Development of Sensors for High-Temperature High-Pressure Liquid Pb/Pb-16Li Applications

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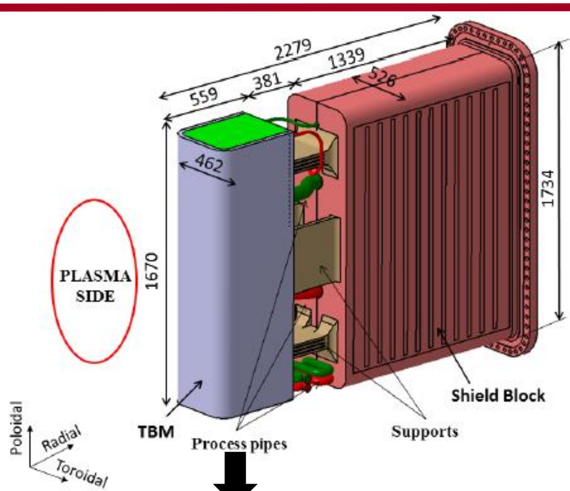
Outline

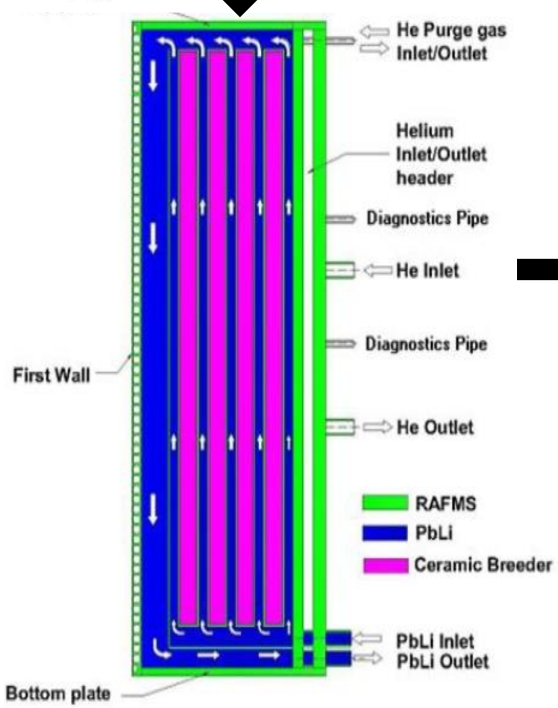
- LLCB TBM & Lead Lithium Cooling System (LLCS)
- Motivation & challenges
- Sensor selection
- Experimental facilities: Designs, methods & results
- Future experimental plans
- Summary

LLCB TBM & LLCS

Objectives:

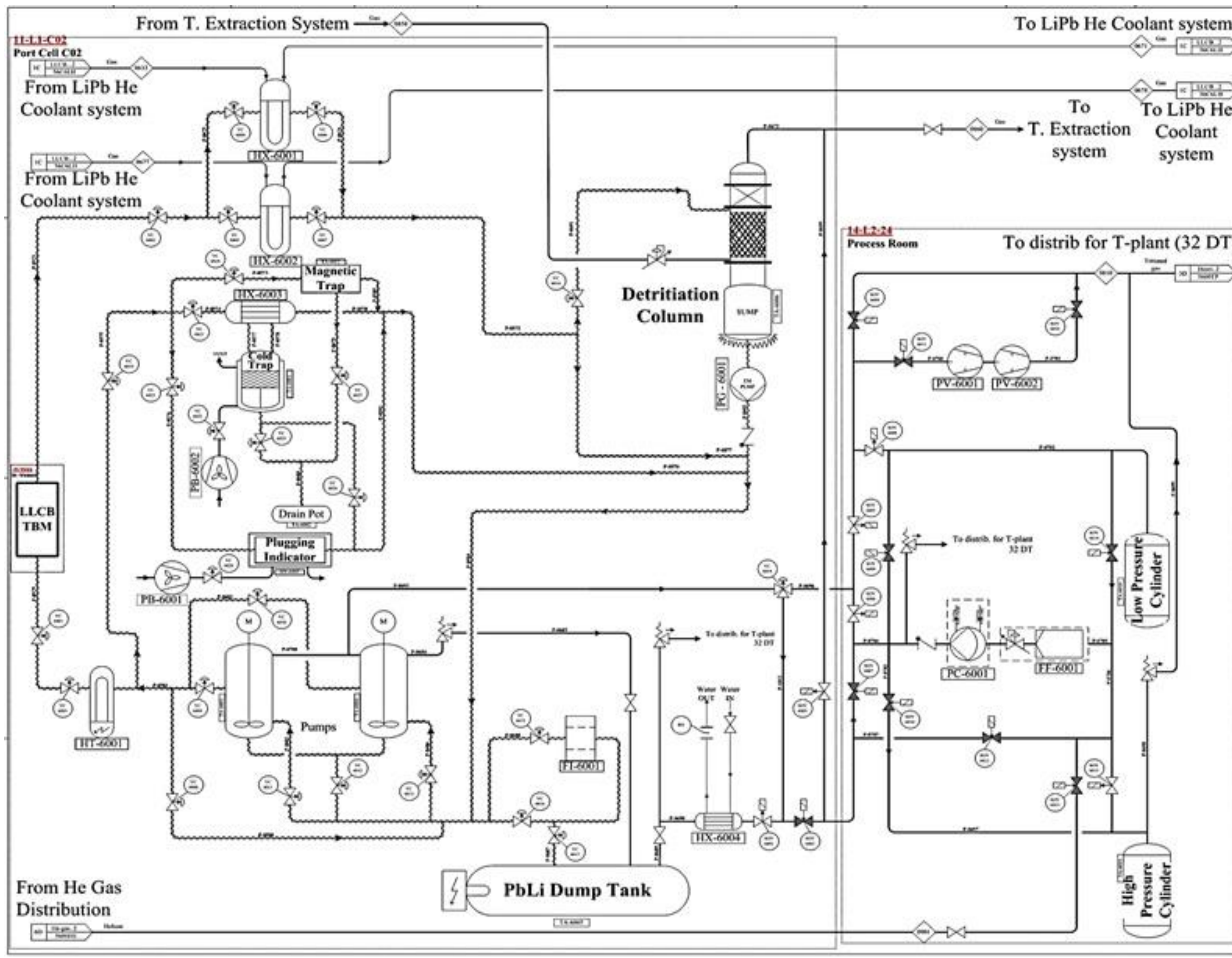
- Demonstrate **T self-sufficiency** (Li_2TiO_3 and Pb-16Li breeders).
- High grade **heat extraction** (Helium and Pb-16Li coolants).





