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Development Plan for Ultrasonic Pressure Sensors

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Changing the World's Energy Future

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Advanced Sensors and Instrumentation

Acoustic Pressure Sensor Testing and Development Plan

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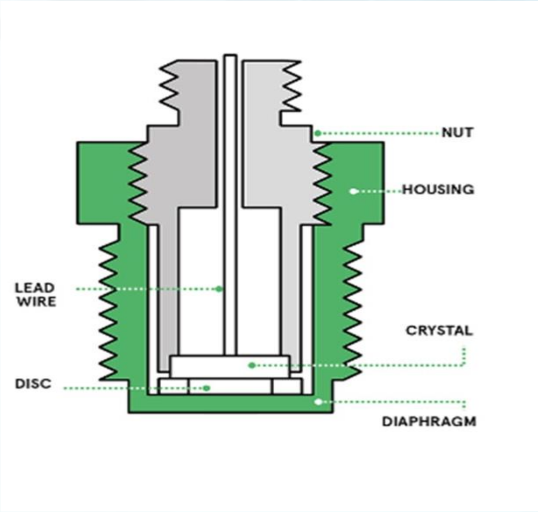
Need for Pressure Sensors in Nuclear Industry and Research

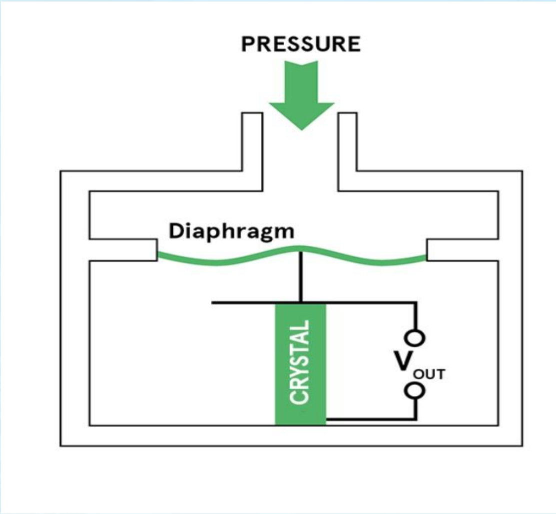
- Current LWRs utilize differential pressure sensors, which are based on strain gauges and are remotely located from the reactor vessel via impulse lines. These pressure sensors measure the liquid level in the vessel and give a general indication of system health by enabling the detection of leaks and flow system fouling.
- The advanced reactor types currently under development generally operate at higher temperatures than LWRs and utilize coolants that may be highly corrosive (i.e., liquid metals). They employ pressure measurements to calculate various measurands (e.g., liquid level and flow rate) and to indicate accident conditions.
- Research reactor experiments may utilize pressure sensors to monitor fission gas release, loop pressures, flow rates, and coolant pressures, or to detect fuel rodlet burst. The conditions associated with these types of tests are summarized in [1].
- The development strategy detailed in this document addresses only pressure sensors that use the same base technologies traditionally associated with acoustic or ultrasonic transduction (i.e., piezoelectric and magnetostrictive).
    - Other current ASI workscopes exist to address pressure sensors that are based on optical fibers, strain gauges, and linear variable differential transformers.

Assessment of Current Technology: Commercial

Commercial Dynamic Pressure Sensor



Commercial Dynamic Pressure Sensor Configuration

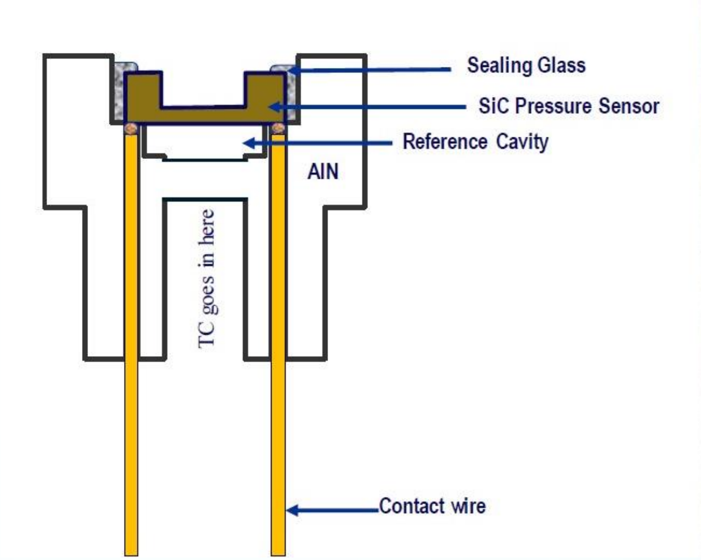


Commercial Dynamic Pressure Sensor Alternate Configuration

The commercially available piezoelectric pressure sensors operate by generating a charge in the active crystal under applied stress/pressure.

