Development of LOCA Qualified Absolute Pressure Sensors for Nuclear Reactor Applications

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Abstract
LOCA qualified absolute pressure sensors with remotely mounted electronics are developed for nuclear reactor applications. The pressure sensor located inside the containment is connected to the electronics module located outside the containment through long screened cable. During accident, only the pressure sensor will encounter the accidental ambient conditions. The pressure sensors are designed to withstand and operate under the atmosphere of steam water mixture at 180°C temperature, 10 bar pressure and high gamma radiation which may arise during Loss of Coolant Accident (LOCA). The pressure sensors are developed to meet stringent application requirements, high pressure, high temperature, nuclear radiation endurance, stringent environmental qualification requirements, EMI/EMC, Shock and vibration qualification requirements. The salient features and qualifications of indigenously developed LOCA qualified absolute pressure sensors are presented in this article.

Introduction
In nuclear power plant, for safety reasons, sensors used for pressure measurement of reactor coolant system (RCS) are located within the containment. The pressure sensors which are located inside the containment and used for actuation of reactor safety systems should function during accident and maintain their functionality after the accident to ensure safety of the plant. During normal plant operation, the temperature in the area of sensor installation is 30°C – 40°C, whereas during LOCA, these areas will encounter an atmosphere of steam water mixture at very high temperature, high pressure and high radiation. Commercially available pressure transmitters cannot fulfill these requirements as they fail to perform under high temperature and high radiation conditions. In that harsh condition, the pressure transmitter fails mostly due to the failure of the electronics which is housed in the same enclosure along with the sensor. In view of the above, LOCA qualified pressure sensors are indigenously developed with Bi-bloc structure. Here the pressure sensing unit is designed to support remotely mounted electronics converter (signal conditioning electronics unit). It enables electronics module to be brought out of containment to a conditioned atmosphere and connected with the pressure sensing unit mounted inside the containment through long screened cable. The pressure sensors which are to be mounted inside the containment have been designed to withstand and operate under the LOCA condition. Two types of LOCA qualified absolute pressure sensors have been developed based on two different operating principles.

LOCA qualified Absolute Pressure Sensor mark–I
Absolute pressure sensors mark–I are developed for 2 ranges, 0 – 250 kg/cm² and 0 – 100 kg/cm² with measurement accuracy of ± 1 % of span under normal ambient condition. The over range pressure of the sensor is 150% of full scale. The pressure sensor is qualified to operate under accident
condition of 180ºC, 10 bar saturated steam atmosphere and total integrated dose of 5 MRad of gamma radiation. The pressure sensors are connected to the reactor coolant system and high pressure system of the plant. Fully welded construction has been adopted for the pressure sensor to achieve zero leakage. LOCA qualified Absolute Pressure Sensor mark–I is shown in Fig. 1. Bourdon tube is used as basic pressure sensing element for absolute pressure sensors mark–I. The deflection at the free end of the Bourdon tube due to the applied pressure is converted to electrical signal by customized high temperature Linear Variable Differential Transformer (LVDT). The pressure sensor is provided with back up pressure boundary to contain the process fluid in case of accidental rupture of Bourdon tube.

Remotely mounted electronics module shown in Fig. 2 provides excitation signal to LVDT primary coil, receives the LVDT secondary output, conditions the mV ac output and provides 4-20 mA DC output proportional to input pressure. The electronics module is connected to the pressure sensor with the help of 4 core screened cable with copper conductor of cross section 1.5 mm² and length up to 100m. Remote health-check facility is provided in sensor electronic converters which enables electronic converter health check and ensures connectivity with the control system. On application of the test signal, healthiness of all the components of electronics module is checked and 12 mA output signal (50% of the output span with permissible error of ± 1% of span) is generated. After removing the test signal, the electronics returns to measurement mode and its output becomes proportional to the applied pressure.

**LOCA qualified Absolute Pressure Sensor mark–II**

Absolute Pressure Sensor mark–II is developed based on piezoresistive principle. The mark-II version has better accuracy than the mark-I version. Absolute pressure sensors mark–II is shown in Fig. 3. The measurement accuracy of mark-II pressure sensors is ± 0.25% of span at normal ambient condition for both 0 – 250 kg/cm² and 0 – 100 kg/cm² ranges. This version of sensor is also designed with Bi-bloc structure, with field mountable pressure sensing unit and remotely mounted electronic unit. The pressure sensors are qualified to operate under LOCA condition of 180ºC, 10 bar saturated steam atmosphere and 5 MRad total integrated dose of gamma radiation.