LLCB Test Blanket Module [1]

[1] LLCB TBS System Design Description V1.0



LLCS Process flow diagram

Motivation & challenges

- **Pb-16Li a reference candidate material:** requires validated measurement tools/technologies (for studies in lab-scale facilities, LM blankets).
- **Operating parameters of LLCS & ITER operational cycle schedule:** demand precise validation & reliable performance over long durations for effective blanket operation.
- **LLCB TBS design identifies LLCS isolation safety functions** based on:
- Pb-16Li pressure measurement: TBM inlet/outlet (in-TBM LOCA).
- Pb-16Li level measurement: Dump tank, sump tanks (in-vessel LOCA/ pipe rupture).

- Limited operational experience.
- Relatively high freezing point for liquid Pb & Pb-16Li.
- Limited instrumentation availability for LMs.
- Material compatibility.

Sensor selection

- ➢ **Application of Pb-Li: confined to fusion specific studies.**
- ➢ **Development of LM blanket concepts: triggered studies related to Pb-Li as a process fluid; requirement of technologies adapted to liquid Pb-Li.**

Steps followed for development of sensors:

a) Proper selection of measurement technique

- Commercial availability (diversification: reduces risk of common mode failure).
- Performance history.

b) Sizing of sensors

- MOC (critical for wetted configuration).
- Test environment considerations (temperature & pressure).
- Installation constraints, process connections etc.

c) Engineering modifications/customizations of COTS sensors

- As applicable for specific requirements.

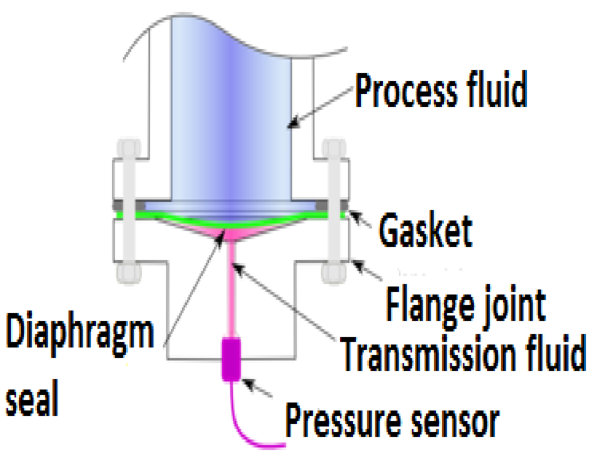
d) Rigorous experimental validation for intended LM application

- Application feasibility.
- Calibration check.
- Long duration performance validation (maintenance requirements / freq. of failures).

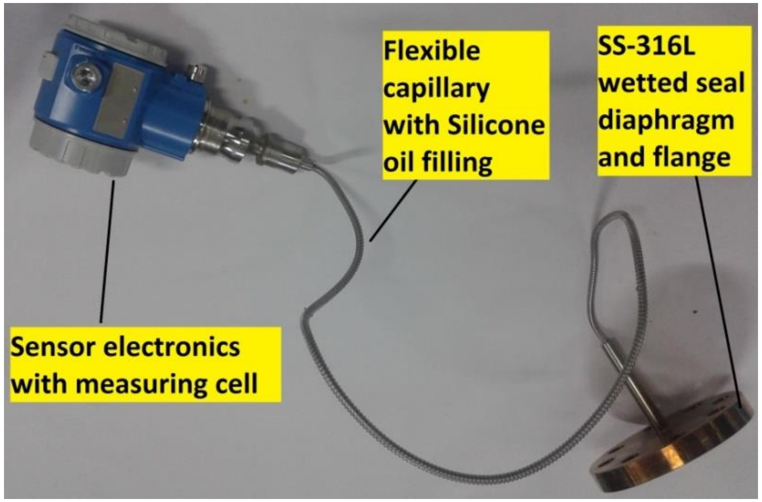
(a) Pressure measurement

Sensor Type: Piezo-resistive principle based remote diaphragm seal type pressure sensor

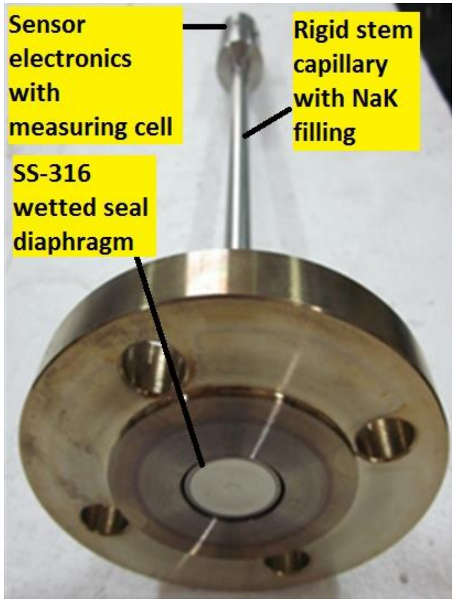
- Sensing element and electronics: mechanically isolated from HT process.
- Pressure transmission through high temperature compatible, incompressible, intermediate fluid (silicone oil / NaK) in a fine capillary ≤ 1mm bore diameter.
- Minimum volume displacement ensures better dynamic response.
- Wetted parts: SS-316/316L flush configuration diaphragm seal; Gasket: Grafoil.