- The materials commonly used are limited in terms of radiation tolerance and maximum operating temperature [2, 3, 4].
  - Lead zirconate titanate
  - Bismuth titanate
- The generated signal will rapidly dissipate as a result of current leakage in any real circuit.
  - Only dynamic pressures can be measured
  - Cyclic pressure changes must meet a minimum frequency

Assessment of Current Technology: Developmental



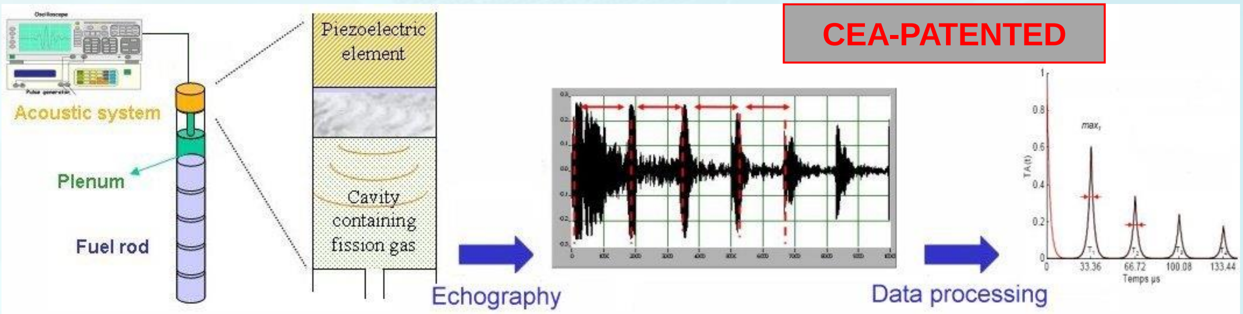
NASA-developed Piezoresistive Pressure Sensor

NASA developed a SiC-based pressure sensor for space applications [5].

- Based on piezoresistivity, in which the resistance of the active SiC element changes under applied pressure/strain
- Tested only under low neutron and gamma doses
  - 10^{15} n/cm^2 (E>1 MeV)

The French Atomic and Alternative Energy Commission (CEA) developed an acoustic fission gas monitoring sensor that functions based on the pulse-echo technique [7].

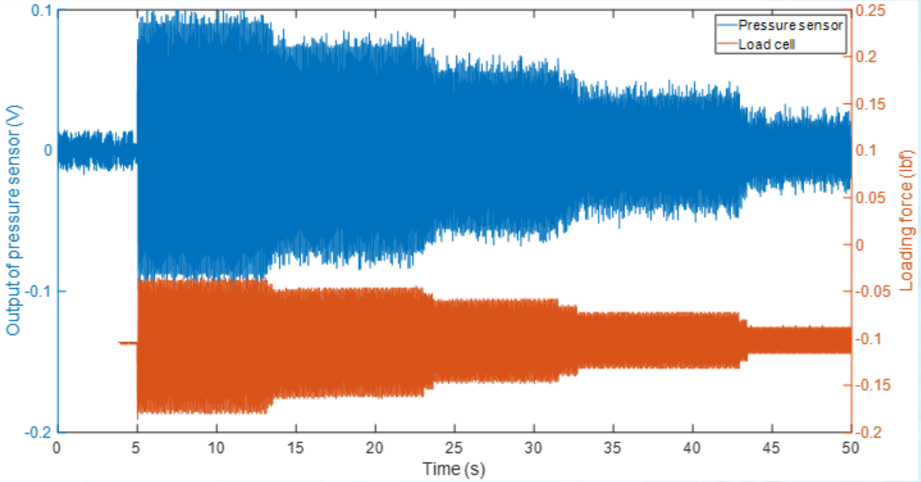
- Gas composition is determined by the speed of sound in the gas
  - Results are excellent, but expected gas species must be known a priori
- Pressure is determined by the attenuation in the gas
  - Amplitude-based measurements are generally unreliable
  - The initially tested piezoelectric materials degrade under irradiation