Remotely mounted electronics module provides constant DC excitation signal to sensor bridge circuit, receives the mV DC bridge output and converts it to 4 – 20 mA DC output proportional to input pressure. The pressure sensor is connected to the remotely mounted electronics through 4 core screened cable of length up to 200m. Remote health-check facility is provided in electronic converters of mark–II pressure sensor also.

**Qualification of Absolute Pressure Sensors**

Qualification of the pressure sensors has been carried out to ensure that the sensors function reliably under high pressure, high temperature, high radiation conditions and perform satisfactorily throughout its life and meet the application requirements. Salient qualification tests carried out on absolute pressure sensor and the observations are given below.

For **environmental qualification**, the pressure sensor was subjected to high temperature test, low temperature test, high humidity test, and salt spray test. During all these tests, the functionality of the sensor was monitored. Fig. 4 shows the pressure sensor assembly placed inside the environmental chamber for qualification tests.

**Accelerated thermal ageing test** was carried out on the pressure sensor to ensure satisfactory operation of the sensor at 40ºC ambient temperature for 10 years.

**Radiation ageing test**: Radiation aging test was carried out on the pressure sensors for total integrated dose of 5 MRad of gamma radiation at a dose rate of 0.1 MRad/hr. After the test, the accuracy was found to be within their reference accuracy (± 0.25% of span for the mark-II version and ± 1% of span for mark-I version).

**Over range pressure test** at 150% full scale pressure was carried out on each pressure sensor.

**Test for Protection against Water Jet** was carried out on the pressure sensors as per IEC 60529 from a distance of 1.5 metres for a period of 15 minutes. No traces of water were present in the enclosure of both versions of sensor after the test.

**Vibration test** was carried out on both types of absolute pressure sensors as per the application requirements. During and after the vibration test,
accuracy observed was within ± 1% of span for mark-I version and within ± 0.25% of span for mark- II version. Fig. 5 shows the vibration test of absolute pressure sensor.

**Shock Test:** The pressure sensors were subjected to shock test. After the shock test, accuracy observed was within their reference accuracy.

**Steam Chamber test:** Both mark-I and mark-II pressure sensors were subjected to steam chamber test for LOCA qualification. The sensors were exposed to 180°C, 10 bar saturated steam atmosphere for half an hour and exposed in moisture laden saturated air at 50 - 60° C for 24 hours. During and after the test, the pressure sensor functionality and operation was verified and it worked satisfactorily. Under harsh ambient conditions of steam chamber test, the accuracy of the absolute pressure sensor mark-I was within ± 4% of span. In case of absolute pressure sensor mark-II, enhanced performance was observed during steam chamber test. The accuracy of mark-II pressure sensor was ± 2.5% of span during the test. Fig. 6 shows the steam chamber test set up.

**EMI / EMC qualifications** were carried out on the electronic converters of the pressure sensors as per MIL-461 E.

**Conclusion**
LOCA qualified absolute pressure sensors based on two different operating principles have been developed for nuclear reactor applications. The LOCA qualified pressure sensors are designed such that they perform their intended functions reliably when exposed to normal and extreme service conditions. Manufacturing process, fabrication & assembly procedure and inter-stage testing methods have been developed for these sensors. Testing and qualification requirements for these pressure sensors have been formulated. The pressure sensors are fabricated with participation of indigenous industries and tested to meet the application requirements of nuclear reactor plant, high pressure, high temperature, nuclear radiation endurance, stringent environmental qualification requirements, EMI/EMC, Shock and vibration qualification requirements. The technical know-how is transferred to ECIL for manufacturing of these pressure sensors for future projects.
Fig.1: LOCA qualified Absolute Pressure Sensor mark-I

Fig.2: Electronic Converter for Absolute Pressure Sensor

Fig.3: LOCA qualified Absolute Pressure Sensor mark-II

Fig.4: Absolute Pressure Sensor placed inside the environmental chamber for qualification tests

Fig.5: Vibration test of Absolute Pressure Sensor

Fig.6: Steam Chamber Test Set up