# Sensing systems for “harsh” environments

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Rice University
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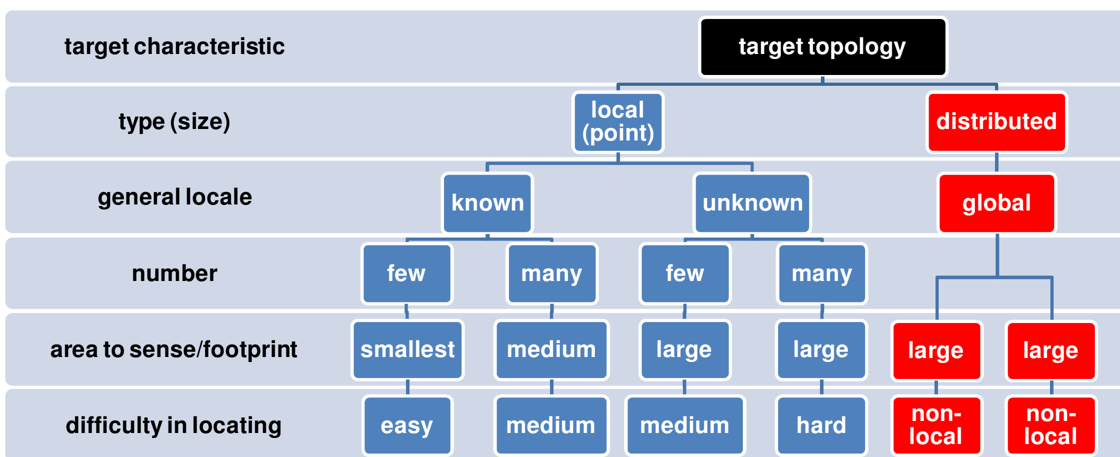
# How do you prevent a problem?

- you either prevent the cause
  - which implies you know what the cause is
  - if the cause is not present, applying a “cure” may be worse than doing nothing
- or you “remediate” before a minor problem becomes a major one
  - which implies you have a means of early detection
- in either case you have to see (i.e., sense) something with sufficient warning time to take action
  - in the parlance of the field, you need a sensor – actuator pair
  - sensor must communicate with the actuator via a “controller”
    - this also requires intelligence in the controller so the action is appropriate to the cause

# “Defect” taxonomy

- designing new sensor systems: organize “targets” (defects) into families
  - defect dimensionality - either point-like or distributed
  - location of the defect - either known *a-priori*, or completely unknown
  - number of distinct defects - either few or many
  - how often do defects occur, and how soon do you need to know
- from these properties many consequences depend…
  - easy case: small number of isolated defects, general location known from other considerations (e.g., cracks in high stress regions, known from design of structure)
    - would require only a few sensors placed in predetermined locations
  - harder(est) case: isolated point defects occurring anywhere at any time in a structure
    - reliable detection requires surveillance of entire structure all the time
    - for small number of defects may be possible to identify their location with only moderate effort
    - for large number of defects “under-sampling” can lead to significant uncertainties in location (in both space and time!)



# “Seeing” a defect

- to “see” a defect (or its cause) requires both something that detects (the sensor) and a way to communicate that information to the controller
- remote, or stand-off, detection
  - in some sense, always an imaging technique
    - still requires a sensor / transducer as the “receiver”
    - you need to know the path over which the “transduction physics” integrates
    - “communications channel” is the media you look through
    - requires some sort of (most likely non-unique) inversion process
  - examples: vision, hearing
- point, or local, sensing
  - usually provides highest sensitivity
  - still need to know “where/when” the data came from
  - to determine the state of large, complex objects you need a LOT of sensors
  - “communications channel” carries information from point of contact to controller
  - examples: touch, smell
- the quality of the communications channel has a strong influence on
  - where the sensor can be relative to the problem
  - how big an area one sensor can see
  - how “smart” the sensor has to be…

# An "ideal" sensor-actuator pair

- self healing materials
  - objective: a material that contains components that respond to damage to repair that damage
    - contains MANY "point sensors" and "actuators"
    - the point sensor is in direct "communication" with the actuator
      - in fact, it may not be easy (or desirable) to separate the sensing from the actuation…
  - autogeneous (self) healing on frost deteriorated concrete has been studied for many decades
    - McHenry D. and Brewer H.W.: J. of the ACI, Vol.41 p.272, 9-12 (1945)
    - Abrams A.: Concrete V. 10, p.50, August (1925)
  - application to prevent hydrocarbon leaks: Schlumberger FUTUR self-healing cement technology

# Remote, point, wired, and/or autonomous sensors

- **with power and money you can do many things (or at least sense many things)**
  - remote sensing
    - "complex" receiver
    - with a "light source" bright enough you can see at least a little way through even opaque media
  - point sensors
    - external wired connection allowed: wireline systems
      - excellent communications channel
      - "unlimited" power consumption and data rate
    - autonomous systems: no "physical" external connection allowed
      - critical issue is total system power budget
      - locally powered: battery or scavenged
      - "un-powered": powered from outside via communications channel
        - rf id tags and electronic structural surveillance (ESS) tags
        - rf powered, but severely limited range, especially in conductive medium
          - e.g., attenuation in sea water @ 1MHz: ~10dB/ft

- **Drilling and Excavation Technologies for the Future, Committee on Advanced Drilling Technologies, National Research Council**
  **[ISBN: 0-309-57320-3, 176 pages, 6 x 9, (1994)]**

TABLE 2.1 Key Elements of Drilling Systems and Areas of Possible Evolutionary and Revolutionary Improvement

| DRILLING SYSTEM PROCESS | CURRENT STATUS | ANTICIPATED LEVEL OF IMPROVEMENT |
|---|---|---|
| Rock breaking | Key element in drilling process: bottleneck to increased drilling rate | Evolutionary |
| Debris removal | Potential bottleneck, especially in tunneling | Evolutionary |
| Borehole stabilization | Discontinuous process | Evolutionary |
| Drill bit sensing and evaluation | Technology not available | Revolutionary |
| Rock properties sensing and evaluation | Some measurement-while-drilling capability now exists | Revolutionary |
| Drill bit positioning and steering | Notable recent advances in steering | Revolutionary |
| Borehole sensing | Technology not available | Revolutionary |

state-of-the-art :
’94 world record extended reach well: North Sea, accessed target at horizontal distance of 23,917 ft (4.53 miles) at depth of ~9,000 ft. Length of hole was 28,743 ft (5.44 miles).

# Sensor systems for down-hole use

- **Advanced Energy Consortium**
  - vision: facilitate pre-competitive research in micro- and nanotechnology materials and sensors that have potential to create positive and disruptive change in recovery from new and existing reservoirs
  - goals:
    - develop intelligent subsurface micro and nanosensors that can be injected into reservoirs to characterize the space in three dimensions and
    - improve the recovery of existing and new hydrocarbon resources
    - leverage existing surface infrastructure, the technology will minimize environmental impact
- our AEC project: Near Borehole Condition Sensing

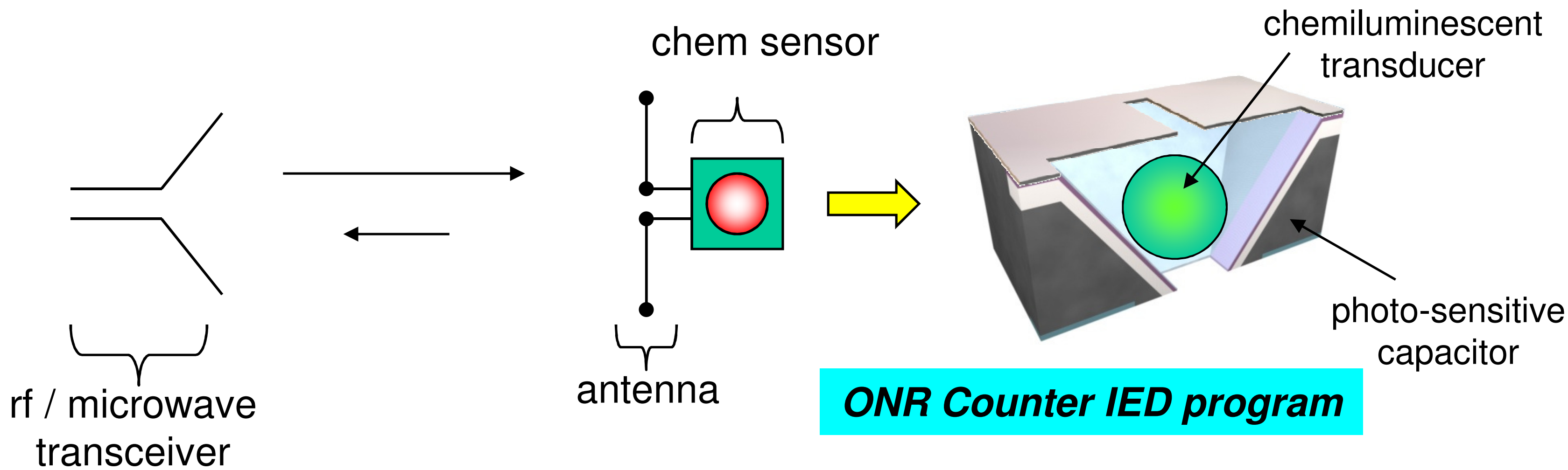
# An example: UT electronic structural surveillance (ESS) sensor platform

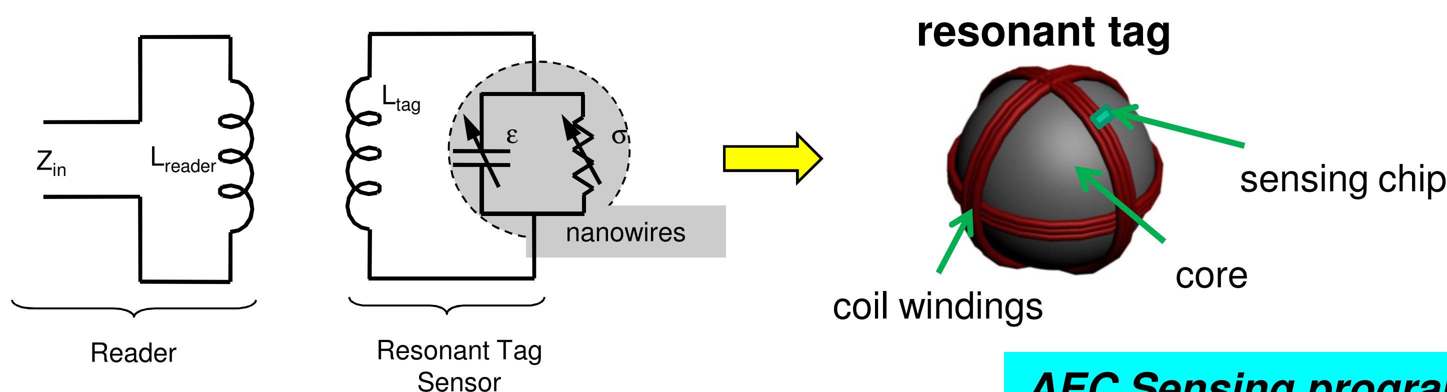
- with Sharon Wood, UT-Austin Civil Engineering
  - funded by the NSF and by a NIST TIP award
- sensor embedded in concrete, sealed against potentially harsh, corrosive environment
- periodically assess sensors – months to years
  - external reader coil powers and interrogates the sensor
- our ESS wireless passive sensor platform can be used to sense
  - corrosion, conductivity/resistivity, temperature
- things that happen when you leave the lab…
  - installation / placement is a big deal
  - continuous field tests have now been underway for over eight years
    - long term survival and packaging are serious issues
- so must balance out-of-the-box thinking and constraints of the application….


S. Wood and D. Neikirk, US-Japan Joint Workshop, US-Japan Cooperative Research in Urban Earthquake Disaster Mitigation, Seattle, 2001.
L. Novak, K. Grizzle, S. Wood, D. Neikirk, Proc. SPIE's Vol. 5057 8th Annual International Symposium on NDE for Health Monitoring and Diagnostics: Smart Systems and NDE for Civil Infrastructures, March 3-6, 2003, pp. 358-363.

