Development of a High Temperature Neutron Flux Detector

Martin Shaw, Bradley Campbell, James Ballantine, Kevin Roberts
Ultra Electronics, Energy, UK

Ultra Electronics, Energy is currently the supplier of neutron flux instrumentation to the UKs Advanced Gas Cooled Reactor (AGR) fleet. Neutron flux instrumentation provides a safety critical function, giving operators the fastest indication of any transient power behaviour in a nuclear reactor.

The operating requirements for these sensors in an AGR reactor are higher than those for equivalent instrumentation in a Pressurised Water Reactor (PWR) or Boiling Water Reactor (BWR). Whilst the underlying physics of these devices is the same, the engineering challenges for AGR instrumentation are different. Design and manufacturing processes have to be more precise due to susceptibility of device performance to a number of factors post installation.

The AGR sensor therefore provides a sound engineering platform for the development of an equivalent device for the harsh environments expected in Generation IV reactors.

This paper discusses the capabilities of the Ultra Electronics neutron flux detector manufacturing facility and how these capabilities are being expanded to cover the anticipated operating conditions for Generation IV reactor designs.

A prototype design has been manufactured and mechanically tested, the sensitive coating process has been developed and the Mineral Insulated (MI) signal cable has been tested at elevated temperature.

I. Introduction

Ultra Electronics (Ultra) is currently the supplier of neutron flux detectors to the entire UK Advanced Gas Cooled Reactor (AGR) fleet. This follows from its long involvement in the design and development of such devices over a period of 50+ years. The AGR's are unique as commercially operating reactors in that they have an operating temperature much higher than the more prevalent Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) designs. As the neutron flux detectors are effectively positioned 'in-core', they and their associated cabling have to operate reliably at temperatures up to 550°C and a pressure of 70 Bar. The plans for the build of future nuclear power platforms now include smaller, more efficient devices that operate at temperatures well beyond even the AGR level of 550°C. The concept designs for these Generation IV High Temperature Reactors utilise a range of heat transfer mediums and in many cases have a requirement for neutron flux detectors to drive control or safety circuits. In anticipation of this requirement, Ultra has been investing in the development and build of a proof of concept fission chamber. The initial concept has the goal of delivering neutron sensitivity comparable to equivalent commercial devices and stability at temperatures of up to 825°C, but with the potential to operate at even higher temperatures.

M. Shaw, B. Campbell, J. Ballantine and K. Roberts are with Ultra Electronics Energy, Unit 7, Lancaster Road, Ferndown Industrial Estate, Dorset, BH21 7SQ.
(e-mail: martin.shaw@ultra-ncs.com).

II. Ultra Electronics, Energy Manufacturing

In order to manufacture neutron flux instrumentation for the UK AGR fleet, it was necessary for Ultra to first establish a manufacturing facility. In 2013, a building was acquired and over the following 3 years fully outfitted with the necessary equipment to perform manufacturing and testing operations.

Due to the lack of available test reactors within the UK, it is necessary to perform characterisation of detector performance at room temperature, 550°C and under the influence of irradiation separately to assess the expected performance in-core.

Consequently, test capabilities include a linear accelerator driven thermal neutron source capable of delivering 1×10^7 $n\cdot cm^{-2}\cdot s^{-1}$ in continuous operation, a 10 TBq ^{137}Cs source for gamma irradiation testing as well as large chamber ovens capable of achieving 650°C.

Failure of these devices during manufacture and service is typically caused by the presence of contamination in the neutron sensitive volume of the detector. To minimise the risk of contamination during build, a clean assembly area has been incorporated into the manufacture facility. Design of the system for providing the gas filling of the sensitive volume has also been designed to minimise the risk of contamination.

Historically, there has been variability within certain manufacturing processes that have contributed to device failures. Wherever possible, automated processes have been implemented to reduce this risk as the time taken to manufacture is of the order of months and the financial cost is significant.

