Building a Successful Company in Superconductivity

Ronald E. Sager
Quantum Design, Inc.
The "Quantum Way"
(Small Company Viewpoint)

* Biased in favor of small companies
* Biased against venture capital investment
* Biased against public offerings
Quantum Design, Inc.
(Incorporated April 13, 1982)

Founders

* Dave Cox, B.S. Video Engineering
  - Cryogenic Design and Fabrication
* Barry Lindgren, B.S. Physics
  - Sales, Management, Administration
* Ron Sager, Ph.D. Physics
  - Research, Product Development
* Mike Simmonds, Ph.D. Physics
  - Research, Product Development
Why We Started Quantum Design

* QD founders were S.H.E. employees
* “Rules of Thumb”
  - $100K - $140K/man year
  - 2-3 month cash / credit reserve (revenues)
  - Debt to equity ratio (< 1)
  - Prompt payment of payables
* S.H.E. in 1982
  - Overstaffed (105 people - $3.5M revenue)
  - Payables (> 90 days)
  - Bad management decisions - struggle to meet payroll

Quantum Design - July 2000
Quantum Design, Inc. - Day 1
(Incorporated April 13, 1982)

* Assets: One bay, 4 keys, $8,000, 4 warm bodies

* Liabilities: $15,000 3-year lease
QUANTUM DESIGN

Helping to bridge the gap between theory and application

Call Quantum Design for expert consultation or engineering support in any of the following areas:

- Cryogenic engineering and electronic design
- Superconducting Instrumentation
- Ultra-low noise magnetic and electrical measurements
- Josephson junction physics and SQUID devices
- Experimental solid-state physics.

Meet the QUANTUM Design team

Four highly qualified specialists ready to help you meet your design goals within affordable time/cost parameters.

Michael Simmonds
Dr. Simmonds has extensive experience in the design and development of superconducting instrumentation, advanced quantum interference devices and electronic control systems. He has been heavily involved in both fundamental research and product development, is intimately familiar with all aspects of cryogenic measuring techniques, and has designed optically pumped and fusing gate magnetometers.

Ronald Sager
Dr. Sager has acquired a broad background in both theoretical and experimental disciplines. He has supervised the development of a low-power cryocooler designed to reach temperatures below 10K, has experience in oceanographic applications of cryogenic detectors and has studied noise suppression in magnetic gradiometers using both empirical measurements and computer modeling.

David Cox
Dave Cox is a specialist in the engineering aspects of superconducting devices and cryogenic design. He has the unique ability to express difficult concepts in working prototypes and to provide Quantum Design customers with thoroughly tested, reliable instrumentation. Among many projects, Dave has to his credit the successful fabrication of several prototype instruments for biomagnetic research.

Barry Lindgren
Our general manager is your contact at Quantum Design—the person to call to discuss a new research, design or development project. He has a strong background in cryogenics, experience in both laboratory and field instrumentation and is well attuned to our customers' need for application support.

QUANTUM DESIGN

11404 Sorrento Valley Road, Suite 114, San Diego, California 92121 (714) 457-0248
INTRODUCING A UNIQUE NEW ENGINEERING COMPANY IN APPLIED PHYSICS

QUANTUM DESIGN

Helping to bridge the gap between theory and reality.

Call Quantum for rapid and extremely effective consulting and assistance in the following areas of applied physics

☐ Cryogenic Engineering  ☐ Ultra-low noise magnetic and electrical measurements
☐ Application and design of SQUID amplifier-based equipment and Josephson junction physics
☐ Experimental solid-state physics design, engineering, and hardware development.

Meet the QUANTUM Design team

Michael Simmonds
Dr. Simmonds has extensive experience in the design and application of superconducting instruments, including magnetometers, gradiometers, and susceptometers. He has been heavily involved in the design and fabrication of advanced quantum interference devices. Dr. Simmonds has also designed optically pumped and fluxgate magnetometers.

Ronald Sager
Development of 4.2K cryocooler, research and development of hybrid SQUID devices, and oceanographic application of SQUID sensors. Also noise suppression in magnetic sensors and computer modeling. Assisted in cesium magnetometer development.

David Cox
Specialist in the design of superconducting instruments — hands-on ability to rapidly fabricate concepts into application — such as one-of-a-kind gradiometers for medical research.