# Remotely monitored point detectors

- **chemically sensitive un-powered point detectors interrogated using rf / microwave signals**
  - **the only "on-board power" required is in the chemistry**

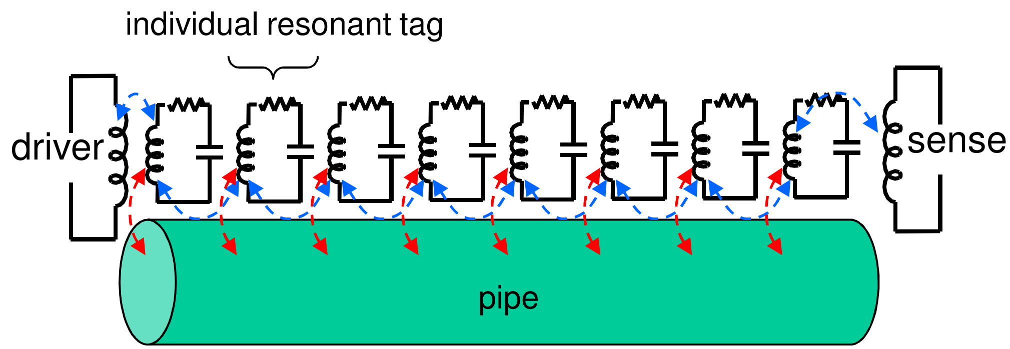


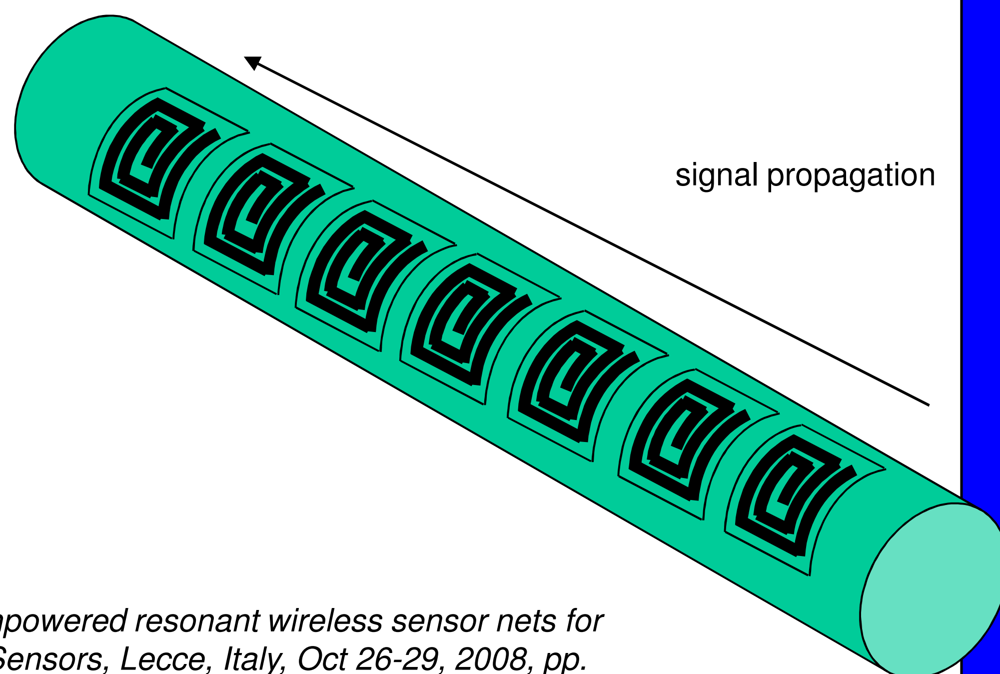




***AEC Sensing program***

# Other ideas: sensing and communications using "Wireline-in-cement"?

- **sensing and data path in the cement surrounding the casing**
- **electrical transmission path does not require dc electrical contact between "segments"**
  - **use inductively coupled resonators (magneto-inductive waveguide) as interconnect**
    - **use as pick-up for sensors in interstitial space**
      - **corrosion monitoring?**
      - **cement failure?**





*Pasupathy, P., Zhuzhou, M., Neikirk, D.P., Wood, S.L., "Unpowered resonant wireless sensor nets for structural health monitoring," 2008 IEEE Conference on Sensors, Lecce, Italy, Oct 26-29, 2008, pp. 697-700*

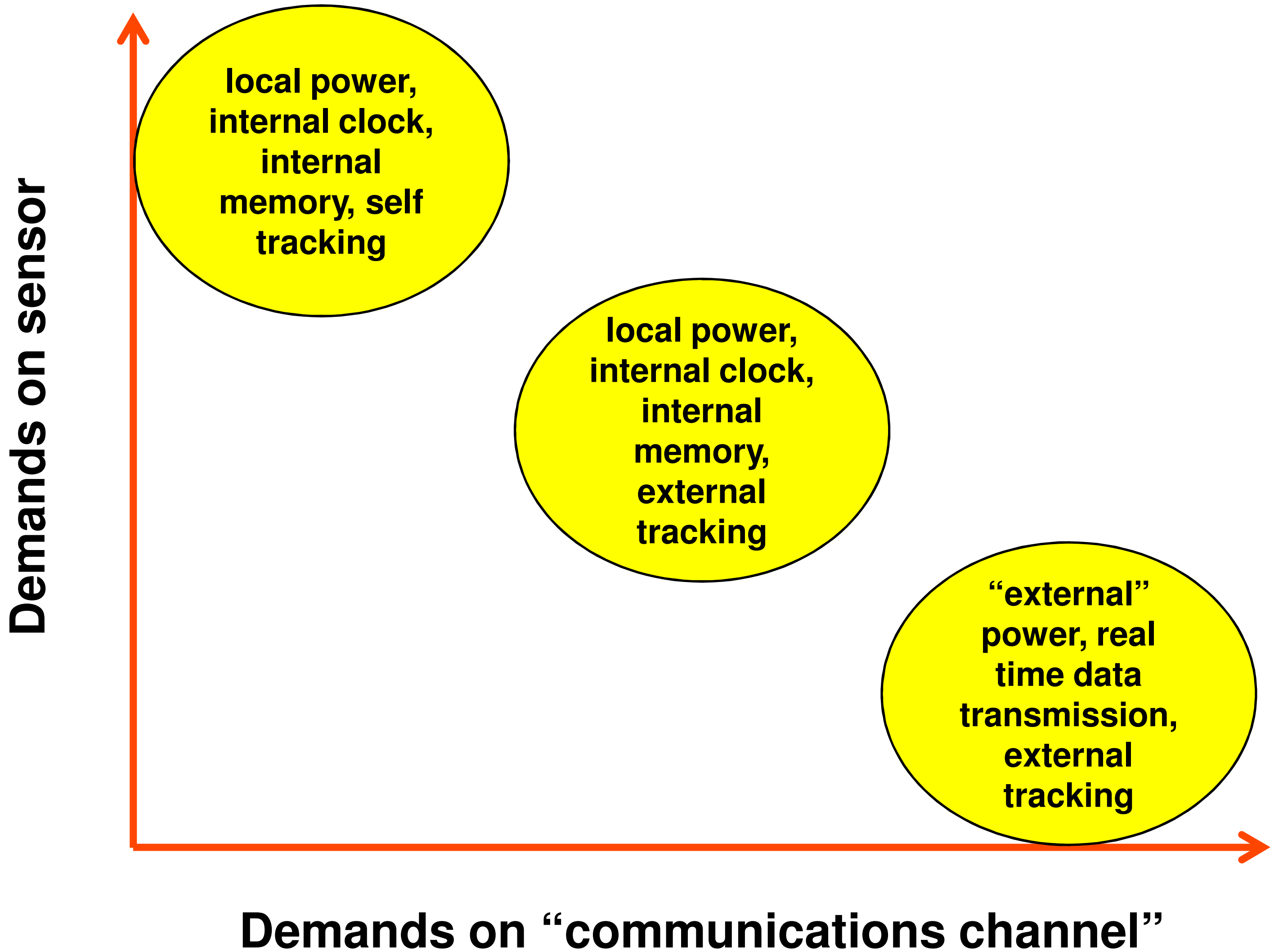
# Not only what, but WHERE

- you probably really need to know where data came from
  - geo-location is critical
    - would like 4D (time and 3D)
      - even 1-d (distance) would be better than nothing…
  - active guidance during placement would be nice
    - but "self guidance" without track data is of limited value…
- "external" position monitoring
  - track object using some form of "wave" interaction
    - time of flight, direction from known observation location to sensor
      - electromagnetic
      - acoustic
- "dead reckoning"
  - completely internal determination and storage of track data
    - need VERY accurate clock and acceleration data…

# Sensor system types

- completely autonomous
  - sensor sub-system + memory, plus:
    - 3C accelerometers, internal clock, internal memory
      - accuracy is demanding since errors are cumulative (track calculation requires two time integrations…)
  - read sensor and track data "on demand"
  - "low" demand on communications channel
- partially autonomous
  - sensor sub-system + memory, but track externally
    - tracking via communications channel
  - read sensor data "on demand"
    - still need internal clock to correlate sensor data to track
- "dumb"
  - sensor sub-system, track externally, and use communication system to allow real time data transmission
    - no memory requirement
  - very high demand on the communications channel

# Sensor system requirements

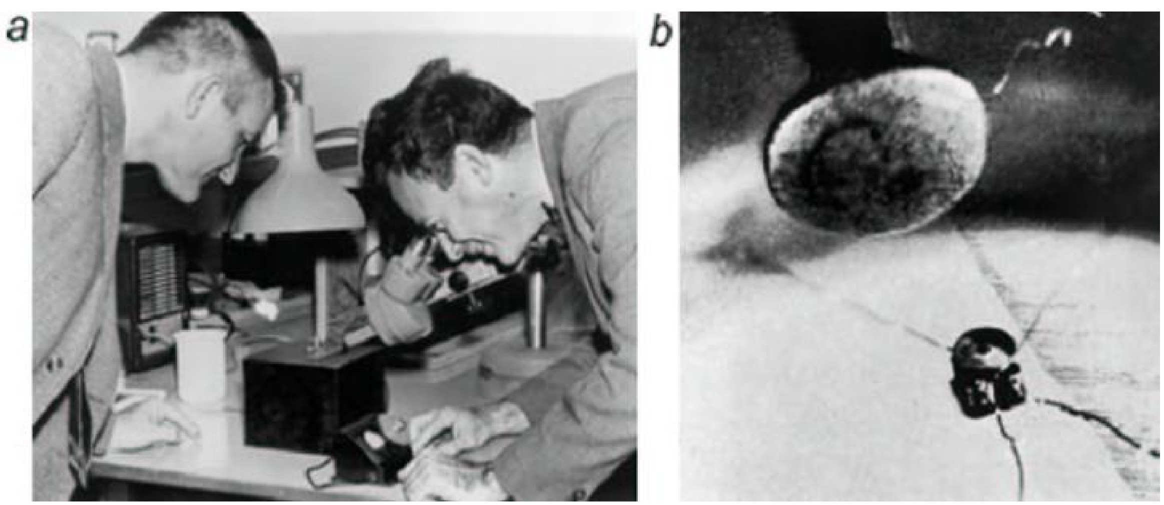


# 1959: “There's Plenty of Room at the Bottom”

- talk by Richard Feynman, December 29th, 1959 at the annual meeting of the American Physical Society
- http://www.its.caltech.edu/~feynman/plenty.html
- Feynman’s micro challenges:
  - “Just for the fun of it, and in order to get kids interested in this field, I would propose … some kind of high school competition.… The Los Angeles high school could send a pin to the Venice high school on which it says, ‘How's this?‘’ They get the pin back, and in the dot of the ‘I’ it says, ‘Not so hot.’“
  - “… I want to offer another prize---if I can figure out how to phrase it so that I don't get into a mess of arguments about definitions---of another $1,000 to the first guy who makes an operating electric motor---a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube.”

# Within one year of the challenge: the “tiny motor” winner is

- William McLellan (left in photo)
  - the motor was hand-made, 0.38 mm wide, and weighed 250 micro grams
  - it generated only a very small torque
  - adding a reduction gear system clearly defeats the original objective of small size. Furthermore, electromagnetic forces do not scale well with decreasing size because it becomes difficult to obtain the needed current in very small motors




(from the Caltech archives)

# More from “There's Plenty of Room at the Bottom” (December 29th, 1959)

- “A friend of mine (Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and “looks” around. (Of course the information has to be fed out.) It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ. ”
    - http://www.its.caltech.edu/~feynman/plenty.html

# 1966: Fantastic Voyage

- the book by Isaac Asimov
- the movie: Oscar for Best Visual Effects
  - Director: Richard Fleischer
  - Writer: Jerome Bixby (book); David Duncan (screenplay)
  - Cast: Raquel Welch; Stephen Boyd; Edmond O'Brien
  - Tagline: A Fantastic And Spectacular Voyage... Through The Human Body... Into The Brain
- Memorable quote: “Very poetic, gentlemen. Let me know when we pass the soul.”

# Summary, and some generic issues…

- remote, or stand-off, detection
  - in some sense, always an “imaging” technique
    - you need to know the path over which the transducer integrates
      - under-sampling / aliasing can be a serious problem
      - new “contrast enhancement dyes” that help map paths could be very useful
- point, or local, sensing
  - only local environment is sensed
  - for borehole environment sensitivity is probably not the main problem
    - high concentration environment
    - specificity, multi-analyte capability is more important
    - location may be hard to determine
- non-contact reading of point sensors
  - in some sense, is now an “imaging” technique
    - small size is required: placement in interstitial space
    - but remote coupling to small objects is VERY POOR at RF frequencies
      - compromise between size and range probably required
  - collective behavior due to neighbor-to-neighbor coupling may produce larger “read range” for collections of resonant tags

# backup

# National Research Council study, 1994

- Drilling and Excavation Technologies for the Future
- Committee on Advanced Drilling Technologies, National Research Council
- ISBN: 0-309-57320-3, 176 pages, 6 x 9, (1994)
  - Geothermal Division of the Department of Energy is one agency of the U.S. government that hopes to find better and less costly ways of penetrating rock in order to harness geothermal energy resources more efficiently. With this goal in mind, the Geothermal Division asked the National Research Council to establish a committee to examine opportunities for advances in drilling technologies that would have broad industrial, environmental, and scientific applications such as energy exploration and production, mining, tunneling, water well drilling, underground storage, and environmental remediation.