Operational principle of diaphragm seal



Silicone oil filled capillary based pressure sensor

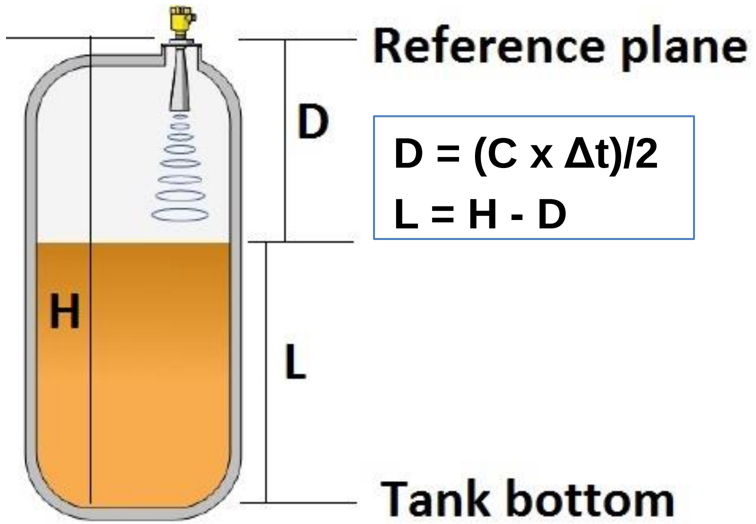


NaK filled capillary based customized pressure sensor

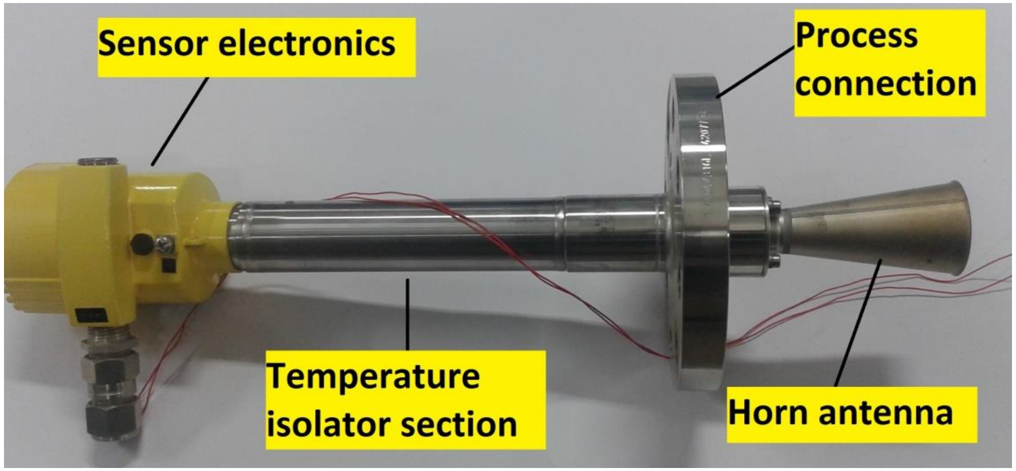
(b) Level measurement

Sensor Type: Non-contact configuration pulse radar level sensor

- Immune to oxide/impurities deposition, corrosion, bending stresses.
- Distance measurement using TOF method (level estimation by configuration).
- Unaffected by process conditions (temperature, pressure, gas composition etc).
- Electronics is isolated from HT process using temperature isolator section.
- Operating frequency 26 GHz (K-band): smaller process connections, focused beam.
- Horn Antenna: SS-316L; Antenna cone: Ceramic (Al_2O_3); Gasket: Grafoil.



Operational principle of pulse radar level sensor

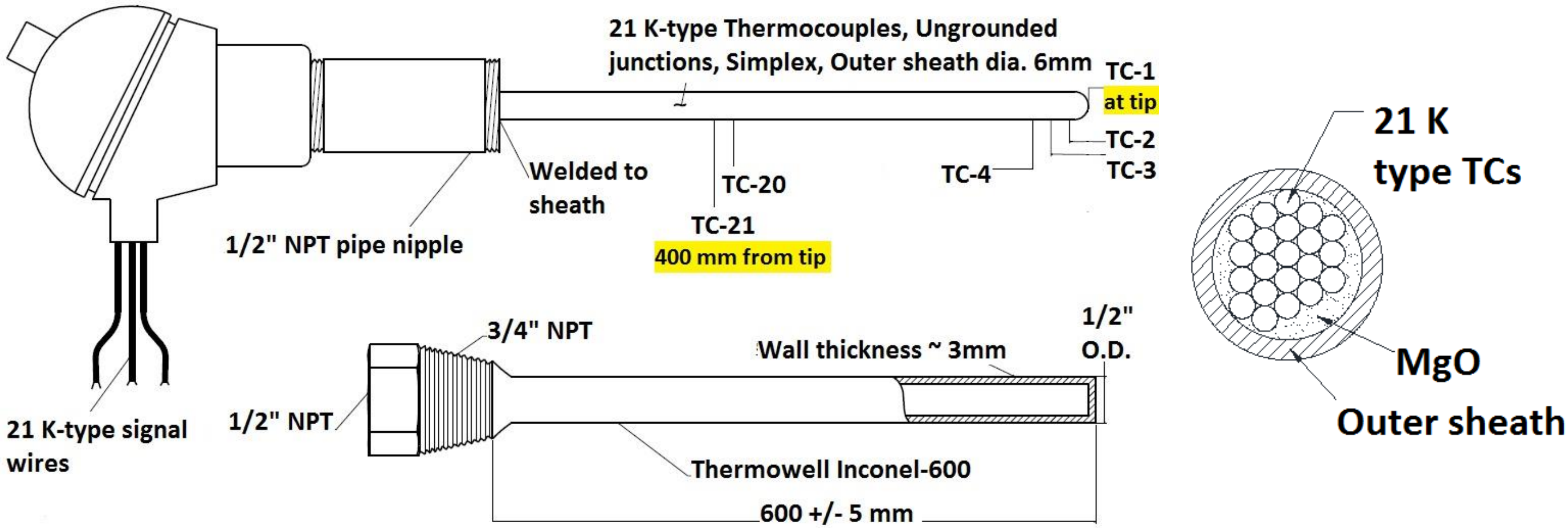


Non-contact type pulse radar level sensor

(c) TeLePro (Temperature Level Probe)

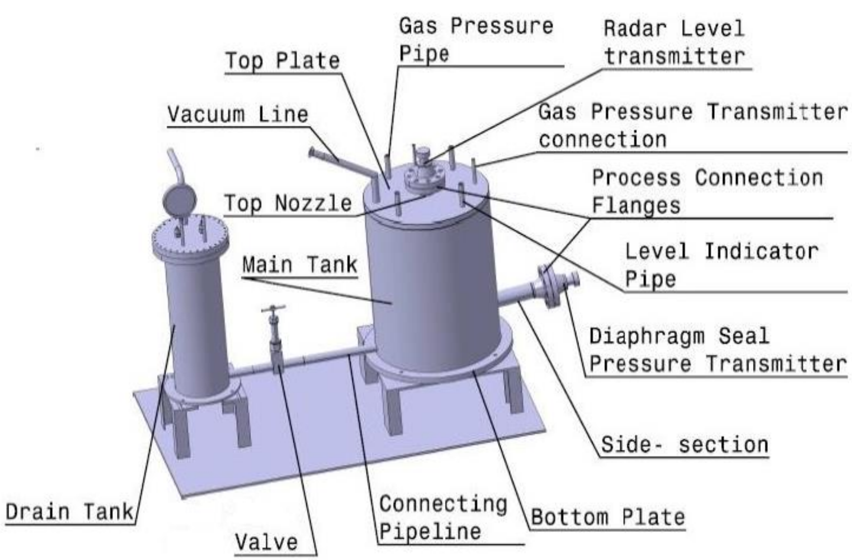
Sensor Type: Customized K-Type multilevel thermocouple with thermowell

- Equidistant junctions (20 mm apart) provide bulk temperature profile.
- To study feasibility of development as a level sensing technique using differential bulk temperature measurement (abundance of data from multiple junctions for validation).
- Can be further enhanced for better accuracy, resolution and response.
- Limited by manufacturing feasibility and detectable temperature gradients.