Barry Lindgren
Our general manager is your contact at Quantum Design — the person to call to discuss a new research, design or development project. With a strong cryogenic background, as well as extensive experience with ultra-low temperature refrigeration systems and superconducting magnetometers/gradimeters for field use, Barry is well attuned to your applications support needs.

11404 Sorrento Valley Road, Suite 114, San Diego, California 92121
(714) 457-0248
"FRACING" GAS WELLS

HYDRAULIC FLUID & MAGNETIC PROPANT

≈ 1 km

> 5 km

.5 km

MAGNETIC PROPANT

MAGNETIC PROPANT

B_{earth}
Fracture Proppant Mapping by use of Surface Superconducting Magnetometers


*Member SPE-AIME

ABSTRACT

A surface array of sensitive superconducting magnetometers was deployed in the first set of a planned series of field tests and successfully mapped a shallow, magnetically tagged proppant in a horizontal fracture. In the project, a coordinated GRI-Hunter-Amoco-Dowell effort, the magnetometer array was supported by tiltmeters, borehole television, and stimulation pressure/flow data to analyze a complex vertical-horizontal fracture formation process. The horizontal propped disk radius was determined to be 60 feet at shut-in, with disk center offset to the east-northeast of the wellbore. The complexity of fracture formation and proppant deposition during the initial field tests emphasized the importance of using a well-coordinated set of complementary geophysical instruments for future proppant mapping tests at greater depths.

INTRODUCTION

Low-permeability gas reservoirs contain vast amounts of potentially recoverable gas resources [1, 2]. Massive hydraulic fracturing (MHF) has been found to be a viable method for increasing production in low-permeability reservoirs [3, 4]. Optimal application of this type of stimulation requires detailed knowledge of the results of the in-situ fracturing process. In recent years, several geophysical techniques have been applied with the goal of determining information about fracture azimuth, including surface electric potential surveys [5, 6, 7, 8], passive and active seismic monitoring [6, 9, 10], pressure transient testing [11], and surface deformation measurements [3, 5, 12, 13, 14]. Of these, surface electrical potential and surface deformation surveys (using tiltmeters) have been shown to be viable at 8000-foot depths in the Wattenberg gas field north of Denver, Colorado [7, 12, 13, 15].

Even if the geometry of the hydraulic fracture can be identified, optimal stimulation performance depends on proppant transport and final propped geometry [16, 17]. Thus the ability to map the propped region of a hydraulic fracture is of primary importance. Proppant mapping goes as step beyond measuring azimuth to determination of propped fracture length and orientation. In 1982 Hunter Geophysics entered into a contract with the Gas Research Institute to develop a surface superconducting magnetometer field system for application in fracture proppant mapping. Amoco Production Company and Dowell Division of Dow Chemical U.S.A. agreed to become industry partners and to provide resources and field support to the research program. To date Hunter has developed field hardware and software for an array of magnetometers, and has supplied an ancillary array of tiltmeters for mapping of fracture azimuth. Two field experiments have been carried out at an Amoco research site near the Port of Catoosa, Tulsa, Oklahoma. This paper will focus on the results of the second tests, called "Catoosa II Tests," with emphasis on magnetometer measurements of proppant dimensions. Ancillary results from measurements by an array of surface tiltmeters, borehole television camera observations, and pressure/flow data will also be presented.

APPROACH OF THE PROPANT MAPPING PROJECT

The methodology presented in this paper is the result of the first phase of a broad-based fracture/propant diagnostic program which presently involves a joint GRI-Hunter-Amoco-Dowell effort. The program will be expanded in the near future to incorporate other supplementary geophysical methodologies. The present approach involves use of a surface array of highly sensitive cryogenic magnetometers to detect the anomalous spatial magnetic field of a magnetically tagged proppant. From the characteristics of the anomalous vector magnetic field, proppant dimensions were inferred using
figure 1. instrument arrays: catoosa ii tests.

figure 2. squid magnetometer.
Figure 9. Simultaneous measurements of background magnetic field (Raw Data).

Figure 10. SQUID magnetometer rotation during injection; as recorded by internal orientation sensing devices (OSD's) (Raw Data).

Figure 11. Magnetic field differences during injection (Raw Data).

Figure 12. Magnetic field residuals as a function of time at SQUID #5.
FIGURE 5. THREE STAGES OF FRACTURE FORMATION
(During and After Fluid Injection, as Recorded by Array Tiltmeter).

