer) usable in high pressure (30-70 MPa) and high temperature (200 °C) environment
- Remote control of SQUID magnetometer

Development of elementary technologies started in 2012
FY2012  JOGMEC “Innovative technology in oil and gas development field” program
FY2013-2015  JOGMEC “Technical solution project”
SQUID receiver system for use in a test well

Outer Vessel: CFRP (nonmetal)

1800 mm

CFRP covered by silicon rubber

Outer: 95mmφ

t=12.6mm

Pressure tightness

> 70 MPa confirmed

Electronics

x,y,z-SQUIDs

Glass Dewar

FLL controller

Battery

Optical fiber and Electrical cable

A/D E/O converter

Control of SQUIDs through 3 km long optical fiber confirmed
SQUID receiver system for use in a test well

- XYZ-SQUID
- Thermal sensor
- Cable with plastic tube for N₂ gas release
  - Inner diameter: 3.2 mmφ x 3
- Outer diam. of cable: 17.8 mmφ
- 700 mm  690 cc
- LN₂ holding time: 40 h
- Temperature rise: 0.3 K at -270 m
  caused only by difference of elevation
Field test (real measurement in a borehole with steel casing)

Feasibility of induction logging was examined by detecting primary magnetic field.

2\textsuperscript{nd} magnetic field \sim 1/3 of primary magnetic field.

SQUID receiver
Test results

Stable operation in borehole filled with oily water at $\sim 300$ m confirmed.

Indicating possibility of long distance EM logging : $> 1000$m
Summary

- At SUSTERA, HTS-SQUIDs with the multilayer structure and ramp-edge junctions are routinely fabricated using the facility transferred from ISTEC.

- These multilayer HTS-SQUIDs have been applied to various systems for use at and under the ground including TEM systems for exploration of metal and geothermal resources, EM logging system for monitoring of oil layer, and NDE system.

- Detection of backside crack-like defects in a steel plate at 80 mm lift-off has been demonstrated, indicating a possibility of application of HTS-SQUIDs to NDE of infrastructure.

- A SQUID receiver system for cross-hole EM logging has been developed. Stable operation of SQUIDs at about 300 m depth in a steel-cased well and observation of transient magnetic field from a coil placed at 800 m distance have been demonstrated, indicating possibility of application to long-distance EM logging.
Possibilities of HTS-SQUIDs for use at and under the ground in the near future

Seabed resources survey (hydrothermal polymetallic ore, methane hydrate)
SUSTERA Products

**HTS SQUID gradiometer chip**

**DL35**

- **SUSTERA Catalog No. 0001**
- **http://www.sustera.or.jp/**

*High sensitivity chip to detect minute magnetic field gradient*

<<< General-purpose SQUID gradiometer chip utilized by any users>>>*

- **Design:** 1st order planar gradiometer (directly coupled)
- **Working Temp.:** 77 K (Liq. N₂ Temp.)

![Image of DL35](image)

Pickup coil

Baseline 5.5 mm

4.3 mm

5.0 mm

15.0 mm

[Guaranteed properties]

- Critical current $I_c$: > 15 μA
- Modulation voltage $\Delta V$: > 15 μV
- Flux noise $\phi_0$ (white): <100 μ$\phi_0$/Hz$^{1/2}$
- Effective area $A_{eff}$ (for one pickup coil): $\sim$ 0.1 mm$^2$

*(2016.10.31)*

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**Portable cryostat for HTS devices**

**CD1**

- **SUSTERA Catalog No. 0002E**
- **http://www.sustera.or.jp/**

*For easy testing using HTS-SQUID sensor*

<<< For use of external pickup coil, suitable for outdoor use>>>*

- **Specifications:** Aluminum outer container, inner glass Dewar
- **Cooling Temp.:** 4.7 K (with liquid N₂)

**Example of usage**

- Junction generator
- Rock in amp
- Pick-up coil
- Induction coil

![Image of CD1](image)

- **D:** 140 mm
- **H:** 370 mm
- **Weight:** 4.2 kg (incl. probe)

[Features]

- Liq. N₂ keeping time: > 14 hours (with SQUID probe inserted)
- Magnicon and STARCryo FLL attachable
- Permalloy shield installable (option)
- Flange, port, connectors can be customized

*(2016.11.1)*

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Thank you for your attention.