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- Drilling and Excavation Technologies for the Future, Committee on Advanced Drilling Technologies, National Research Council [ISBN: 0-309-57320-3, 176 pages, 6 x 9, (1994)]
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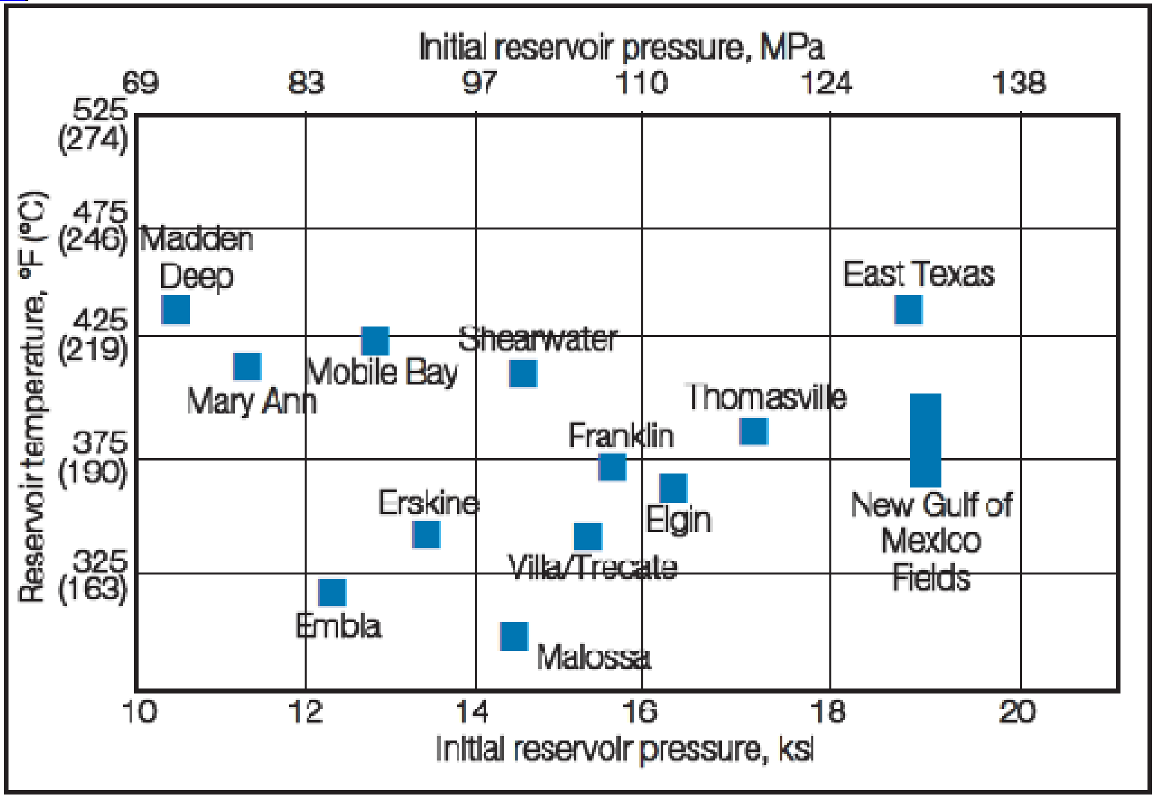
  - A.S. Argon, MIT; N.G.W. Cook, UC-Berkeley; G.A. Cooper, UC-Berkeley; M.M. Herron, Schlumberger-Doll Research; S.E. Laubach, UT-Austin; W.C. Maurer, Maurer Engineering, Inc.; J.E. Monsees, Parsons Brinckerhoff, Inc.; D.S. Pye, UNOCAL Corporation; J-C Roegiers, University of Oklahoma; E.D. Shchukin, Institute of Physical Chemistry RAS; M.D. Zoback, Stanford University
- state-of-the-art then:
  - ’94 world record extended reach well: North Sea, accessed target at a horizontal distance of 23,917 ft (4.53 miles) at a depth of about 9,000 ft (Anon., 1993b). The length of the hole was 28,743 ft (5.44 miles).

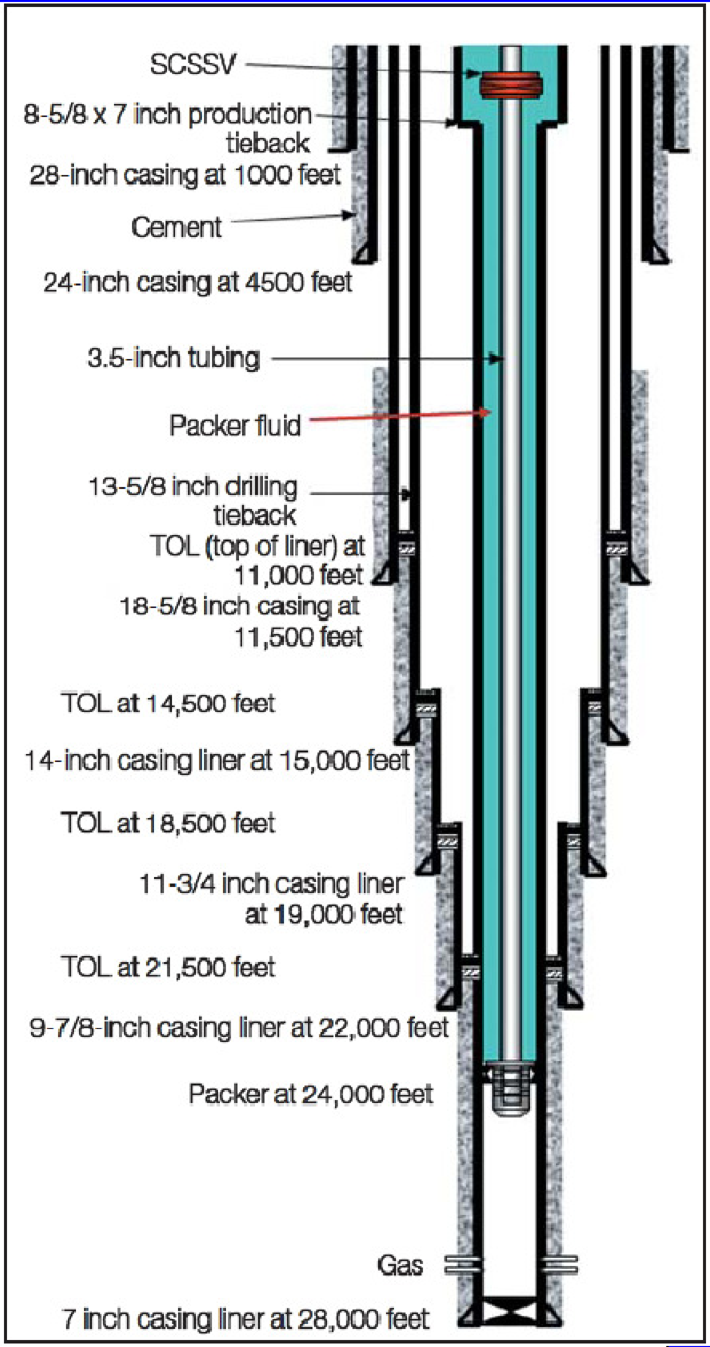
# Key recommendations

- emphasis of the NRC study seemed to MWD (measurement while drilling)
  - smart drilling system requires sensors that are capable of detecting and measuring the following (p. 106):
    - Conditions at the drill bit: Sensors are needed for in situ measurement of pressure (including pore pressure), temperature, permeability, mineralogic and chemical composition of the rock and heterogeneities, borehole fluid composition (at the part-per-million level for environmental applications), stress state, and rock strength.
    - Conditions ahead of the drill bit: Sensors are needed that measure rock properties (such as porosity, elastic properties, and wave attenuation) ahead of the drill bit to adjust drilling parameters, such as the weight on the drill bit and the rotary speed, and to avoid potential problems (e.g., blowouts or loss of circulation) while drilling.
    - Spatial position of the drill bit: Sensors are needed that are capable of detecting the position of the drill bit in space in order to steer the bit around undesirable zones and reach desired targets.

# Temperatures, pressures, depths….




Bruce Craig (MetCorr), MATERIALS FOR DEEP OIL AND GAS WELL CONSTRUCTION, ADVANCED MATERIALS & PROCESSES/MAY 2008, p. 33, 34.



# AEC “recommended” conditions

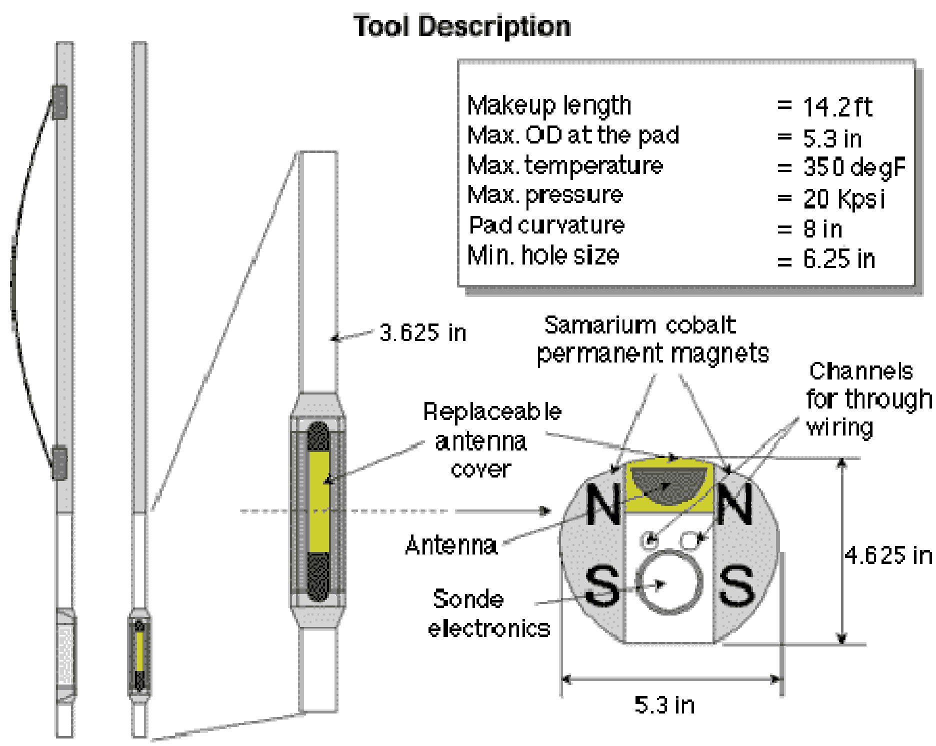
| Parameter | Range and Max |
|---|---|
| Pore Throat Size | 0.03mm to 0.2mm (Max 0.2mm) |
| Temperature | 75 - 125º C (Max - 200º C) |
| Reservoir Pressure | 1000 - 6000 psi (Max - 25000 psi) |
| Pressure at Injection Site for Frac Jobs | 2500- 7500 psi (Max - 26500 psi) |
| Depth of Injection | 2000-12000' |
| Background Magnetic Field | 0.3 - 0.6 gauss |
| Casing Material | Steel - 0.375" thickness nominal |
| Fracture Size | Width - 0" unless propped open. With 20/40 prop, it's 0.06", and for 40/60 prop, it's 0.03" |
| pH | 6.5-8.5 (Max - 12.5 for frac jobs) |
| Salinity | 50,000 ppm- 150000 ppm (Max - 300,000 ppm as NaCl) AEC recommends usage of API standard brine which is composed of 8% wt/wt NaCl and 2% wt/wt CaCl2 (anhydrous basis) in DI water |

# Conventional wireline logging tools

- typically rated to 350°F (177°C) and 20,000 psi (138 MPa)
  - LWD tools to 300°F (150°C) and 20,000-25,000 psi (138-172 MPa)
- recently introduced new wireline and MWD/LWD tools
  - Schlumberger quad-combo wireline toolstring rated to 500°F (260°C) and 30,000 psi (207 MPa)
  - Weatherford LWD tools rated to 330-360°F (165-180°C) and 30,000 psi (207 MPa)
  - Pathfinder's Survivor HPHT LWD tools rated to 350°F (175°C) and 25,000 psi (172 MPa)
    - tool suite includes compensated propagation resistivity, neutron-porosity, MWD/gamma ray and annular pressure
- from: S. Prensky. "Recent advances in well logging and formation evaluation", *WorldOil Magazine, vol. 229, 2008*

# Borehole NMR

- from http://www.seed.slb.com/en/scictr/watch/nmr/tool.htm
- see also http://www.seed.slb.com/en/scictr/watch/nmr/index.htm
- Schlumberger tool



# Formation sensing

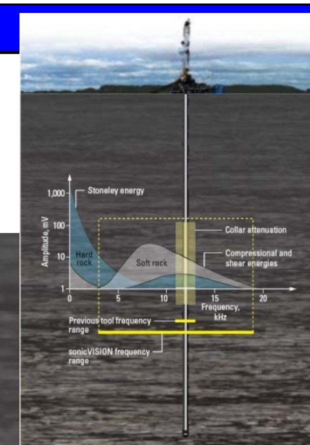
**Table 1. Sensors that are permanently deployed in wells**

| Sensor category | Sensor type | Property measured |
|---|---|---|
| Production | Flow | Production & flow rate |
| | Composition | Fluid phase, water-cut, GOR |
| | Pressure | Reservoir pressure |
| Formation | Resistivity & EM | Saturation |
| | Temperature | Temperature of fluid |
| | | Flow behind pipe |
| Seismic | Geophones | Vp, S1 & S2 |
| | | Microfractures (natural & induced) |
| | Hydrophones | Vp |
| Noise | Acoustic | Production noise |
| | | Sand production |
| | | Mechanical integrity of pumps |

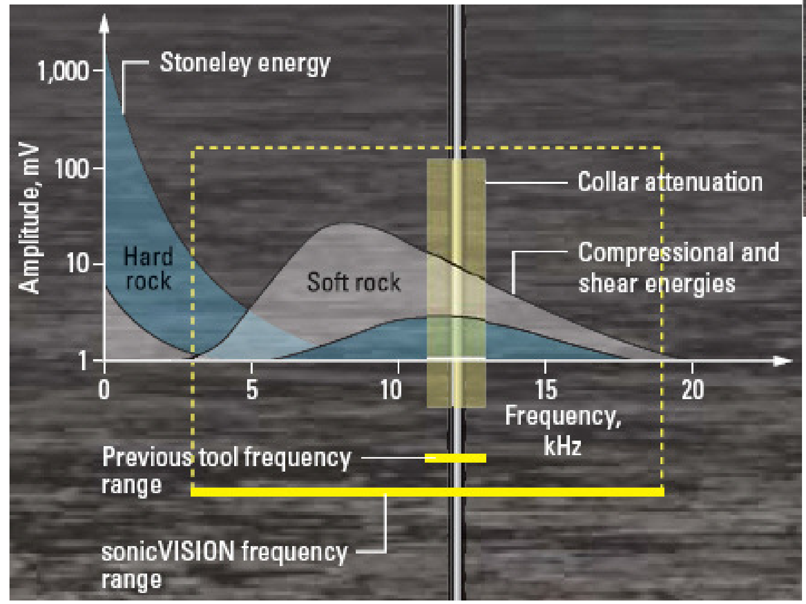
**from "Borehole seismic sensors in the instrumented oil field"**
**W.E. HOTTMAN and M. P. CURTIS, Halliburton Energy Services, THE LEADING EDGE JUNE 2001, p. 630.**