III. AGR Neutron Flux Detector Challenges

Ultra manufactures 4 different designs of detector, all of which are gas-filled ionisation chambers in which the sensitive coating materials are ^{10}B or ^{235}U. The devices are optimised to operate in the following modes: pulse mode, DC mode, logarithmic/linear DC mode and pulse/Campbell mode.

These devices were designed between the 1960s and 1980s and have been used in-core since that date. Ultra has had to demonstrate equivalence of new build devices to these designs to justify their use without having to perform full re-qualification of the devices prior to use. The number of changes permissible are therefore small and have to be justified to the licensee and regulatory body prior to installation.

Legacy designs and specifications include manufacturing information that constrain certain processes, occasionally to the detriment of manufacturing yield or device performance.

Key challenges to successful manufacture are:

- contamination/cleanliness (including purity of the gas in the detection volume)
- Adhesion of the sensitive coating
- Processing under vacuum
- Material selection

As an example of sensitivity of these devices to low levels of contamination, the graph in Fig. 1 shows the effect of gas contamination on the performance of a device over approximately 1 year, at the end of which, the level of contamination is of the order of 50ppm. This leak rate in this case is nitrogen from the containment volume leaking into the

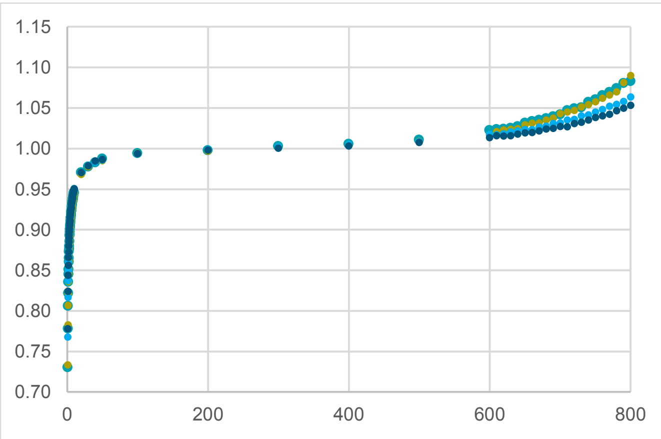

Fig. 1. Normalised current versus applied voltage for a device that is leaking gas into the sensitive volume of the detector, measured over 1 year. The avalanche breakdown region in the region >600V will eventually disappear, the saturation current voltage will increase and the device will become unusable

neutron sensitive chamber volume.

As a consequence of the failure shown in Fig. 1 and similar problems, processes have evolved to reduce the risk of failure and maximise the yield of useful components.

IV. Generation IV Reactors

Ultra has achieved the ability to satisfy the lifetime requirements of neutron flux instrumentation for the UK AGR fleet. Through this development cycle, a significant level of knowledge and experience has been gained on the impact of high temperature and neutron flux on the performance and behaviour of these devices.

Over the last few years there has been global interest in the development and deployment of new nuclear generating capability, specifically for Small Modular Reactors (SMR) and Generation IV technologies. Ultra is already working in collaboration with NuScale Power in the USA to address the instrumentation and control aspects of their SMR design. These requirements are similar to those for PWR/BWR technology and therefore provide a complex engineering challenge regarding their implementation rather than research and development programmes to identify solutions.

Generation IV reactors are being considered for a number of reasons, most importantly the ability to burn-up waste products, the increased temperature leading to increased efficiency and in certain instances to operate at atmospheric pressure. The conditions expected in a Generation IV reactor type are therefore expected to be very different to that experienced in existing power stations. The neutron fluxes will not only be larger, but also of different energy spectrum due to

TABLE I
OPERATING CONDITIONS FOR PWR, BWR AND AGR AND EXPECTED OPERATING CONDITIONS FOR SOME GEN IV REACTORS

Reactor	Temperature (°C)	Pressure (bar)	Neutron Flux ($n \cdot cm^{-2} \cdot s^{-1}$)
PWR / BWR	125	1	1×10^{9}
AGR	550	70	1×10^{12}
MFR (e.g. SFR / LFR	700	1	1×10^{15}
VHTR	1000	100	1×10^{15}

All values in the table above are in the location of the sensors, during normal operating conditions.