FIGURE 6. MEASURED TILT PROFILES DURING STAGES I AND II OF FRACTURE FORMATION.

FIGURE 7. THEORETICAL TILT VECTOR AND SURFACE DEFORMATION PATTERNS.

FIGURE 8. MAGNETIC FIELD PROFILES FOR HORIZONTAL DISK PROPPANT
(Empirical Data from Scale Model. Magnetic Field Components are in Relative Units.)
FIGURE 15. SCENARIO FOR PROPPED FRACTURE EVOLUTION: CATOOSA II TESTS.
Figure 13. Magnetic residuals at shut-in, as a function of squid magnetometer location east and west of wellbore.

Figure 14. Dimensions of fracture proppant.
What Makes A Good Product?
What Makes a Good Product?

* Many people want to buy it

* You can sell it for a profit
Why Do People Want To Buy It?

* Personal enjoyment
* Provides convenience
* Solves a problem
* Helps make or save money
* Cost is commensurate with benefit
* Good economics
What Makes a Good Instrument?

* Performs a needed measurement
* Easy to use
* Reliable
* Well-supported by manufacturer
Commercial Encounters...

* OF THE FIRST KIND
  - You get a government contract to build one

* OF THE SECOND KIND
  - You sell a couple to your friends

* OF THE THIRD KIND
  - You manufacture dozens for a wide range of users
For a Commercial Product

* Engineered for manufacturing and testing
* Entire manufacturing process is documented
* Intuitive and forgiving for wide range of users
* Backed by professional service and support

* Useful enough to be bought with your own money
Quantum Design’s Goals

* Keep your customers happy.
* Make a profit.
* Create an enjoyable place to work.
Contributing Factors

* Good products
* Good Service
* Good financial management
* Good personnel management
Thermal Management Workshop
October 1995

University of Minnesota
WHY USE CRYOGENIC SYSTEMS?

VERY LARGE MAGNETIC FIELDS
LABORATORY MEASUREMENTS/SCIENTIFIC MEASUREMENTS
MAGNETIC FUSION PLASMA CONFINEMENT

HIGH SENSITIVITY DETECTORS
QUANTUM MECHANICAL DEVICES (SQUIDs)
REDUCED THERMAL NOISE

HIGH SPEED ELECTRONICS
HIGH SPEED SWITCHING OF JOSEPHSON JUNCTIONS
FASTER CONVENTIONAL ELECTRONICS

SCIENTIFIC INVESTIGATIONS
SUPERCONDUCTIVITY
SUPERFLUIDS
GENERAL QUANTUM MECHANICAL PHENOMENA
## TYPICAL REFRIGERATION SYSTEMS

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>G-M</th>
<th>BOREAS</th>
<th>G-M / JT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINIMUM TEMPERATURE</td>
<td>7-12K</td>
<td>&lt;4K</td>
<td>4.1K</td>
</tr>
<tr>
<td>COOLING POWER</td>
<td>1-10 W @ 10K</td>
<td>1W @ 4.2K</td>
<td>1-10W @ 4.2K</td>
</tr>
<tr>
<td>INPUT POWER</td>
<td>2.2-5.0 KW</td>
<td>2.9 KW</td>
<td>5-10 KW</td>
</tr>
<tr>
<td>COST</td>
<td>$15,000 - $20,000</td>
<td>$38,000 - $50,000</td>
<td>&gt;$30,000</td>
</tr>
</tbody>
</table>
Josephson Junction Computers

Good News:


4-bit Josephson Computer - 1988
1841 Modified Variable Threshold Logic (MVTL) Gates
MVTL Gate: 1-2 psec Switching @ 12 μWatts
5 mm x 5 mm Chip - AM 2901

<table>
<thead>
<tr>
<th>Device</th>
<th>Clock (MHz)</th>
<th>Pwr Dis. (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>30</td>
<td>1.4</td>
</tr>
<tr>
<td>GaAs</td>
<td>72</td>
<td>2.2</td>
</tr>
<tr>
<td>Josephson</td>
<td>770</td>
<td>0.005</td>
</tr>
</tbody>
</table>

(Leads - 1-2W, Cryostat - 1.5W)

1990: 8-bit Josephson DSP Chip
6300 MVTL Gates, 4 bytes Memory
Memory: 500 psec Access Time
100X Faster than CMOS Version