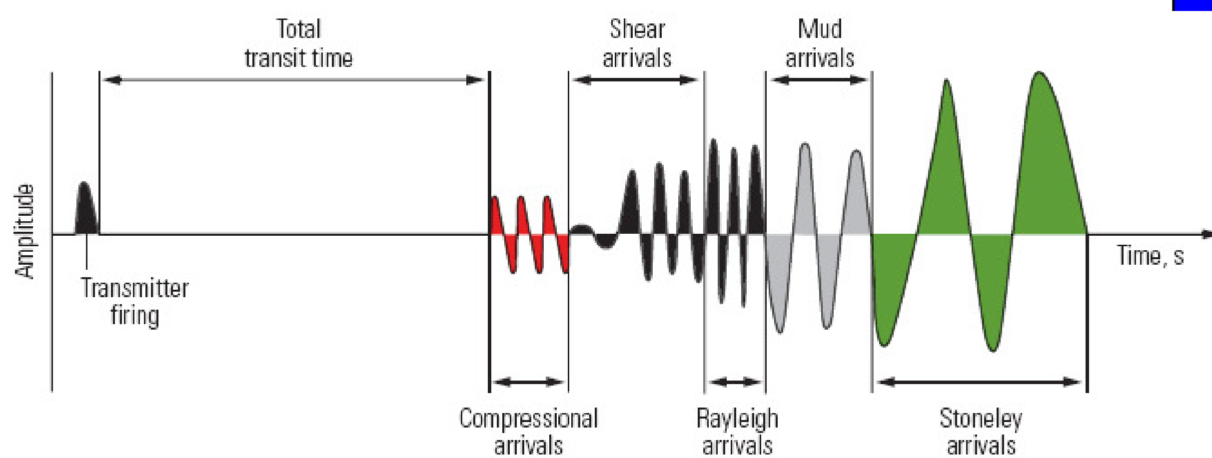
**Figure 1. One level of a permanent digital array for acquiring time-lapse 3-D VSPs. A series of bow-springs each with a 3-C geophone attached are clamped to production tubing which is then deployed inside the casing. Photo taken during a deployment and coupling test.**

# Seismic / acoustic / ultrasonic



- travel times: [ 100 µsec/ft = 3000 m/sec ]
  - 50 µsec/ft for compressional
  - 100-150µsec/ft for shear
  - about 200µsec/ft for Stoneley (surface wave, along the walls of fluid-filled borehole)
- typical "surface" seismic exploration frequency <~ 100Hz, 500Hz is pretty "high"
  - in borehole may go to 20 kHz range
- clocks to about 0.05msec error over the time of operation might be good enough
  - that's about 0.015 ppm per hour
  - Baker Hughes has proposed using down-hole atomic clocks




Alford, et al., A sound approach to drilling, Schlumberger Oilfield Review, Winter 2005/2006, pp. 68-78

# position & time

- Patent No.: US 6,976,392 B2, Dec. 20, 2005
  - ATOMIC CLOCK FOR DOWNHOLE APPLICATIONS
  - Assignee: Baker Hughes, Inventors: Rocco DiFoggio, Peter W. Reittinger,
  - Typical deployment times for the above-described tools is 12-48 hours. … translates into a need for clock stability better than $1 \times 10^{-8}$ over the deployment time. Downhole clocks commonly use piezoelectric crystal oscillators…. Using the best techniques known in the art, downhole clocks rarely exceed a stability of $1 \times 10^{-7}$.

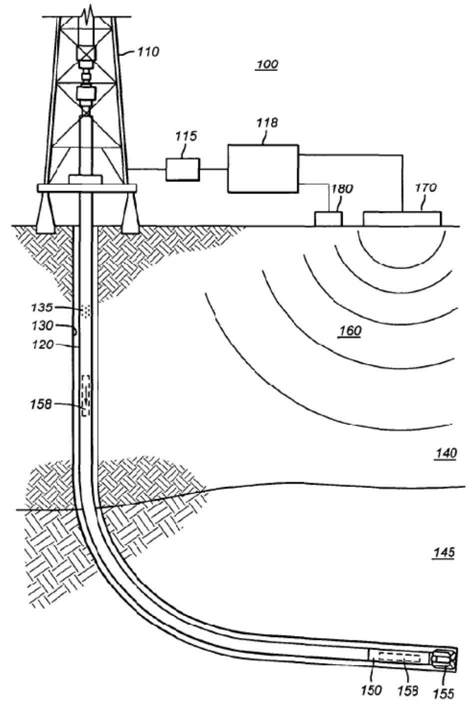
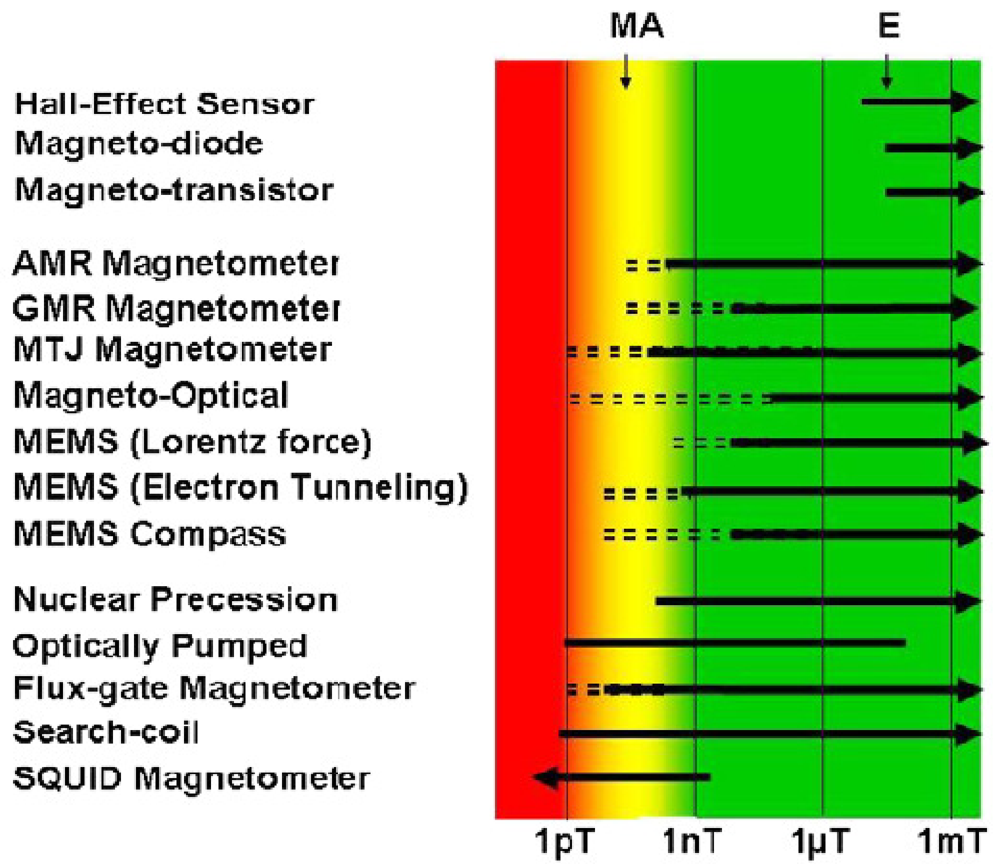


FIG. 1

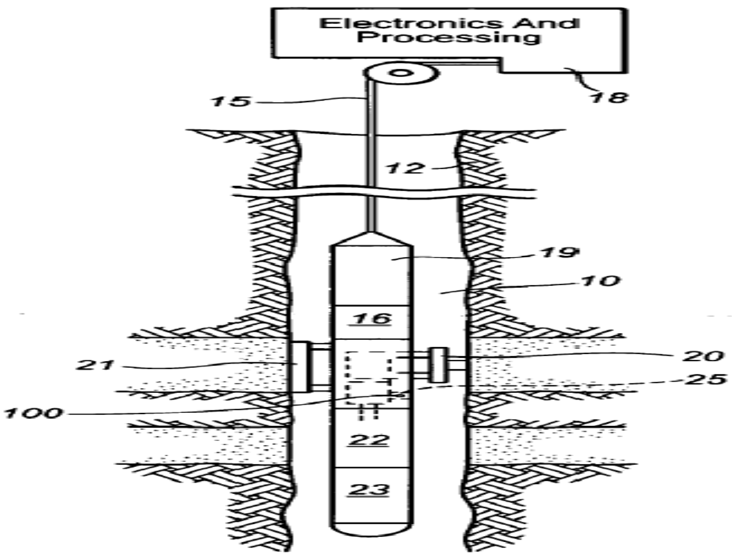
# Magnetometers

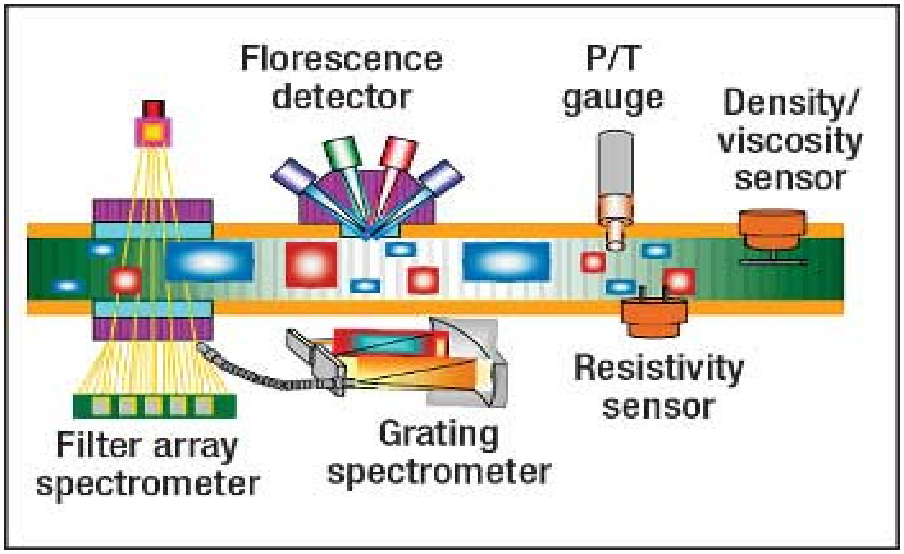
- **Superconducting Quantum interference devices (SQUID) are most sensitive of common magnetic sensors.**
- **Sensitivity of SQUID devices is limited by magnetic field noise.**
- **For commercial dc SQUIDs this noise is of order 10fT.**
- **AMR**
  - **possible partner: Measurement Specialties, Inc. (MSI)**




A. Edelstein, J. Phys.: Condens. Matter 19, 165217 (2007)

# Down-hole analysis systems

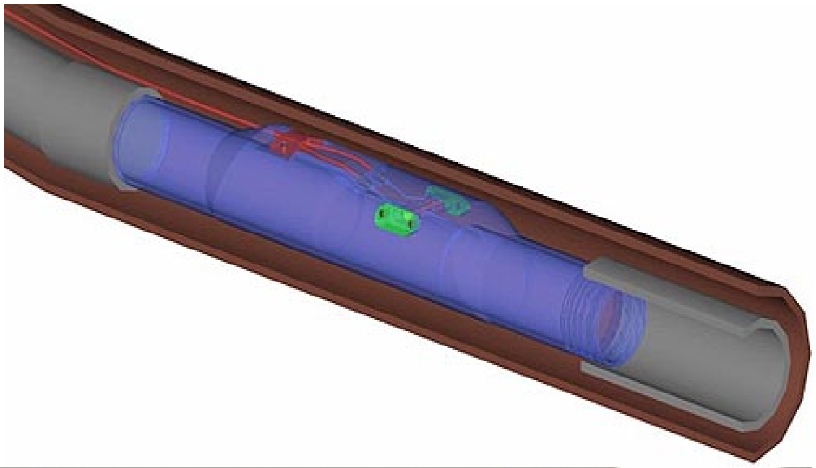


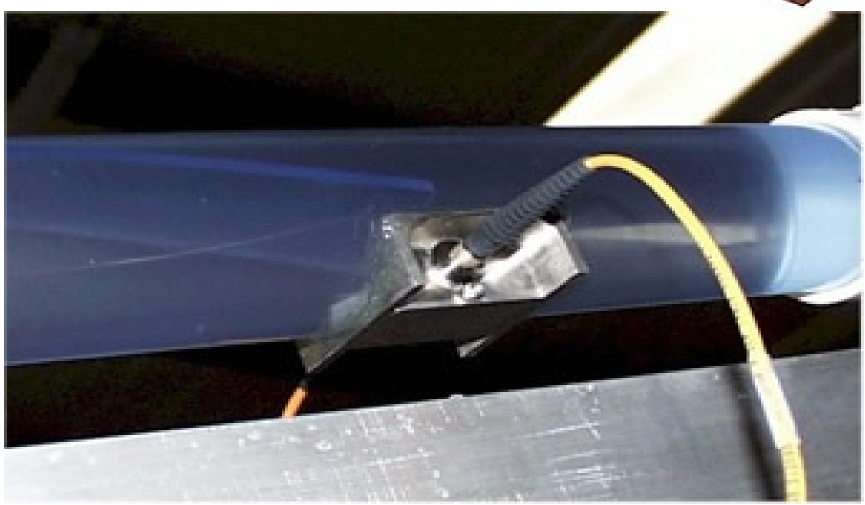




- **(WO/2007/034276) APPARATUS FOR DOWNHOLE FLUIDS ANALYSIS UTILIZING MICRO ELECTRO MECHANICAL SYSTEMS (MEMS) OR OTHER SENSORS – Schlumberger**
  - **spectral unit as optical fluid analyzer**
  - **in situ optical absorption spectra of the fluid**
  - **optical fibers to transmit spectral data**

http://www.freepatentsonline.com/y2007/0062274.html
http://www.worldoil.com/Magazine/ ,
S. Prensky. "Recent advances in well logging and formation evaluation", *WorldOil magazine, vol. 229, 2008*