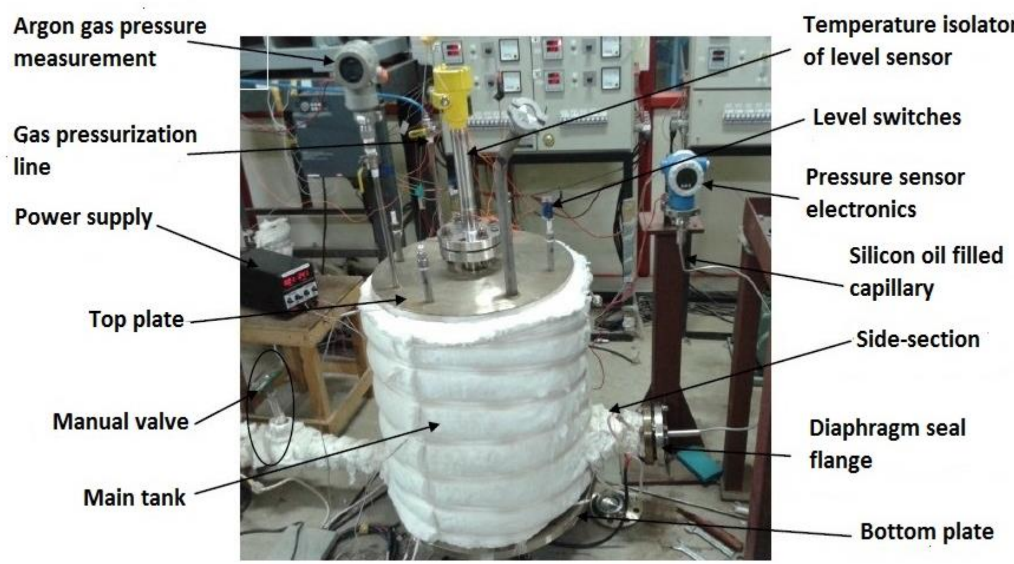


Schematic for TeLePro sensor assembly

Test Facility-1: Design & constraints



Schematic diagram of test facility-1

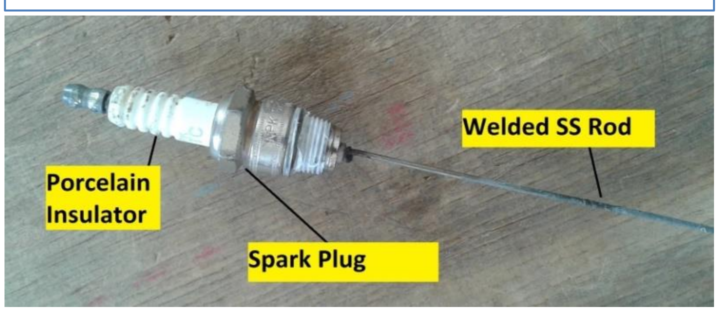


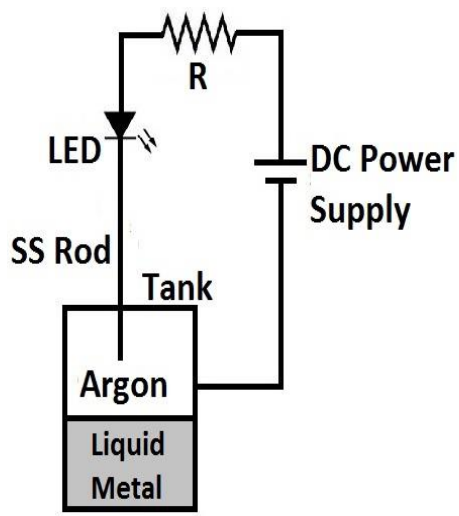
Level and pressure sensors installed on main tank

Design constraints:

- Maximum height of top nozzle
- Minimum I.D. of main tank

Liquid Pb as an economical substitute.





Conductivity level switch construction and working principle

Process Medium	Liquid Pb
Operating Temp.	380°C – 400°C
Operating Pressure	Upto 1 MPa (g)
Density of Pb	10,584 kg/m^3 at 400°C
M.P. of Pb	327.4°C

Process parameters for test facility-1

Test Facility-1: Calibration & test methods

For Pulse radar level sensor calibration:

- Known inventory of Pb ingots (405 kg).
- **First calibration point:** Using the total inventory of Pb, density of Pb at operating temperature & dimensions of test facility-1, liquid Pb level was analytically estimated & compared with radar level sensor output.
- **Second calibration point:** Liquid Pb was transferred to drain tank (upto 555 mm); remaining level in main tank was analytically estimated & compared with radar level sensor output.
- Over **700 hour continuous** performance test with cover gas pressure upto **1 MPa (g)**.

For Silicone oil filled capillary based pressure sensor calibration:

- $\boldsymbol{H}_{effective} = \boldsymbol{H} - 145\ mm$

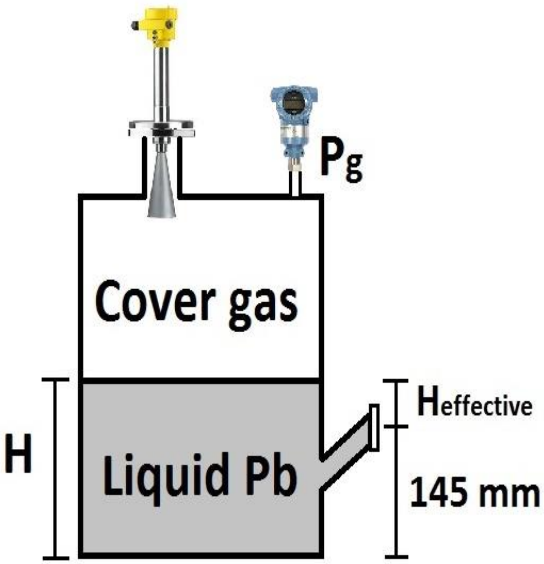
  *where **H** is measured by validated radar level sensor*

  $\boldsymbol{P}_{effective} = \boldsymbol{H}_{effective} \cdot \boldsymbol{\rho}_{Pb} \cdot \boldsymbol{g}$

  $\boldsymbol{P} = \boldsymbol{P}_{effective} + \boldsymbol{P}_g$

Hence possible to vary total pressure applied to seal diaphragm by varying cover gas pressure (P_g) alone while ensuring that diaphragm seal is in contact with liquid Pb.