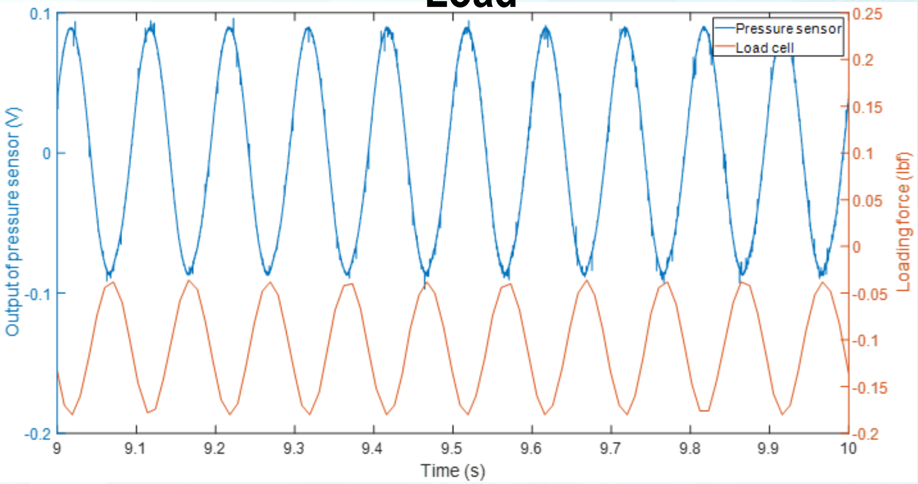
CEA-patented Fission Gas Monitoring Sensor