# DOE program





http://www.netl.doe.gov/technologies/oil-gas/NaturalGas/Projects_n/EP/DCS/DCS_A_40481DownholeAnalyz.html

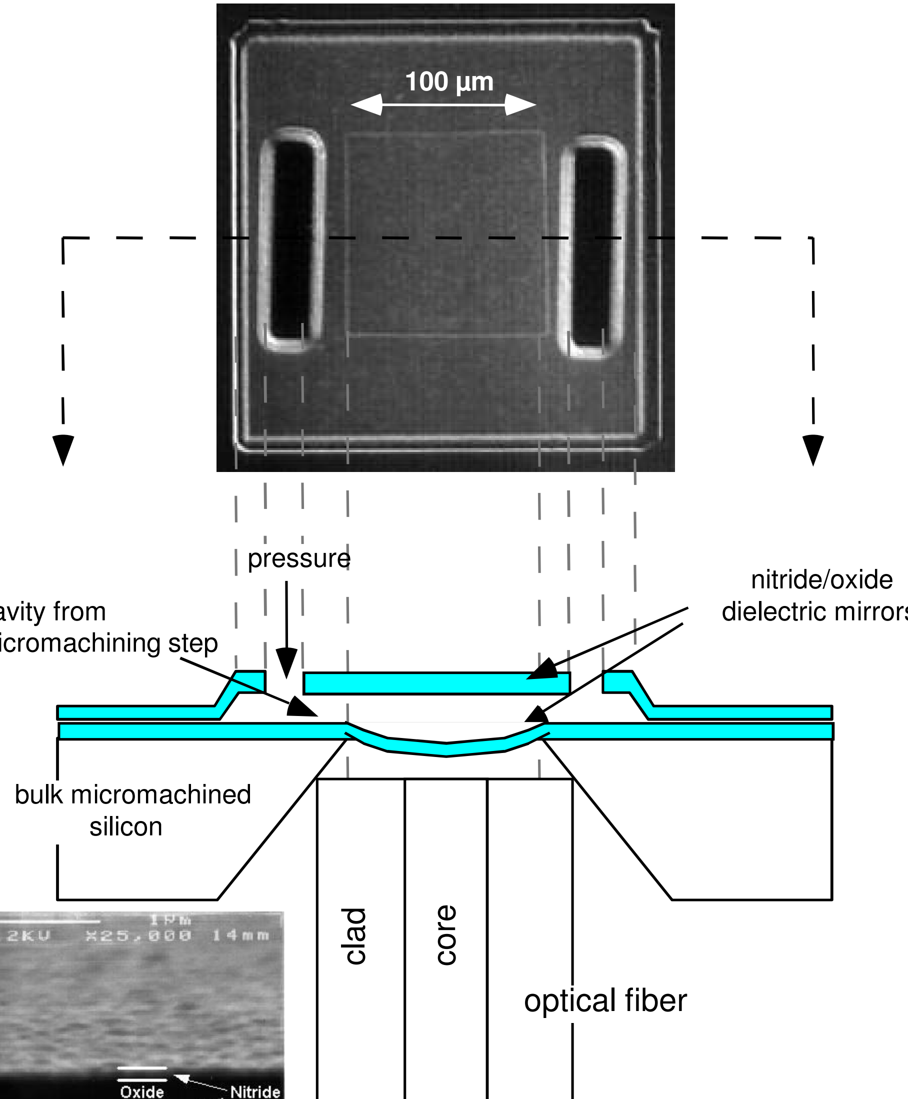
- **APS Technologies**
- **NIR spectroscopy and induced fluorescence; only "light" is down-hole**
- **Phase I – Testing and development**
- **Phase II – PetroMax™ fluid composition system in oil well**
- **field demonstration Chevron Texaco**

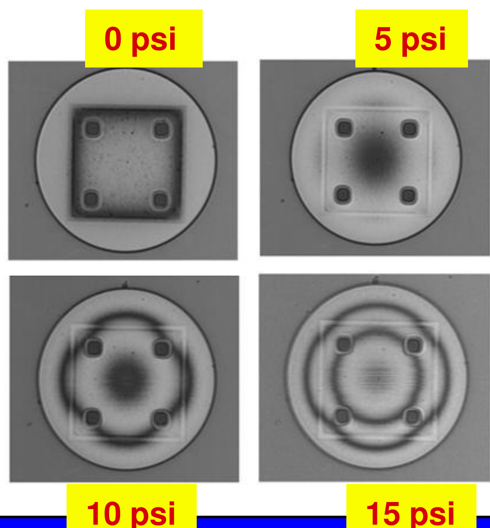
## Dean Neikirk: Micro-Electromagnetic Devices Group
## UT-Austin, Microelectronics Research Center
## and Dept. of Electrical and Computer Engineering

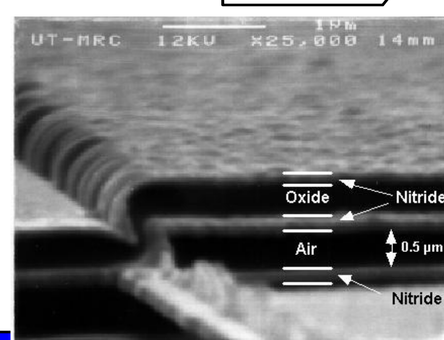
- sensors suitable for harsh environments
  - electromagnetic sensors
    - remote sensing
      - rf / microwave properties of materials
      - integrated antennas and detectors
      - micromachined microbolometers for THz to infrared detection
      - antenna design for “color vision” in the IR
    - eddy current / inductive devices
      - structural health monitoring
        - proximity, damage, corrosion (collaboration with Sharon Wood, UT-CE)
    - tags and resonant wireless sensors
      - “disposable” sensors for harsh environments
        - chemical, pressure, temperature
        - collaborations with Eric Anslyn (UT-Chemistry), John Ekerdt (UT-ChE)
  - micromachined optically-interrogated devices
    - chemical / biological agent detection
    - pressure sensors for harsh environments

# Optical transduction sensors

- micromachined Fabry-Perot displacement sensors
- why use optical sensing?
  - immunity from EMI / noise, suitable for use in harsh environments
- optical fiber "locks" into place
  - after insertion using optical positioner, apply force, fiber does not move
  - the connection between the fiber interconnect and the mems device is probably the hardest part of the whole thing

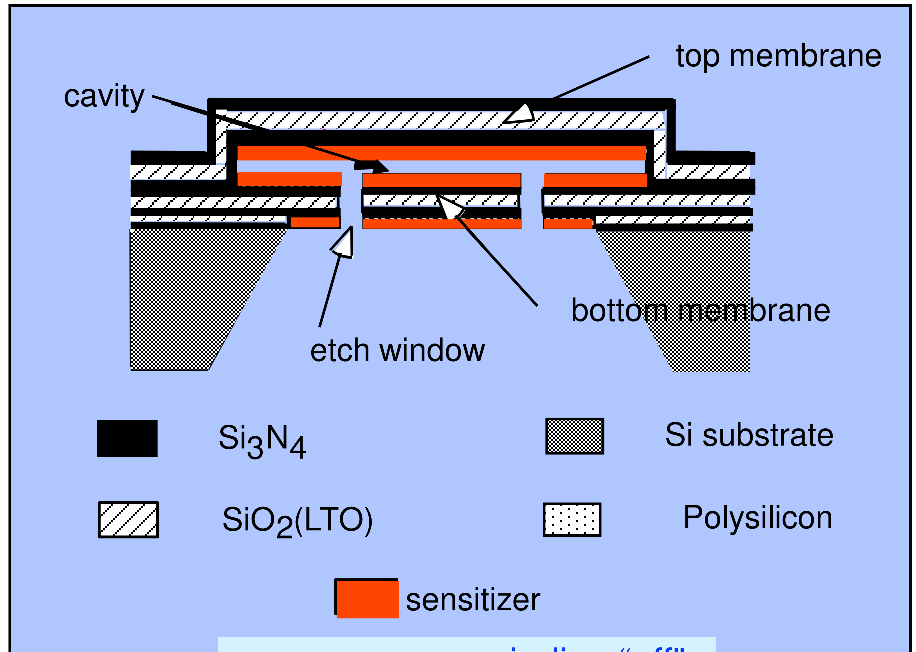


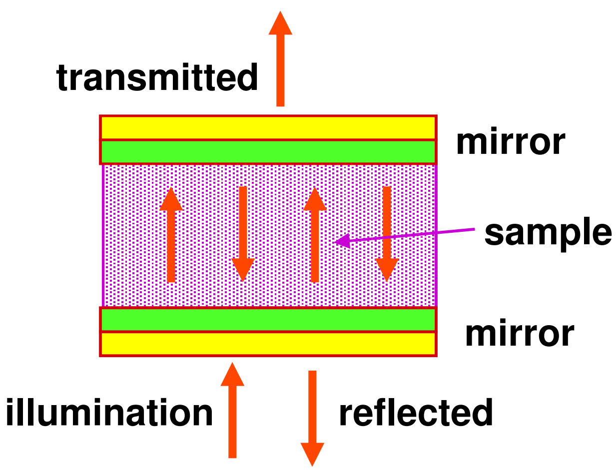



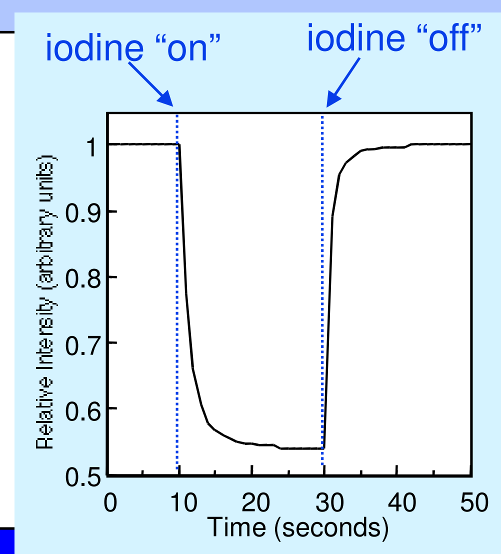



# Fabry-Perot microcavities for spectroscopic chemical detection/analysis

- **micromachined cavity enhanced spectroscopy**
  - **Fabry-Perot cavity substantially increases sensitivity**
    - **can be tuned**
    - **can use either broadband or laser source**
  - **cavity can also serve as a miniature “test tube”**
    - **reactive “sensitizers” can be used to increase specificity and sensitivity**
  - **can use optical fiber or integrated lasers and photodiodes**