- Calculated total pressure *P* was compared with sensor output.
- Over **310 hour continuous** test & cover gas pressure upto **1 MPa (g).**



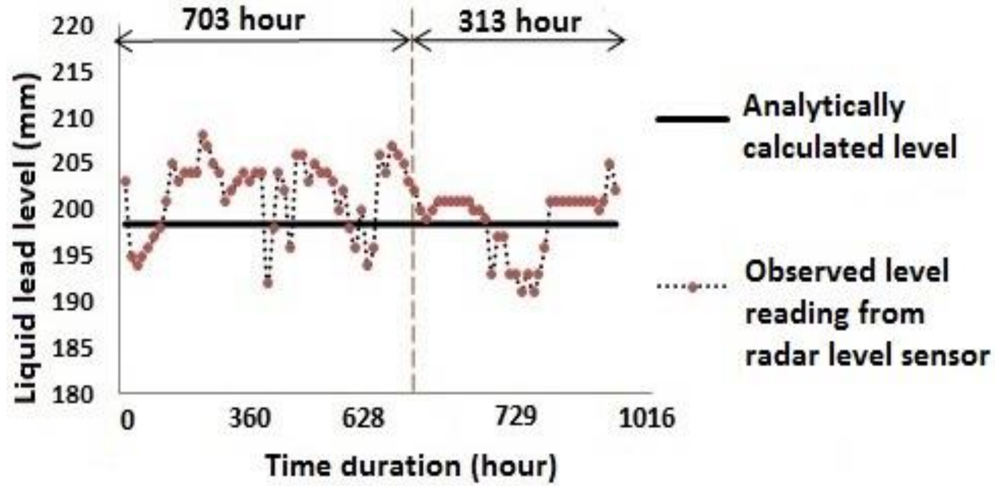
Schematic for pressure sensor calibration

Test Facility-1: Calibration & performance results

Analytically estimated level (mm)	Level indicated by radar level sensor (mm)	Deviation (mm)
198.42	200.91	**+ 2.49**
104.97	112.60	**+ 7.63**

Calibration data for non-contact radar level sensor

- **Over 1000 hour test: [- 7.42 mm, + 9.58 mm]**
- **Ambient Calibration check : [+ 1 mm, + 5 mm]**

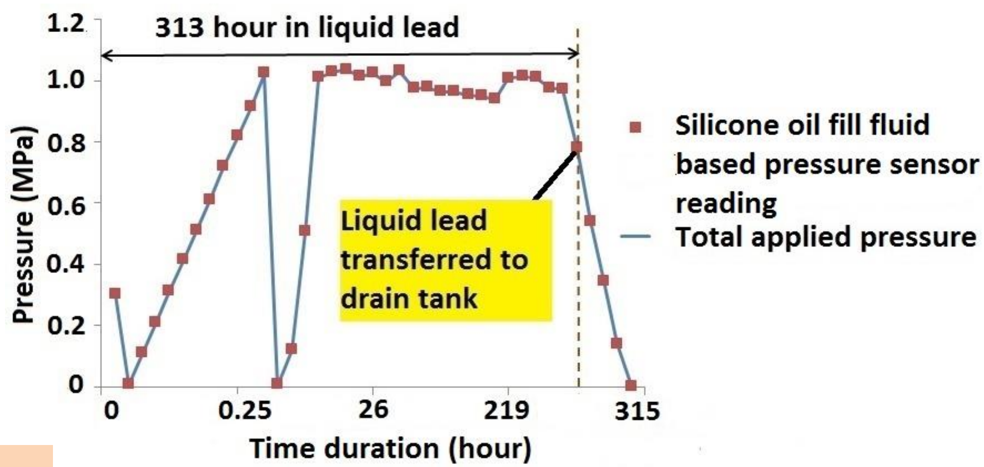


Long duration test data for non-contact radar level sensor

- **Sources of error:** Manually performed dimensional measurements, assumption of a constant bulk density, manual operation of isolation valve, error related to conductivity switch and accuracy of radar level sensor.
- **Data suggests absence of smooth melt surface:** May be attributed to surface topography of oxide layers.
- **Validated for liquid Pb ➡ Validated for liquid Pb-16Li, other LMs and metallic alloys.**

Condition of diaphragm seal after exposure to liquid lead

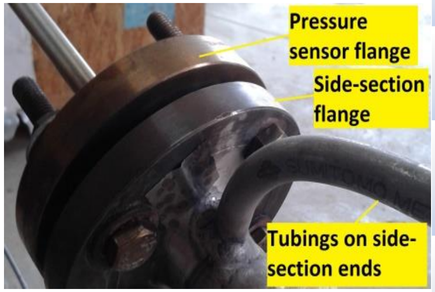
Estimated error over 310 hour test: Within 0.3% of span



Long duration test data for diaphragm seal type pressure sensor

Test Facility-2: Design

- **Experimental validation of sensors:**
  - Compatibility with HT, HP liq. Pb-16Li.
  - Deteriorating effects of corrosion.
  - Feasibility of level estimation using TeLePro concept.
- **Design optimized:**
  Pb-16Li inventory (~23 kg).