Commercial Sensor Testing-High Frequency

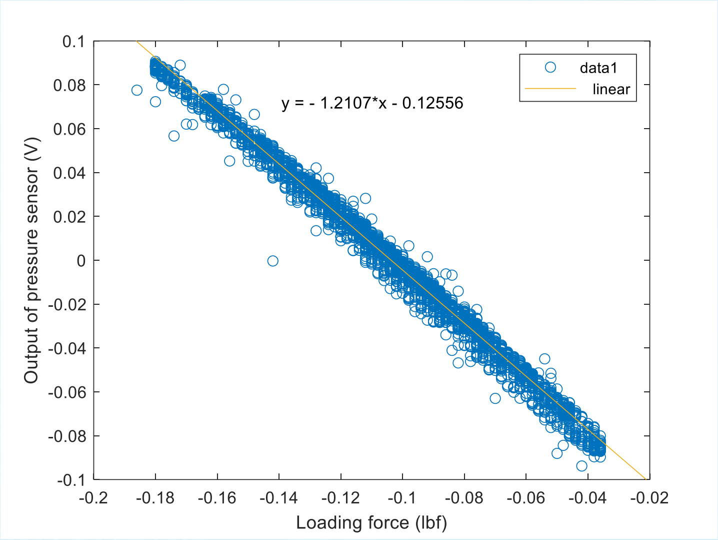
Force Testing Equipment



10 Hz Cyclic Loading with Changing Load



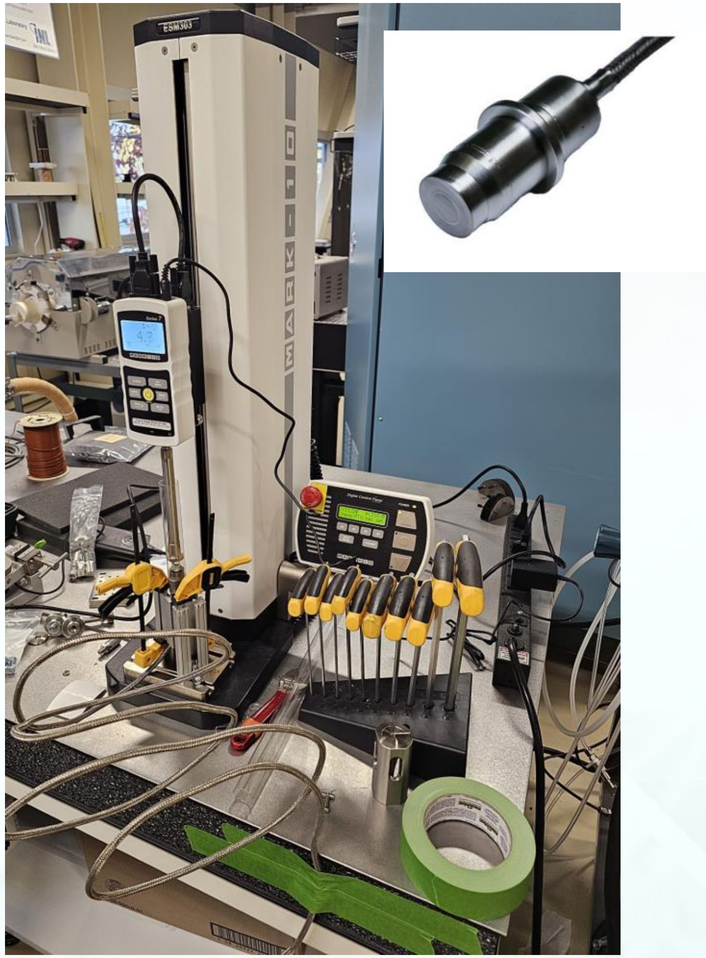
10 Hz Cyclic Loading with Steady Load

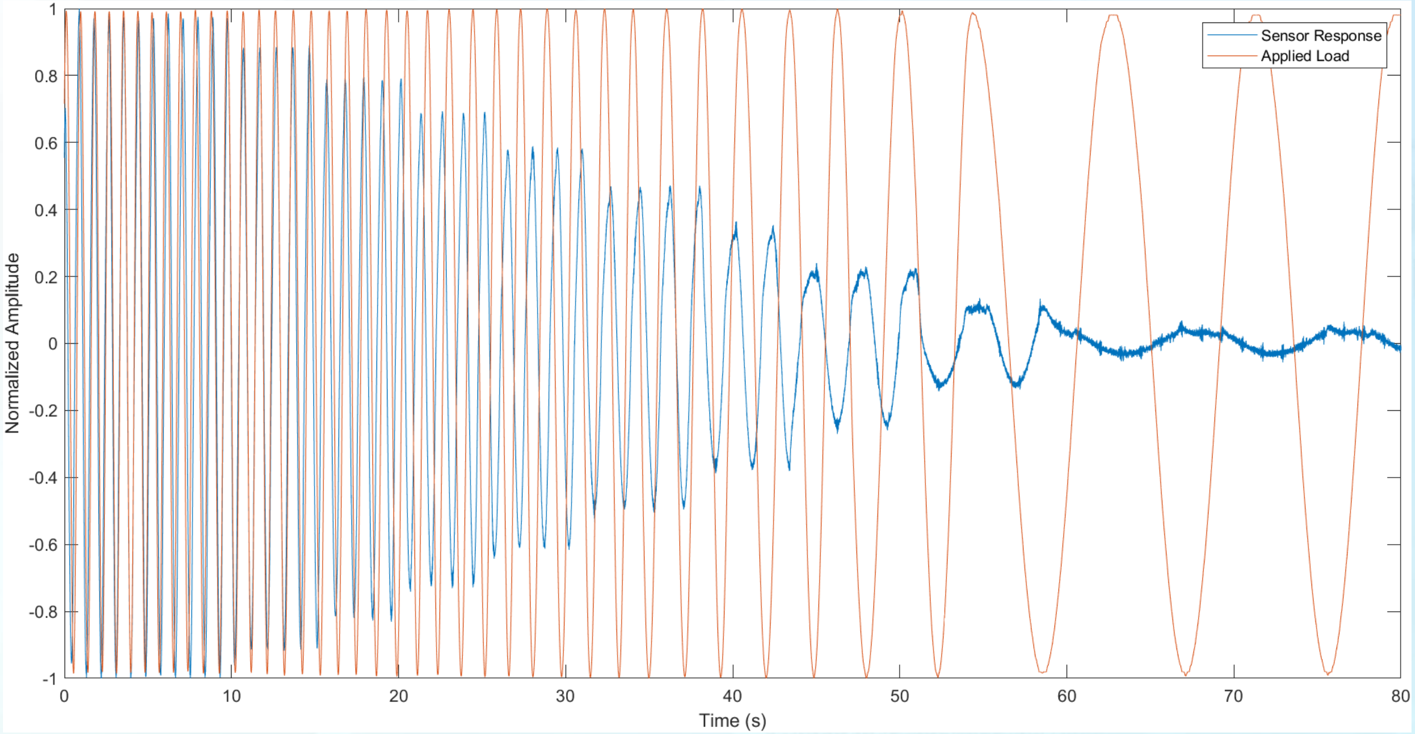


Output vs. Force Curve

- Dynamic pressure sensors were tested using a tensile/compression testing system for frequencies below 1 Hz and acoustic actuators for frequencies above 1 Hz
  - High-frequency performance is excellent.