Josephson MVTL Gate Theoretical Limit ~ 0.2 psec.
\[ \Delta t \sim \frac{h}{\Delta E} \]
\[ \Delta E = \text{Energy Gap} \]
\[ h = \text{Planck's Const.} \]
Josephson Junction Computers

Bad News:

Existing computers require 4.2K temperature
  Reliable Nb technology
  Low power dissipation
  Liquid helium required
  Cryocoolers cost in excess of $30,000

High-T\(_c\) Materials - Good News
  Some reports of reproducible JJs in High-T\(_c\)
  Operate at 77K
  Operate with cryocoolers which are much cheaper

High-T\(_c\) Materials - Bad News
  Dissipation will be 250X greater at 77K
  (V and I are both proportional to temperature)

<table>
<thead>
<tr>
<th>Device</th>
<th>Temp (K)</th>
<th>Power ((\mu)W)</th>
<th>Freq (Mhz)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb JJ</td>
<td>4.2K</td>
<td>5</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Tl JJ</td>
<td>77</td>
<td>1,300</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>1(\mu) CMOS</td>
<td>77</td>
<td>10</td>
<td>50</td>
<td>3.3</td>
</tr>
<tr>
<td>1(\mu) CMOS</td>
<td>77</td>
<td>200</td>
<td>1,000</td>
<td>3.3 (freq-scaled)</td>
</tr>
</tbody>
</table>

Low T\(_c\) Materials - Bad News

  IBM JJ computer (1960s) - Goal was 70 MIPS.
  Today - Silicon has far surpassed this
Josephson Junction Computers

More Bad News:

Density of Components

Silicon now at 0.35 - 0.25μ dimensions
JJ memory cells are limited in size
\( \phi_o = 2 \times 10^{-15} \) webers \((\phi_o = LI_c)\)
Maximum \( I_c \sim 1 \) mamp
Minimum \( L/d \sim 5 \times 10^{-8} \) H/M
Minimum loop area \( \sim 1,000 \mu^2 \) (30μ x 30μ)
To prevent cross talk: 80μ x 80μ
Rapid single flux Quantum (RSFQ) Logic
Similar problem with scaling down size

Present Status of Speed

JJ's now at about 3 GHz - Possibly get to 100 GHz?
Silicon now at about 300 Mhz - 2 GHz in 10 years
(silicon is on track to do this)

Problems of Implementation

Hybrid systems - interface problems (interconnects)
Heat dissipation at cryogenic temperatures
Impedance matching
JJ High Speed - problems similar to silicon (not heat)
Impedance matching difficulties
Propagation times
Josephson Junction Computers

Hasuo’s Conclusions

1) “Both density and speed of transistors will saturate in the near future, independent of material” (??)

2) “Bioelectric or optical computers will be developed, but at present they are still primitive. The Josephson computer will most likely be the solution.”

3) “Commercially, the development of the Josephson computer relies on finding a market.....”

4) “If a full Josephson computer having powerful processors could be developed soon, a large market would be available.”

5) Hasuo suggests several possible uses:
   - Radio astronomy
   - Medicine (neuromagnetometers) - 160 SQUIDs
   - Possibly 1,000 SQUIDs

References:


A Tale of Two Conferences

* Cryocooler Workshop - 1981

* Cryocooler Workshop - 1995
Cryocooler Workshop Attendees

* Government Funding Agents
* Government Scientists
* Academic Community
* Small Cryogenic Research Companies
* Cryocooler Manufacturers
Cryocoolers - 1981

* Cryocoolers will expand superconductivity markets
* Present cryocoolers are too expensive
* Larger demand → high volume manufacturing
* Large volume → reduce cost of cryocoolers
* Cheaper cryocoolers will help superconductivity
Cryocoolers - 1995

* Cryocoolers will expand superconductivity markets
* Present cryocoolers are too expensive
* Larger demand → high volume manufacturing
* Large volume → reduce cost of cryocoolers
* Cheaper cryocoolers will help superconductivity
Mechanical Technologies Market
“Pull” & “Push Experience

- 43 Mechanical technologies
- Insertion only after end-user pull identified
- If ‘pull’ exists, 2-6 years to introduction regardless of difficulty

Advanced Technology Operations
GE Aircraft Engines
IEEE AES Systems Magazine Aug 93