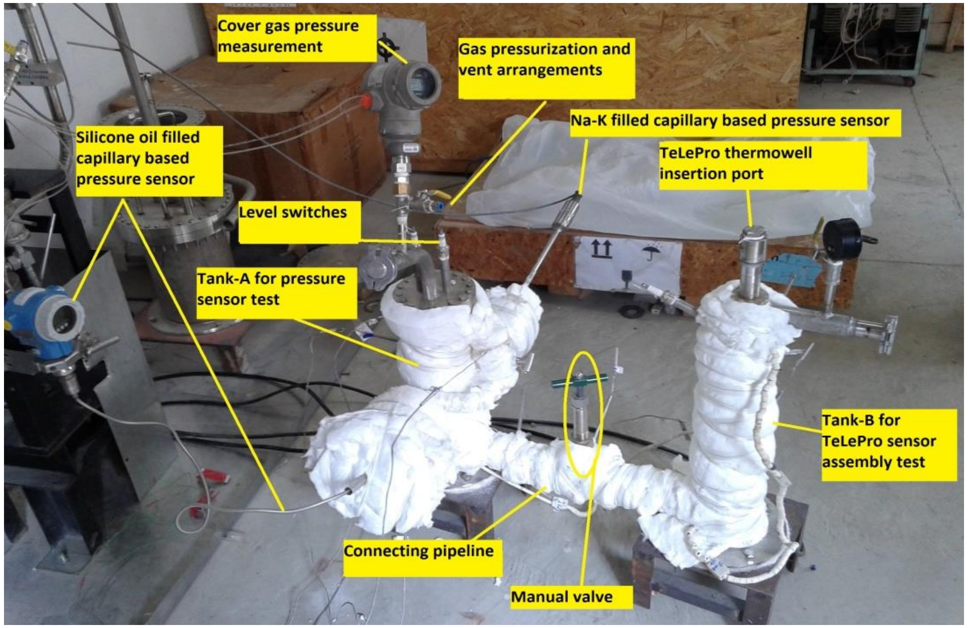


Tubing on side-section end

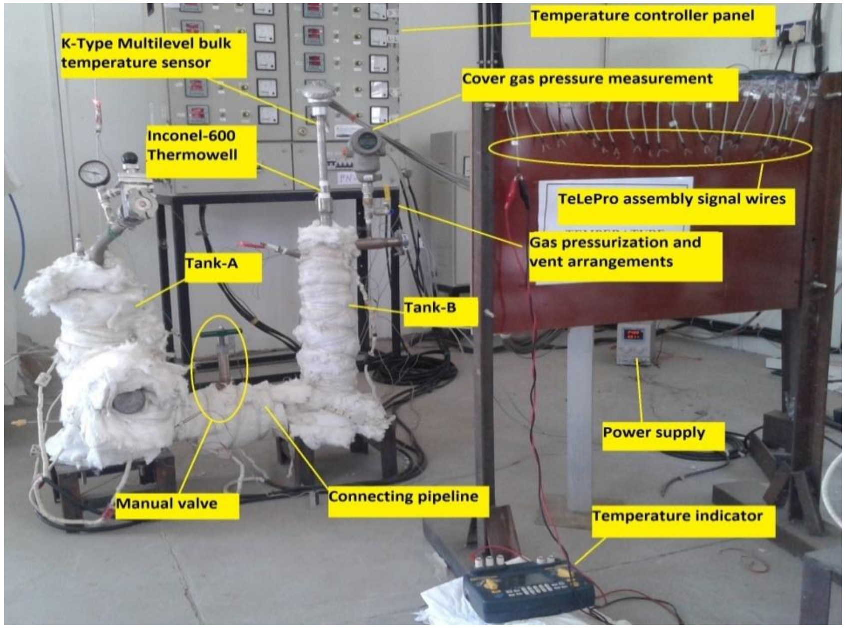
Process Medium	Liquid Pb-16Li
Operating Temp.	250°C – 530°C
Operating Pressure	Upto 1.05 MPa (g)
Density of Pb-16Li	9318 kg/m^3 at 400°C
M.P. of Pb-16Li	235°C

Process parameters for test facility-2

Tubings between end of each side-section and top of tank-A (remove trapped gas volume & ensure proper drainage).



Pressure sensors testing phase



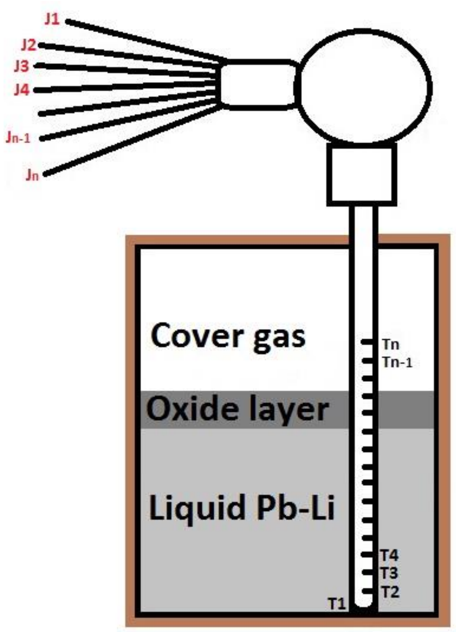
TeLePro assembly testing phase

Test Facility-2: Calibration & test methods

For Pressure sensors calibration:

- Effective Pb-16Li heads estimated using movable conductivity level switches.
- For silicone oil fill fluid based pressure sensor : $H1_{effective} = 66\ mm$
- For NaK fill fluid based pressure sensor : $H2_{effective} = 75\ mm$
- $P_{effective} = H_{effective} \cdot \rho_{Pb\text{-}16Li} \cdot g$

  $P = P_{effective} + P_g$
- Two calibration cycles, each from **0 to 1 MPa (g) & vice-versa**, at the start & end of **continuous 1000 hour** performance test.

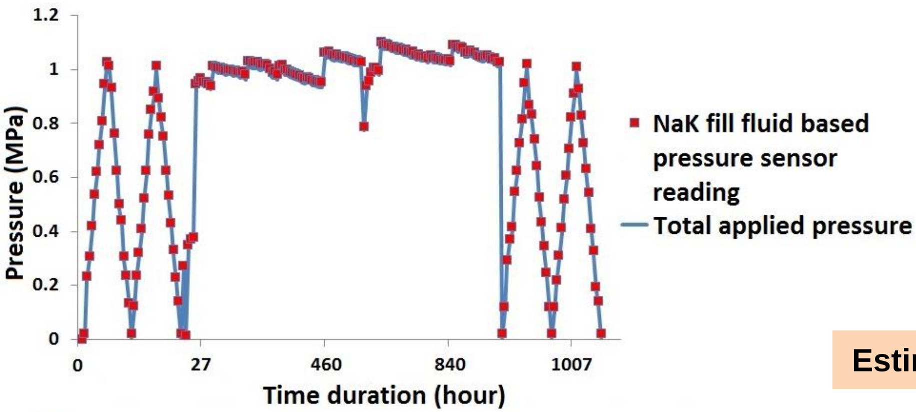


Schematic for TeLePro testing as level sensor

For TeLePro assembly testing:

- **Continuous 1000 hour** performance test.
- Afterwards, TeLePro development campaign:
- Different cover gas pressures at a constant temperature CSP.
- Different temperature CSPs at a constant cover gas pressure.
- **Heater control of tank-B using junction-1 of TeLePro.**
- **Above temperature profiles were taken in steady state.**
- Total test duration for TeLePro in liquid Pb-16Li ~ **1240 hours**.