The Metal cooled Fast Reactor (MFR), including Sodium cooled Fast Reactor and Lead cooled Fast Reactor as well as the VHTR values variants have been estimated. Estimates are based on core outlet temperatures of approximately 800°C X-energy [1] EM2 [2].

the make-up of the fuel and the means of operation.

Table 1 shows estimates of various Generation IV operating conditions compared to those of PWR/BWR and AGR reactor types. It can be seen from the table that the jump from AGR technology to those of MFR and VHTR designs is significantly less than for PWR/BWR technologies.

The aim of the work presented in this paper is to extend the operational envelope of the core processes used on AGR detector manufacture into the MFR and if possible the VHTR operating regions.

V. Chamber Development

The AGR detectors typically consist of a large number of components, designed to operate successfully in the environment to which they are subjected rather than designed for ease of manufacture.

The chamber design for the high temperature detector has been generated around the critical dimensions of the device, but focussing on design for manufacture. As a result a number of key factors have changed:

- The part count has been significantly reduced
- Design of individual components has been changed to simplify machining
- Components have been designed to accommodate welding and joining techniques
- Vacuum processing time has been addressed in the design

The assembly time for a new device is now estimated to be of the order of 21 days, a reduction of approximately 7 days over the most simple of the existing AGR detector designs.

A chamber has been assembled and welded, then subjected to vacuum processing. It was subsequently filled with gas before temperature cycling to 825°C to represent the mechanical stresses expected in service. The electrical resistivity of the chamber was measured during this temperature excursion to characterise the performance, results of which are shown in Fig. 2, below.

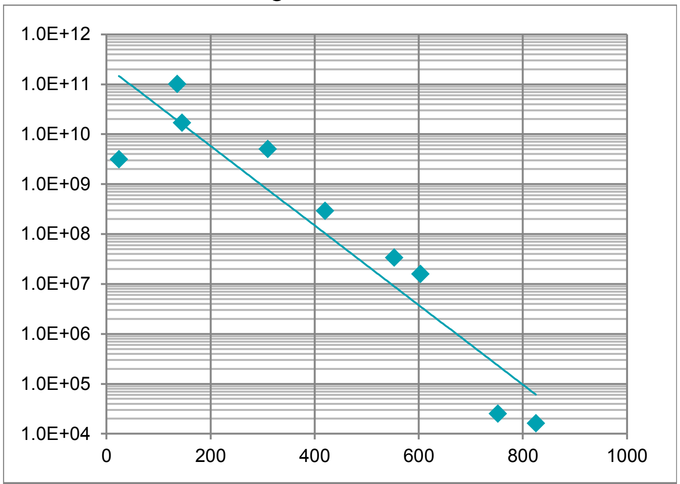

Fig. 2. Resistivity versus temperature for the high temperature detector chamber, tested up to 825°C.

The data from Fig. 2 shows the chamber performance follows the anticipated trend of a 1 decade decrease in resistivity for each increase in temperature of 100°C. This trend is commonly seen in the AGR detectors when tested up to 550°C.

VI. SENSITIVE COATING DEVELOPMENT

Separately to the chamber development, the coating process has been developed based on the technique used for applying ^{235}U to the AGR detector electrodes. This process was considered separately due to the handling risks associated with delamination of coating material during chamber manufacture. To further mitigate the risks, natural U has been used in all trials, which has identical bonding characteristics in the AGR regime.

The change in materials from stainless steel (AGR) to Inconel alloy used here led to modification of the process to ensure that the coating adhered to the electrode surface. Initial trials resulted in some delamination when subjected to temperatures in excess of 650°C.

Changes to the process and surface preparation of the components led to a significant increase in the yield rate of effective coatings. The key contributors to adhesion of the U coating on Inconel have been identified and there are a number of solutions identified to achieve the coating.