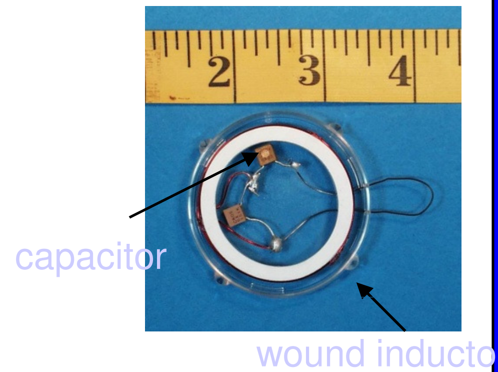


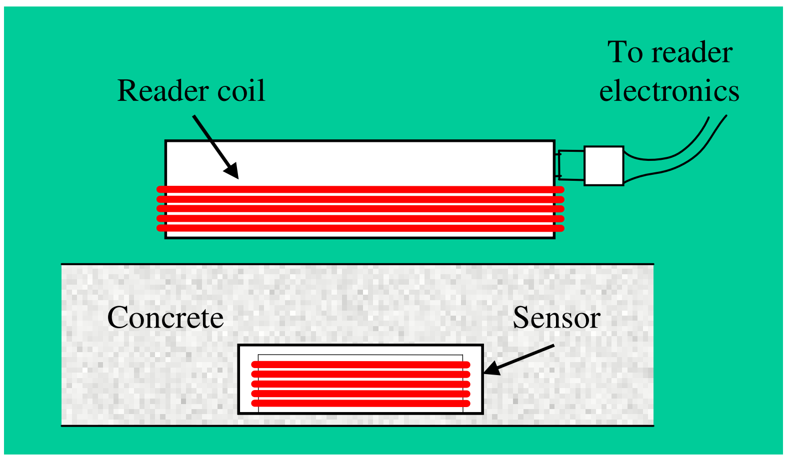



# ESS tag for corrosion sensing

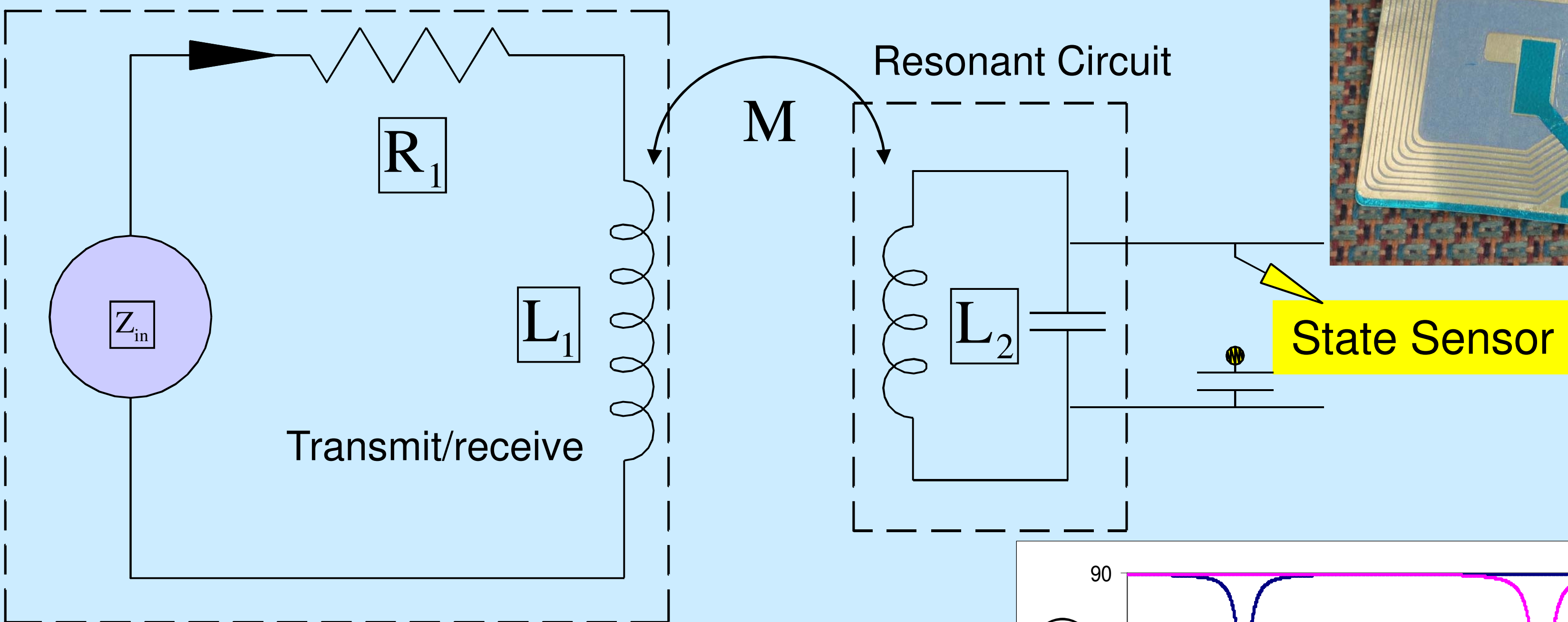
- **sensor embedded in concrete, sealed against potentially harsh, corrosive environment**
- **periodically assess sensors – months to years**
  - **reader coil powers and interrogates the sensor**
  - **can be handheld or mounted on the underside of a vehicle**
- **bare steel wire as transducer, exposed to the same environment as reinforcing steel**
  - **as wire corrodes, Q of resonance decreases, frequency shifts**
  - **selection of wire gauge allows control of amount of corrosion necessary to break wire**

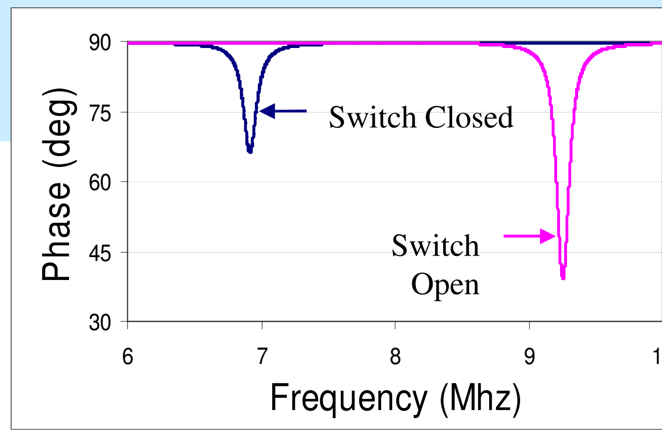



Nathan P. Dickerson, Jarkko T. Simonen, Matthew M. Andringa, Sharon L. Wood, and Dean P. Neikirk, "Wireless low-cost corrosion sensors for reinforced concrete structures," SPIE: Smart Structures/NDE Joint Conference, Proceedings of SPIE Vol. #5765, 7-10 March 2005.

# Passive sensors: Electronic Structural Surveillance (ESS) Tags



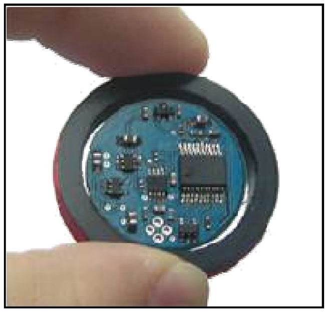




- simple series RLC resonant circuit – similar to Electronic Article Surveillance (EAS) tags
- magnetically coupled to remote reader coil
- suitable for use in harsh environments
- currently under development by our group for corrosion sensing in steel reinforced concrete

Novak, Lisa J.; Grizzle, Kristi M.; Wood, Sharon L.; Neikirk, Dean P., "Development of state sensors for civil engineering structures," Proceedings of SPIE's 8th Annual International Symposium on NDE for Health Monitoring and Diagnostics Vol. 5057, March 3-6, 2003, pp. 358-363.

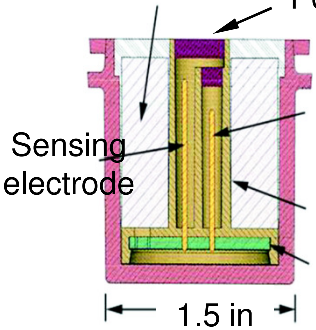
# Semi-passive wireless sensor examples

- radio frequency identification (RFID)
  - low power IC transmits serial number from memory
  - added functionality = added cost
    - basic ID functionality only < $0.50 (quantity ~ $10^9$)
    - with simple sensing: ~$5.00
- EmbedSense™
  - 16 bit A/D integrated with RFID chip
  - short read range (~2 cm)
  - higher cost – development kit ~ $3000, individual sensors ~ $300
- Smart Pebble™ (2003)
  - commercial RFID chip connected to electrochemical cell for pH measurement
  - each cell must be calibrated and is subject to drift over time and with temperature
- ECI-1 (2003) (not wireless or passive)
  - commercially available sensor monitors several parameters in concrete
  - relatively large form factor (83 x 122 x 94 mm)
  - wired communication
  - per-unit cost of $2000

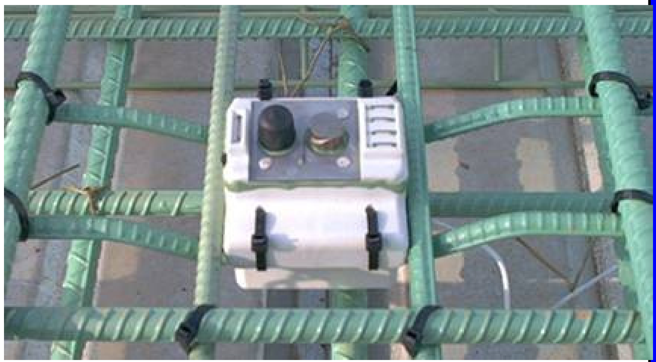


*EmbedSense RFID Tag*

*http://www.microstrain.com/embed_sense.htm*

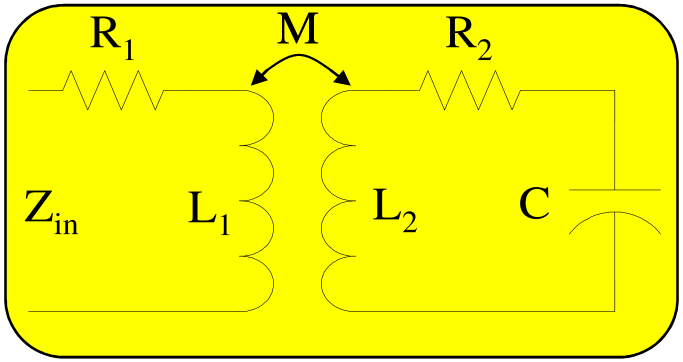



*Smart Pebble™*

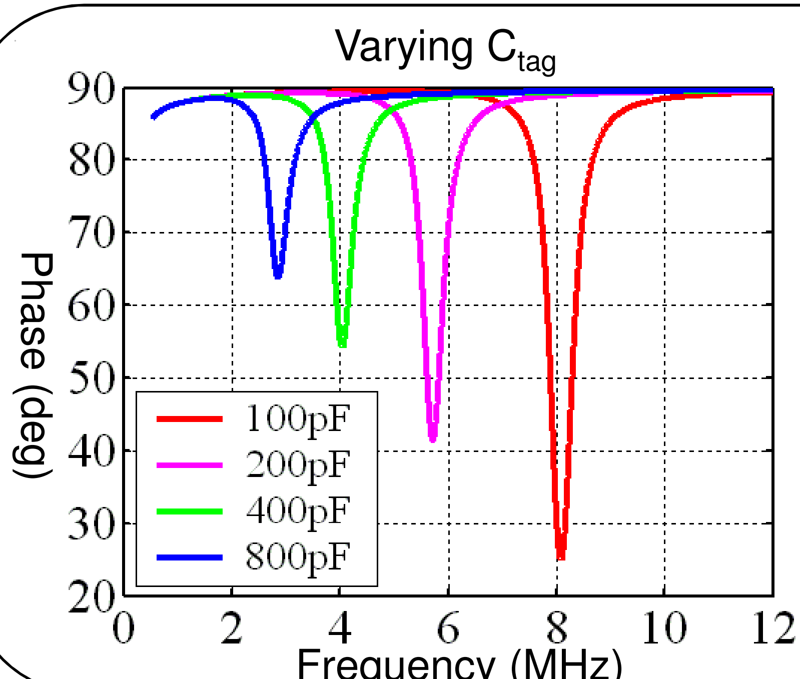


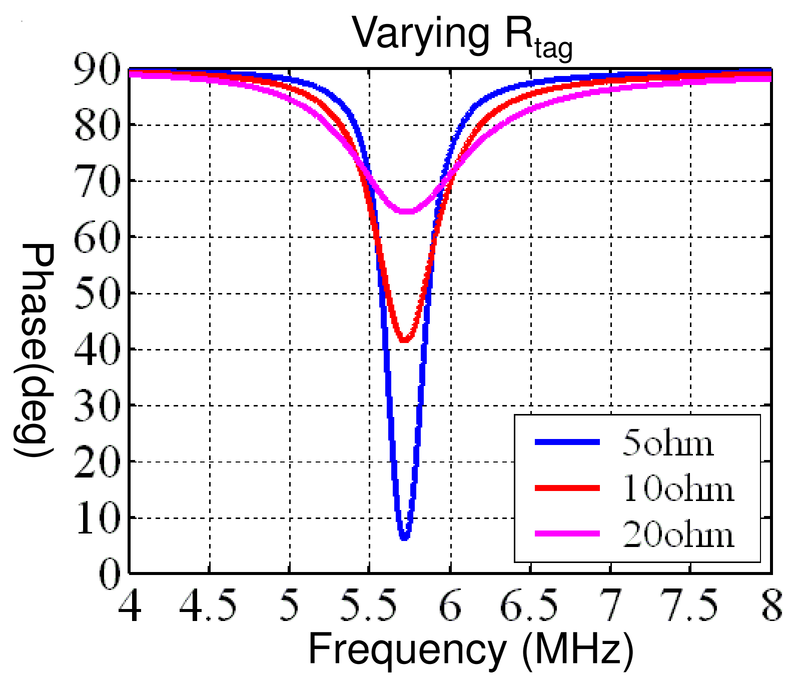
*ECI-1 with supporting rebar cage*

# Basic behavior of resonant "tags"

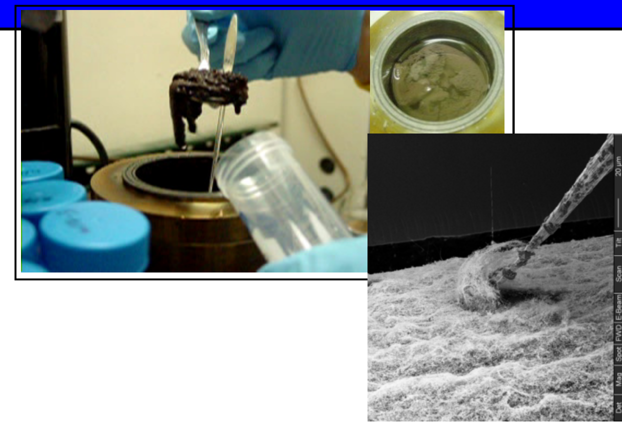



- when C ↑ → $\omega_c$ ↓
- $R_{tag}$ varies → $\omega_c$ remains the same but change in phase response
  - Q changes



**Title:** <u>Near Borehole Condition Sensing</u>
**Project #:** BEG08-019
**PI:** Neikirk
**Location:** University of Texas at Austin



## Project Description:

**Develop solid state resonant tag detectors using meshes of coated silicon and germanium nanowires as sensing elements, coatings designed to target specific compounds, pH, etc.**

## Areas:

**Chemical Sensors, Electronics**

## Impact:

**Goal is to demonstrate concepts leading to "disposable" unpowered packaged sensors.**

## Collaborators:

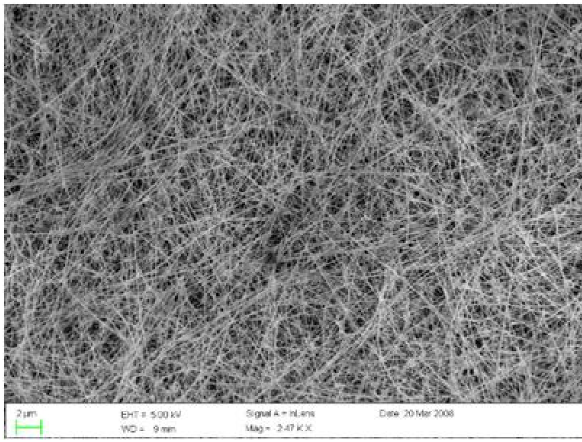
**John Ekerdt & Brian Korgel, University of Texas at Austin**

## Deliverables (yr 1):

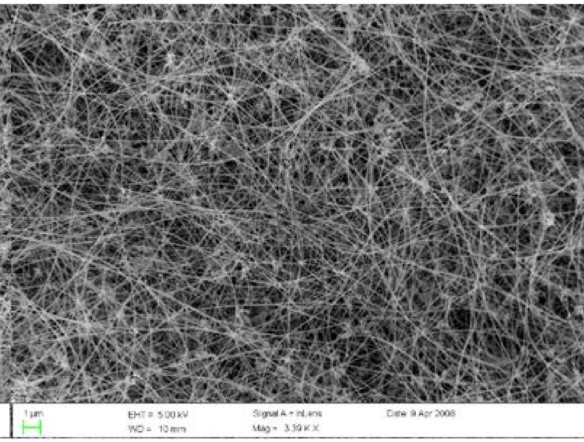
- Test resonant tag platforms for coupling efficiency & read range and determine the requirements for signal acquisition at ranges necessary for near borehole sensing.
- Develop methods to deposit ultra thin polymer films on Ge nanowires and retain porosity of the nanowire mesh.
- Working with specific polymers, test the sensitivity of the coated nanowire mesh to selected hydrocarbons at temperatures ranging from 100° to 250°C.
- Determine which polymers are most sensitive to pH changes in the presence and absence of hydrocarbons and the temperatures over which they are most stable.