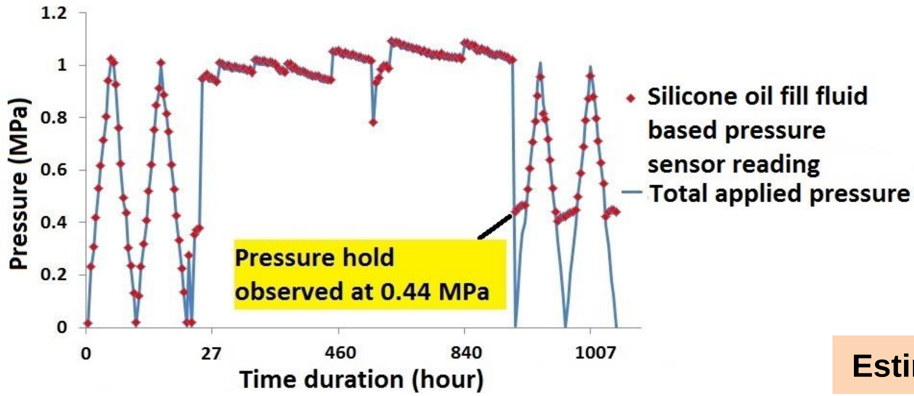
Test Facility-2: Calibration & performance results



Diaphragm seal after exposure to Pb-16Li.

Chemically cleaned diaphragm seal was observed in good condition.

Estimated error over 1000 hour test : Within 1.1% of span.



Diaphragm seal after exposure to Pb-16Li.

Chemically cleaned diaphragm seal was observed in distorted condition.

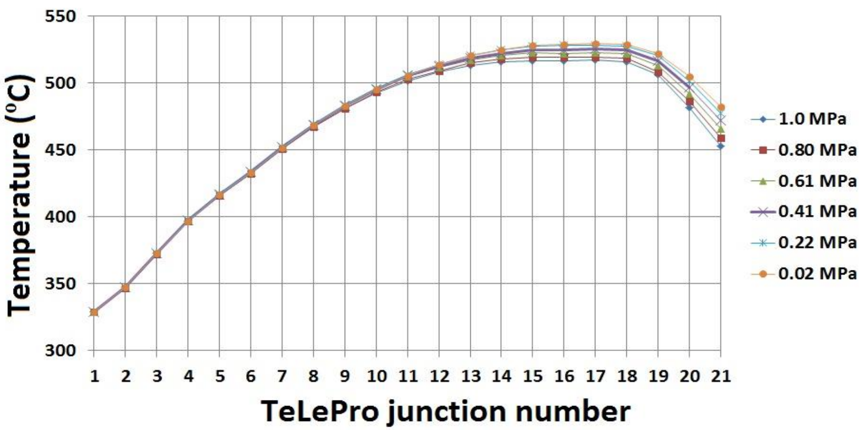
Estimated error : Within 0.9% of span before 3rd calibration cycle.

- **3rd cycle: silicone oil based sensor displayed a hold between 0.4 MPa to 0.46 MPa for applied pressure < 0.4 MPa.**
- **Possible reasons:** Damage/distortion of diaphragm seal, deposition of oxides on diaphragm seal, thermal expansion of silicone oil inside the capillary or a combination of one or more of above.
- **Further diagnosis: Pressure increase upto 0.38 MPa (g) when diaphragm seal heated at ambient pressure.**
- Another silicone oil fill fluid based pressure sensor: Similar behavior after **160 hour** exposure to liquid Pb followed by **210 hour** exposure to liquid Pb-16Li **(reading hold between 0.42 MPa to 0.44 MPa for total applied pressure < 0.4 MPa).**

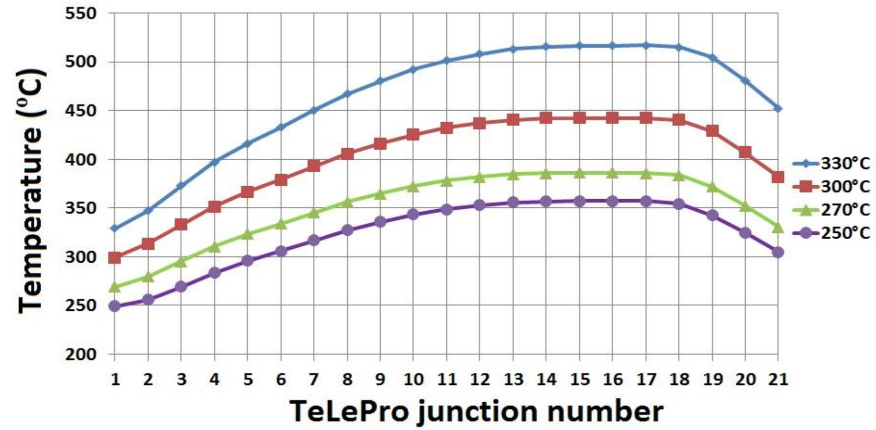
➡ **Suggests dominant thermal expansion of silicone oil fill fluid inside capillary over long durations.**

➡ **NaK fill fluid based pressure sensor showed promising performance over long duration operations.**

Test Facility-2: Performance results (TeLePro)



CSP of 330°C with different cover gas pressures



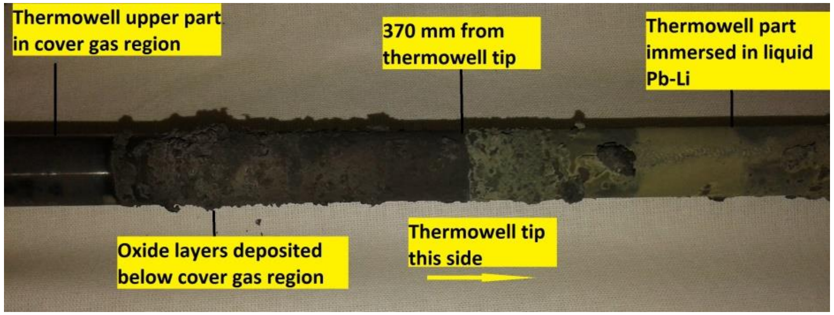
Cover gas pressure ~ 1 MPa (g) with different CSPs

Case-I: Temperature for the region near Pb-16Li top surface decreased with an increase in cover gas pressure.
Case-II: Overall temperature profile shifted upwards with an increase in temperature CSP.