The images in Fig. 3 show Inconel electrodes coated with U after completion of trial activities. This process is now ready to be trialled using enriched ^{235}U on electrodes for the next development chamber.

Fig. 3. Examples of uranium coated onto the surface of Inconel after being subjected to 825°C. the left hand image shows the shape of the electrode and the right hand image is a close-up of the coated surface. It can be seen that the coating is well adhered to the surface, there was no evidence of delamination or flaking of the coating post excursion to high temperature.

VII. MI CABLE DEVELOPMENT

To transmit the signal from the detector to outside the reactor pressure vessel in high temperature power stations, Mineral Insulated (MI) cable is used. In the case of the AGR detectors, this cable is a triaxial copper-copper-stainless steel configuration with a magnesium oxide (MgO) insulating material between each of the metal components. The centre conductor (copper) provides a transmission path for the signal, the inner sheath (copper) acts as a screen for noise rejection and the outer sheath (stainless steel) provides mechanical strength. The stainless steel outer sheath also allows the reactor earth and the instrument earth to be electrically isolated.

The MI cable used in existing detector manufacture was developed by Ultra for use in the AGR fleet. For this study, the cable has been used unchanged but has been subjected to high temperature trials up to 850°C to characterise behaviour at these elevated temperatures.

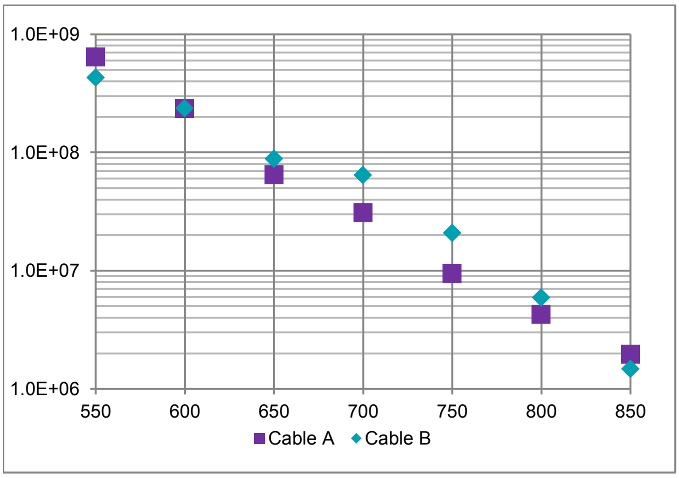

Fig. 4. Resistivity versus temperature for 2 MI cables tested up to 850°C

The graph in Fig. 4 shows the electrical resistivity of two cables as a function of temperature up to 850°C. As was also seen previously in Fig. 2, the data follows the expected trend of a decade decrease in resistivity for every 100°C increase in temperature. This trend is also commonly observed during testing of the MI cables up to 550°C prior to use in manufacture of AGR detectors.

 https://doi.org/10.1051/epjconf/202022503003

VIII. Further Work

A chamber assembly shall be manufactured with a sensitive coating and employing all processes developed to date. This device shall then be tested under a neutron flux whilst subjected to temperatures up to 825°C to determine operational characteristics.

A containment vessel shall be designed and manufactured to permit connection of the MI cable to the chamber. This will provide both interference immunity for the signal as well as a mechanical pressure boundary for the neutron sensitive volume after installation. This design shall be based on those used for the AGR detectors.

It is believed that the operational envelope of the MI cable can be extended by making material changes to the construction of the cable. It is not yet known whether these changes are required , thus trials and implementation will depend on the performance of the device under neutron flux and high temperature.

Generation of an electronics channel to combine pulse mode, DC mode and Campbell mode shall be performed using elements of the existing instrumentation. A separate study shall also be conducted to determine the feasibility of self-diagnostic electronics to show the health of a device over time.

References

[1] H. Bowers, "X-Energy Xe-100 Reactor", presented at the Initial NRC Meeting, September 2018.

[2] General Atomics, "Advanced Reactors Energy Multiplier Module (EM2)" [Online] http://www.ga.com/advanced-reactors