# Coated Ge nanowires for specificity

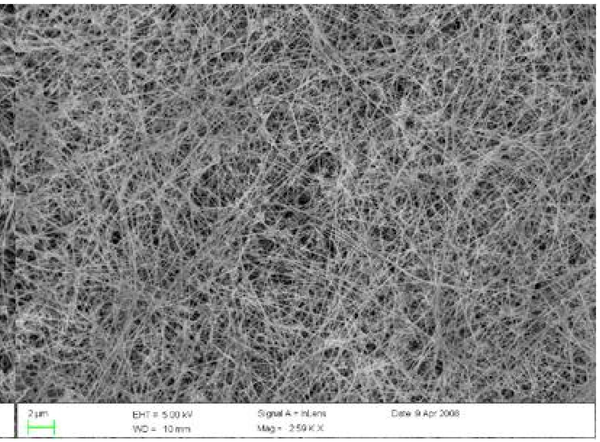
- samples provided Brian Korgel



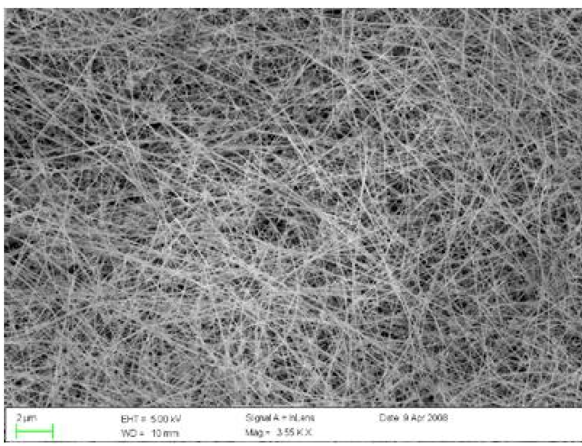
Hexene



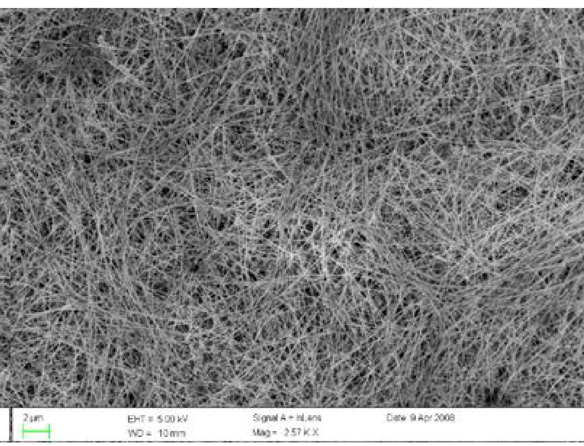
Dodecene



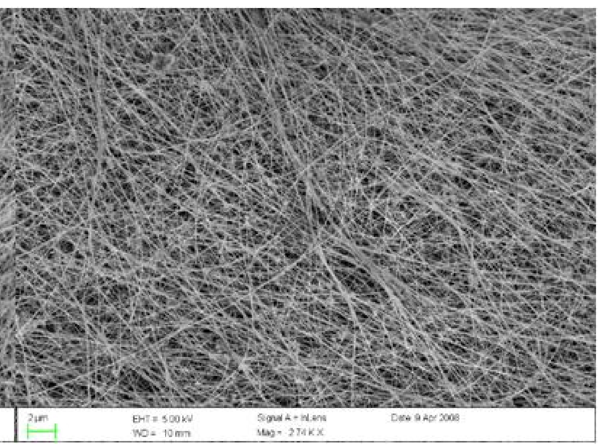
Octadecene



Hexanethiol

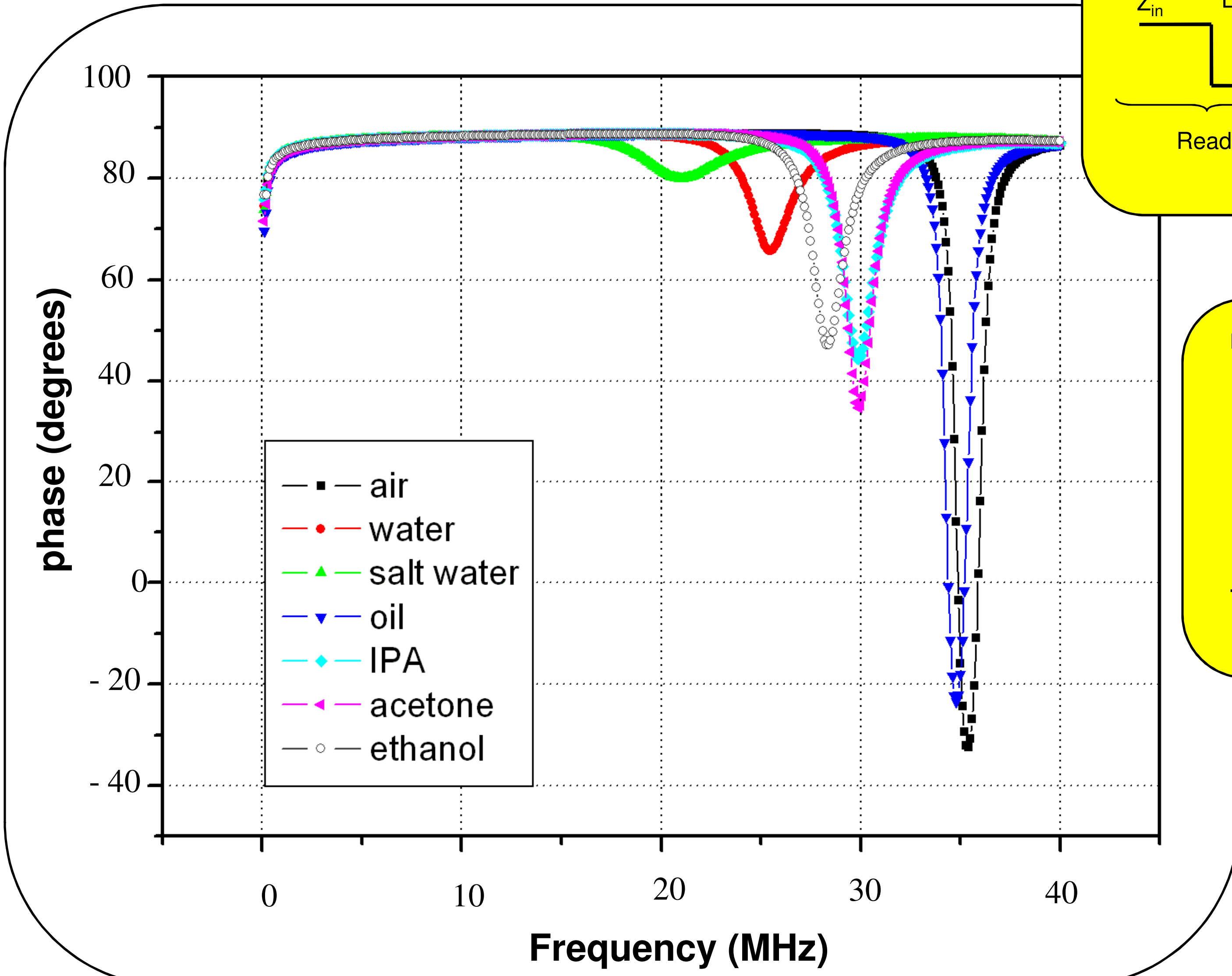


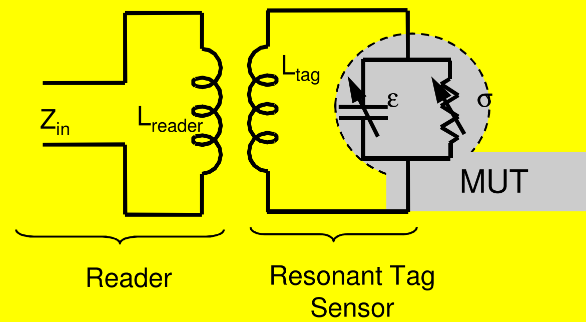
Dodecanethiol

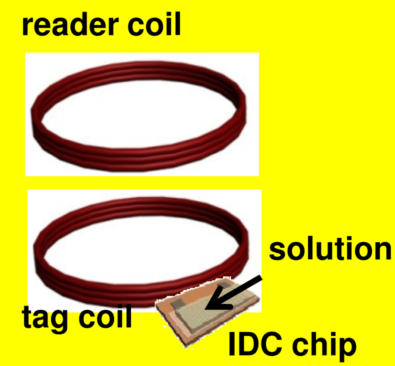


Octadecanethiol

# Resonant tag sensing



# “Autonomous” sensor systems requirements

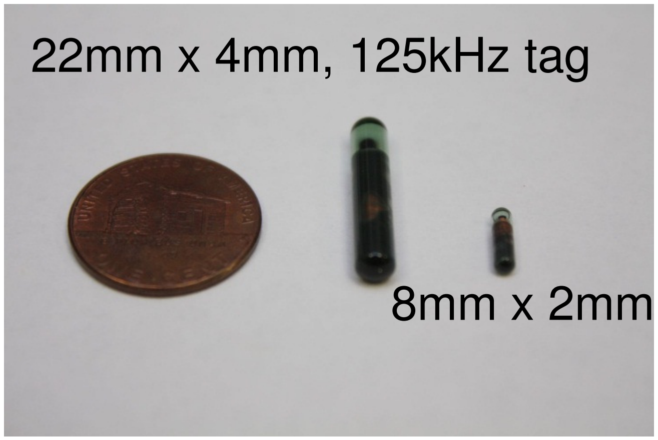
- position detection/path memory/guidance
  - required to know what was sensed, where and when
  - required for remote sensing using seismic/acoustic (time of arrival) or electromagnetic reconstruction
- sensors & devices needed to provide enhanced 4D information:
  - geophones/acoustic transducers: optically transduced, with Neal Hall, new faculty
  - gyros and accelerometers: mems-optical resonant cavity transduction
  - magnetometers: GMR, AMR, with Emanuel Tutuc
  - clocks
    - acoustic travel times: [ 100 µsec/ft = 3000 m/sec ]
      - 50 µsec/ft for compressional , 100-150µsec/ft for shear about 200µsec/ft for Stoneley
    - typical surface seismic exploration frequency <~ 100Hz, 500Hz is pretty high, but in borehole may go to 20 kHz range
    - clocks to about 0.05msec error over the time of operation might be good enough: that’s about 0.015 ppm per hour
      - typical down-hole piezoelectric crystal oscillators about 0.1ppm
      - Baker Hughes has proposed using down-hole atomic clocks

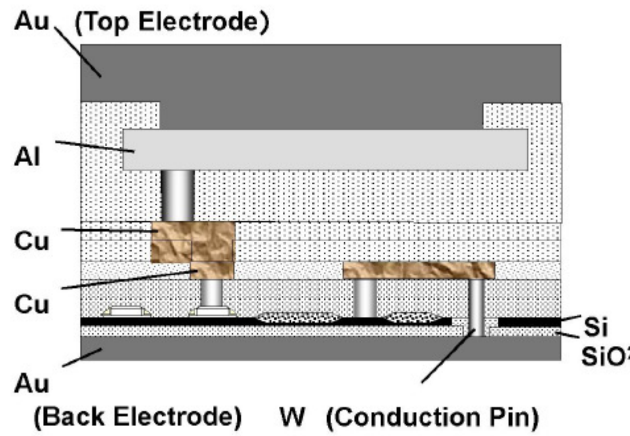
# Down-hole chemical sensing

- with Tutuc, Ekerdt and Korgel
  - aggressively scaled MEMS devices (e.g. nano-wire based resonators) for chemical sensing
  - high temp metal oxides, catalytic materials, nano-wires incorporated into ESS tag platform to allow remote-read
- microcavity enhanced (IR) spectroscopy
  - idea for identification of species in complex multi-analyte mixture
  - use same approach for optically transduced accelerometer, might also be able to use for magnetometer
  - ir spectroscopy sources
    - IR tunable lasers: Seth Bank
    - CW operation has been obtained up to 140C, higher should be possible with new material developments (larger conduction band offset → trade some for more valence band offset → less carrier leakage → higher operating temperature)