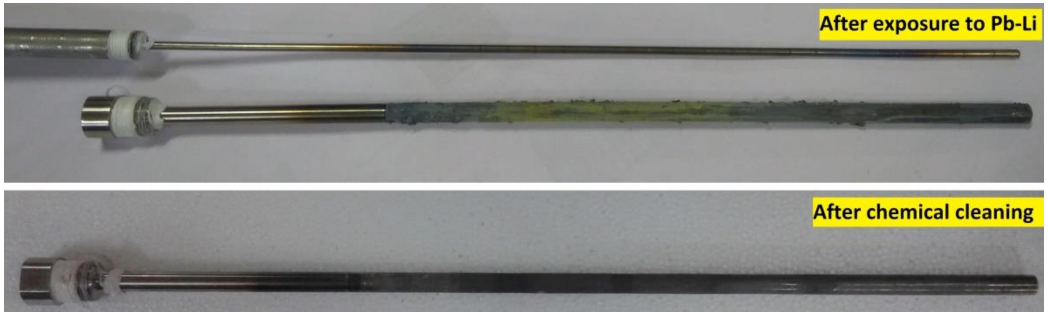
Temperature increased continuously:	**#1 to #15**
Remained nearly constant (within 3°C):	**#15 to #18**
Thereafter decreased continuously:	**#18 to #21**

$\Delta_{18\text{-}19}$ = 7°C to 12°C, $\Delta_{19\text{-}20}$ = 17°C to 25°C, $\Delta_{20\text{-}21}$ = 20°C to 29°C

Location of #19 = 366.4 mm from TW tip (as per design)



Deposition patterns on TW of TeLePro



TeLePro after exposure to Pb-16Li and after chemical cleaning

- XRD analysis: PbO and Li_2O **(no presence of Ni observed in samples taken from thermowell).**
- Precise level estimation governed by resolution: more junctions OR more than one vertically arranged TeLePro.
- The proposed compact TeLePro concept is adaptable for smaller tanks/ tanks with internal installations.

Future experimental plans

Tests for radar level sensor:

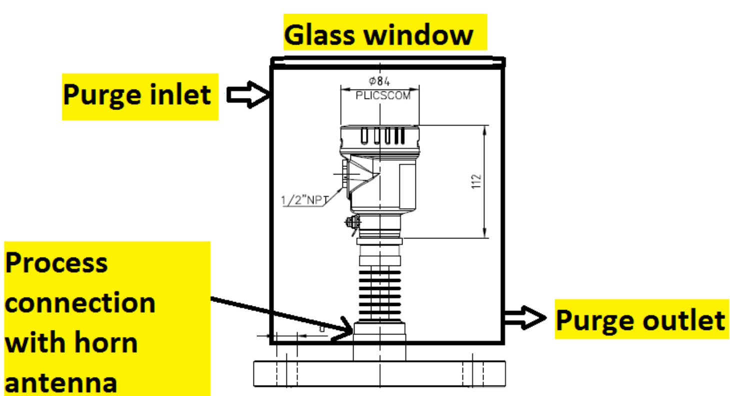
- Validation for smaller tanks (simulating internal installations in a tank): False signal suppression.
- Design modifications and optimization: active purging/ cooling neck and waveguide extensions.

Tests for remote diaphragm seal type pressure sensor:

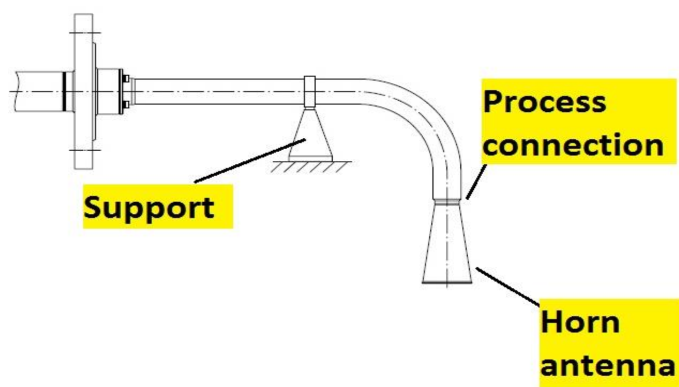
- Validation for pressure measurement in higher bulk temperature (> 400°C) systems: independent temperature control of extended side-section ($M.P._{Pb\text{-}16Li} < T \leq 400°C$).

Tests for temperature sensors:

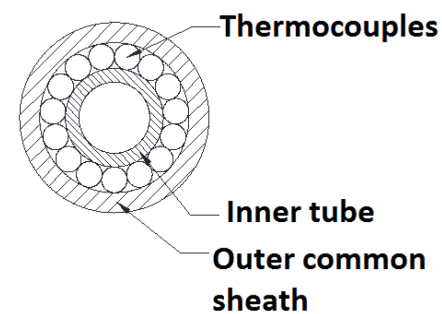
- Calibration & further testing of TeLePro against radar level sensor to estimate accuracy band.
- Temperature sensors with TW assemblies in Pb-16Li loop pipelines (upcoming facilities).



Design modification for compact configuration of radar level sensor



Design modification foreseen for radiation qualification of radar level sensor



Response time equalization for junctions of TeLePro

Summary

- Indigenous calibration & test facilities were designed and fabricated at Institute for Plasma Research for **rigorous experimental validation** of level, pressure & temperature sensors as part of **R&D towards liquid Pb/Pb-16Li process instrumentation.**

- A differential temperature measurement based **interface detection technique using bulk temperature profiling** was studied & validated for liquid Pb-16Li.

- High **reliability and availability** was observed for tested sensors in high-temperature, high-pressure liquid Pb/Pb-16Li applications.

- Error estimated from over **1000 hour** performance tests:
  - For non-contact pulse radar level sensor: **within ±10 mm** on liquid Pb.
  - For diaphragm seal type pressure sensor: **within 1.1% of span** on liquid Pb-16Li.

- Further design optimizations & compatibility with environmental factors (like magnetic field, radiation etc.) need to be addressed for qualification of sensors relevant to applications foreseen in fusion test blankets.

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