Commercial Sensor Testing-Low Frequency

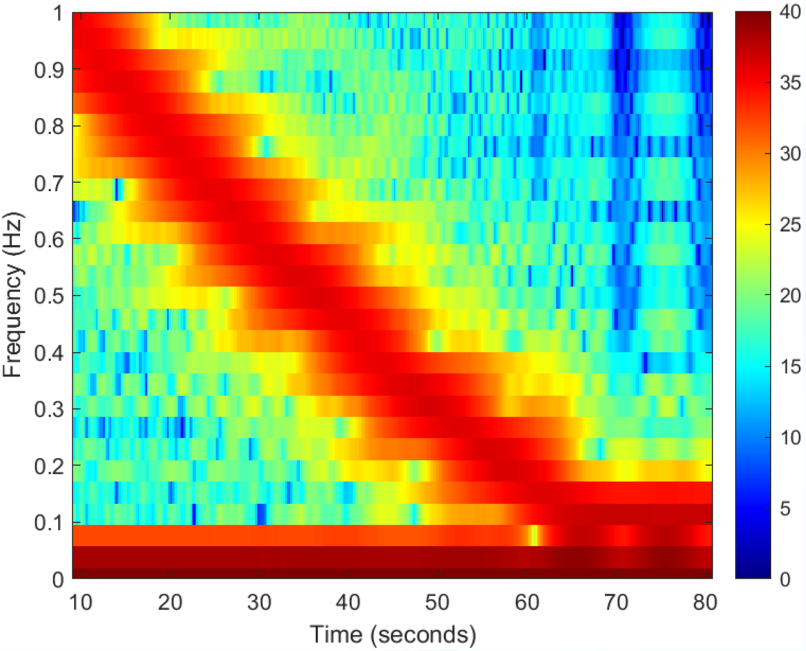




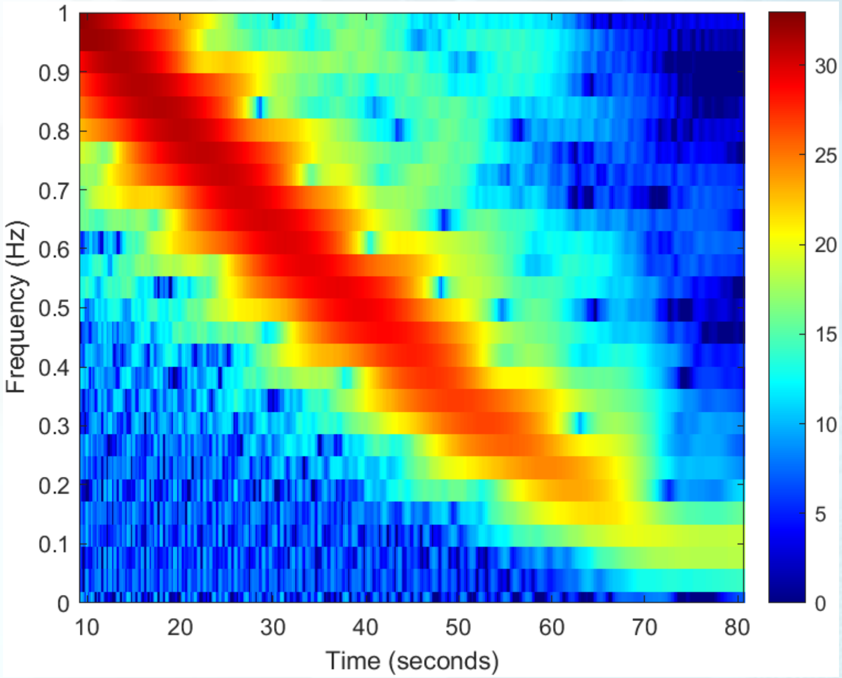
1-0.1 Hz Frequency Sweep with Steady Load