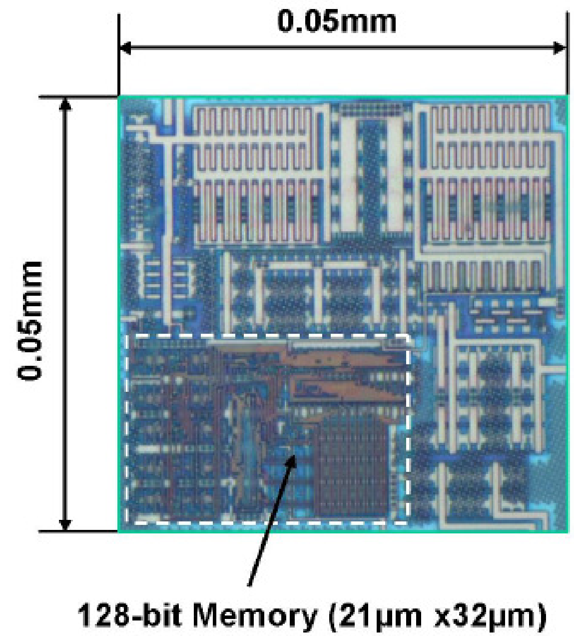
# Hermetically sealed rfid tags

- pet tags may be good prototypical example of a "wireless" system platform



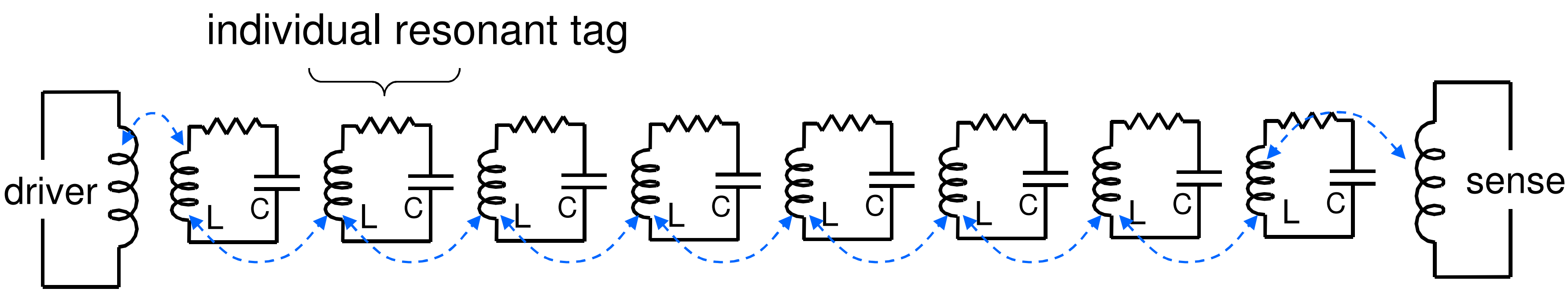



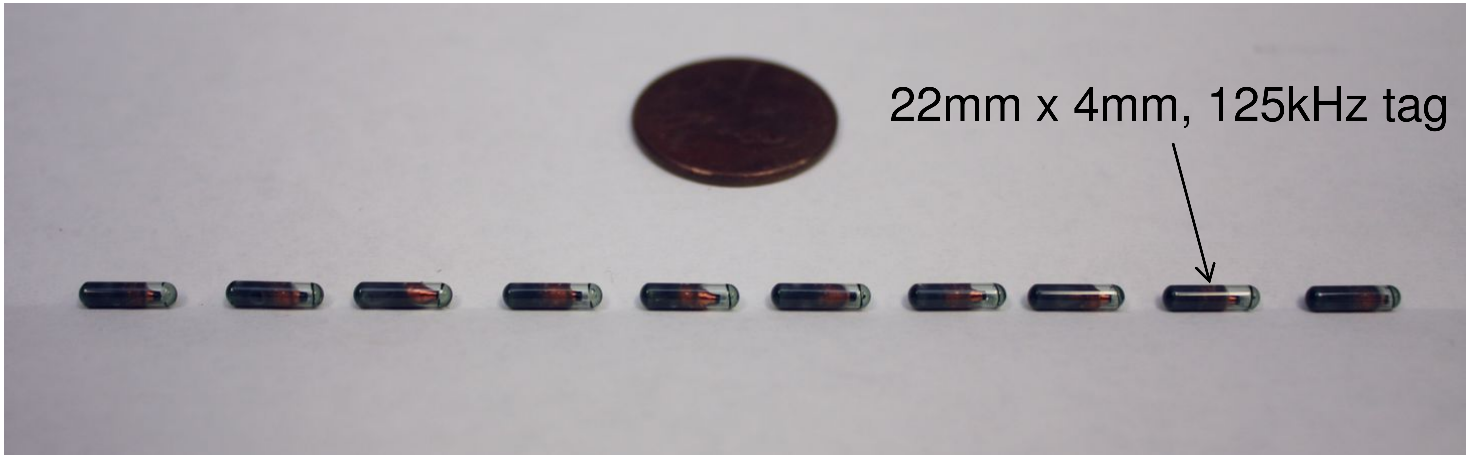

- state of the art in rfid tags: smallest chip I know of is Hitachi 128 bit, 50 µm x 50 µm , 5µm thick, contact pads on both sides, requires e-beam lithography (NOT in production)
  – M. Usami, H. Tanabe, et al., "A 0.05×0.05 mm2 RFID Chip with Easily Scaled-Down ID-Memory," IEEE ISSCC 2007 Digest of Technical Papers
- still needs an antenna!
  – unfortunately, not small…



# Long(er) range communication?

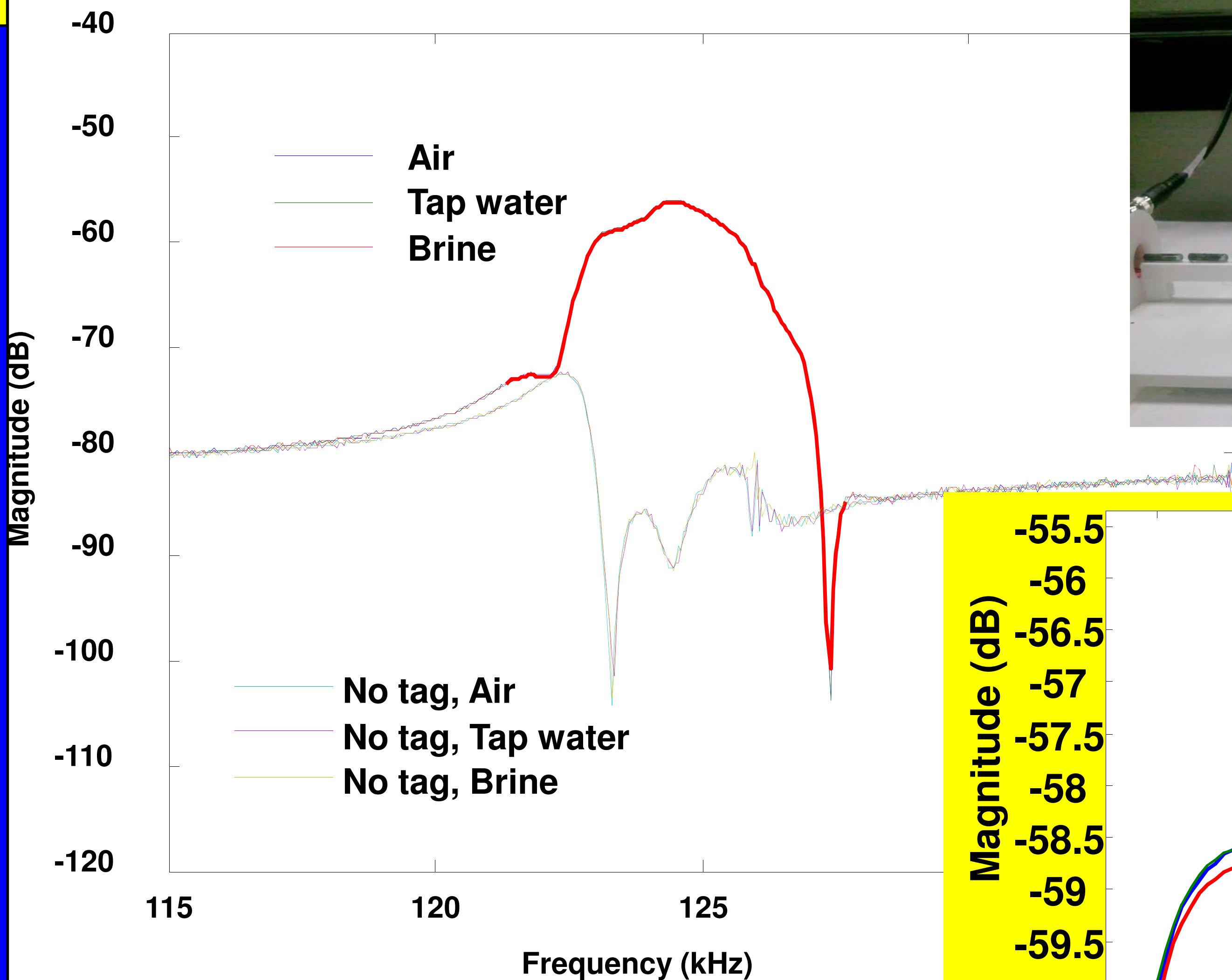
- "chain" of tags forms a magneto-inductive waveguide (MIW)

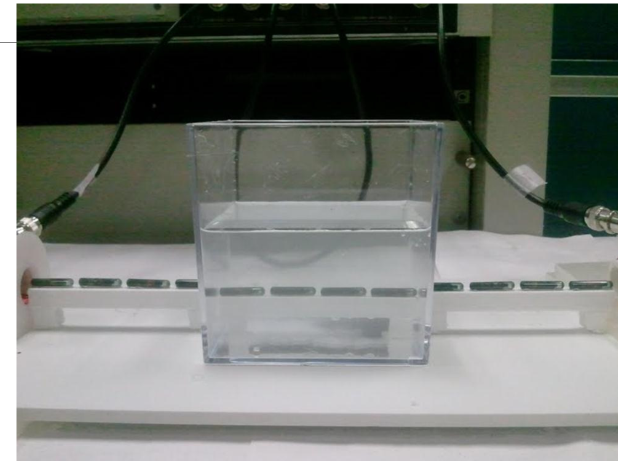


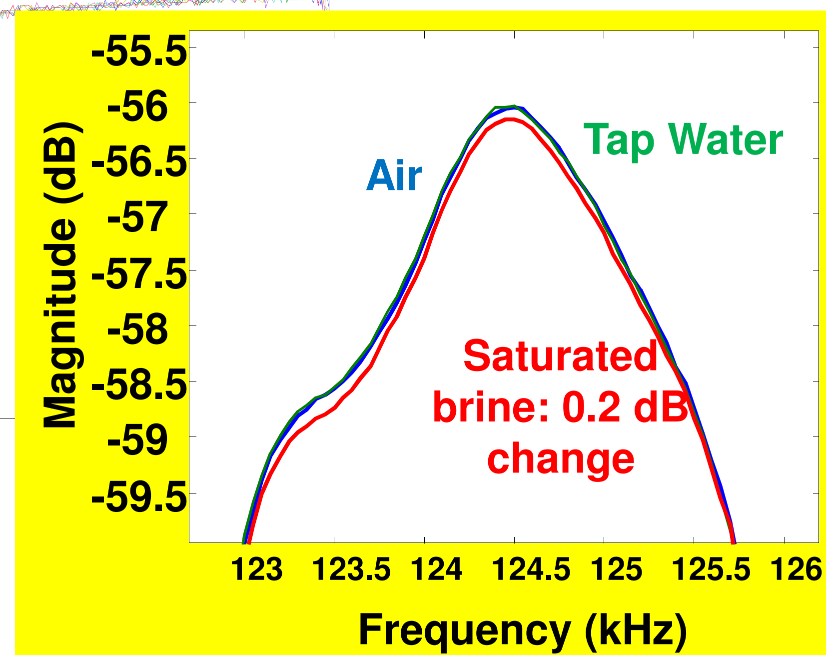




AEC project: Near Borehole Condition Sensing, Project #: BEG08-019

# Signal transmission is insensitive to medium






AEC project: Near Borehole Condition Sensing, Project #: BEG08-019

# The “grand” challenge: sensing needs for improved formation modeling

- device injected with waterflood via injection well at elevated temp and pressure
  - device packaging, sensor protection
- device transport
  - device driven into reservoir with flood front
    - mobility enhancing coatings, shape, and packaging
- sensing: what <u>and where</u>
  - pressure, temperature, local chemical environment
  - sensor geo-location mechanism is critical
    - “one time” sensors
      - if based on a “count down timer” would only need to determine distance
    - “real time” sensors
      - data transmission or on-board storage?
        - continuous time “transmission” requires no memory, but “channel” is hard
        - on-board: transport out of reservoir with produced fluids via producer well for device recovery
          - device separation and identification
          - device interrogation for data recovery

- <u>and all in a 10 cubic micron package</u>

# Taxonomy of sensor net types

- primary property of a “net” is the coupling between sensors
- results in collective or non-collective response of the sensing system
- uncoupled point sensors provide most direct measurement of a local property
- for distributed or many-point defects the number of required point sensors will be very large.
- fully coupled, globally excited and detected nets could provide collective response that may sense distributed or many-point type defects more easily, but usually suffer from problems in localization
  - a smart dye used to enhance image contrast in a “remote sensing” system