- Current leakage inherent to piezoelectric sensors limits use below a minimum frequency
- Both the frequency and amplitude of sensor response are affected

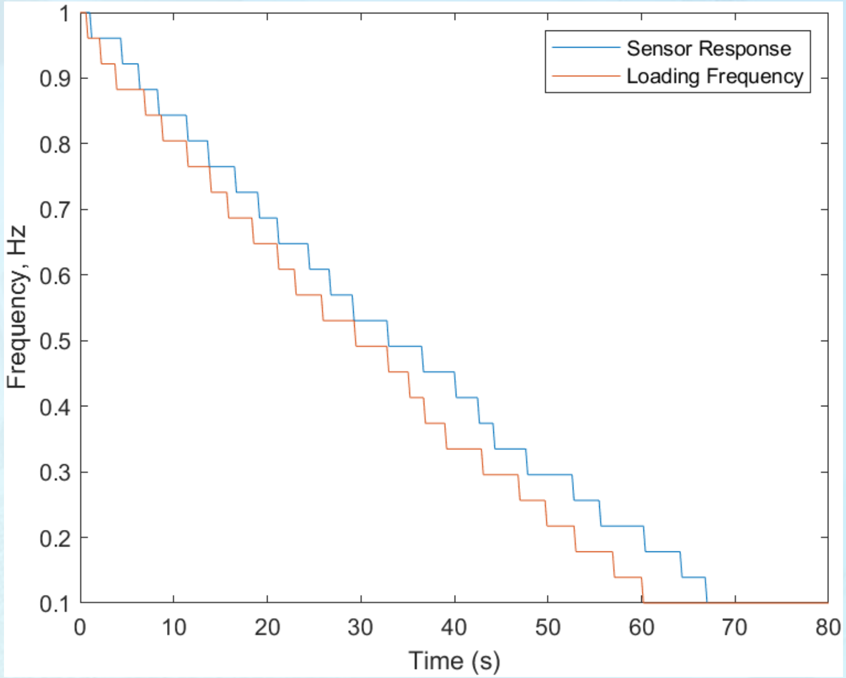
Commercial Sensor Testing-Low Frequency



Spectrogram of Input Signal



Spectrogram of Sensor Response



Frequency vs Time

- Sensor signal diverges from input at ~1 Hz
- Frequency response/time constant of tested sensor limits use to frequencies above ~1 Hz
  - Rapid pressure changes (less than ~1 second) may not be detected accurately
- **Cannot be used for static pressures**

Sensor Development Strategy: Primary Challenges

- Material selection
  - High-temperature, radiation-tolerant active transduction materials
  - Electrode or coil materials and dielectrics
  - Housing fill and acoustic damping materials
  - Housing materials compatible with likely environments (i.e., corrosive coolants)
- Design considerations
  - Bonding of active material to diaphragm
    - Thermal expansion mismatches and chemical compatibility are key
  - Coupling of pressure sensors to working fluid
    - Effects of wetting
    - Temperature standoffs may be necessary
  - Operating frequency range for sufficiently resolving signal features
    - Transient
    - Flow-induced vibration
  - Pressure range
    - TBD, for most applications

Sensor Development Strategy: Development Steps

1. Technology selection:
   - Investigate various acoustic sensor technologies (e.g., piezoelectric, magnetostrictive, and micromachined electro-mechanical sensors), and select the most suitable for specific application requirements.
   - Consider factors such as sensitivity, bandwidth, and robustness against relevant environmental factors.
2. Material selection:
   - Choose appropriate materials for the sensor’s active element, with radiation tolerance being a key factor.
   - Choose structural materials that are compatible with the chemical environment.
   - Sensor materials must also be compatible with each other.
3. Design and prototyping:
   - Develop a detailed design for the pressure sensor, including the transducer, signal conditioning circuitry, and data acquisition system.
   - Utilize simulation tools to model the sensor’s behavior under different conditions.
   - Create prototypes for testing and validating the design’s functionality and sensitivity.
4. Fabrication and manufacturing:
   - Establish a repeatable fabrication process.
   - Implement quality control measures to maintain consistent sensor performance.
5. Testing and calibration:
   - Conduct extensive testing to evaluate the sensor’s sensitivity, frequency response, and noise tolerance.

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