Characterization of boron coating in ionization chambers

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ACKNOWLEDGEMENT

This master thesis would not have been carried out without the contribution of skillful people and close relationships.

First of all, I would like to thank my Rolls-Royce tutor Floriane Drouet who has always been helpful and enthusiastic about my researches. I also appreciated being under the wise and constructive supervision of Mickaël Herman. I deeply thank the operators Denis Oriez, Salvatore Messina, Patrick Nicolas, Kais Elinoubl and Sid-Ali Maguenni as well who undertook challenging tasks in order to help me achieve my work. I am thankful to Franck Buenerd, a technician expert, who always overcomes technical problems in a smartly way. Finally, I greet all my Rolls-Royce colleagues from my open-space whom it has always been a pleasure to chat with.

I am very grateful to all my teachers, both from Phelma Grenoble-INP and KTH University, for their precious pieces of advice, interesting lectures and great support: Elsa Merle-Lucotte, Jan Dufek, Waclaw Gudowski, Olivier Doche, Nicolas Capellan, Pablo Rubiolo and many others. I also thank warmly the Phelma and KTH staffs who have been concerned about my issues.

Above all, I thank my parents. Thank you so much for the education you gave me, your support, and for believing in my projects, which obviously would have never existed without you.
Abstract

The quality of neutron detectors is of paramount importance in nuclear safety. The Rolls-Royce management initiated this MSc project to check detectors quality and to investigate new ways of manufacturing. The compensated ionization chambers are widely used in nuclear power reactors to measure thermal flux in the intermediate detection range (between $10^2$ and $10^{10}$ neutrons/s/cm²). The thesis focuses on the most important design detail of such detectors namely the boron coating layer. The sensitivity of such neutron detectors is mainly determined by the boron coating. For a better understanding of this correlation between the boron coating and the detector sensitivity, three experiments were performed with the “CC80 dévissable” prototype, manufactured by Rolls-Royce for the purpose of this research. Thanks to this sensor, the relationship between the coating parameters (surface and boron concentration) and the detector sensitivity are now better understood. In order to maximize the detector sensitivity, optimal coating parameters have been found. This research investigation permitted to confirm the high quality of such detectors and to investigate new ways of manufacturing which potentially may lead to a more effective and promising mode of production.
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**LIST OF ABBREVIATIONS**

CC80: Compensated ionization Chamber with a diameter of 80 mm, used for CNI
CCA: Container of a CNS and a CNI
CBL: Long ionization Chamber, usually CNP
CNI: Intermediate Range Channel
CNP: Power Range Channel
CNS: Source Range Channel
CPNB44: Proportional Counter used for CNS
EDF: Electricité de France, national company of electricity
HDPE: High Density PolyEthylene
HT: High Voltage Electrode
I&C: Instrumentation and Control
NIS: Neutron Instrumentation System (RPN in French)
PWR: Pressurized Water Reactor
RPN: ex-core instrumentation
S: Signal Electrode
SAS: Société par Actions Simplifiées, one type of company status
UNGG: Uranium Natural Graphite Gas
VVER: PWR reactor of Russian design
INTRODUCTION

Safe exploitation of nuclear power plants is the highest responsibility of nuclear operators as regulated by national governments. The control system relies on detection devices such as manometers, thermometers, boronmeters, etc. Therefore, all these instruments must remain reliable and operational all along the operation time in order to fulfill the safety requirements. Neutron detectors provide vital information for reactivity management, which allows operators to control nuclear power plants. Based on such measurements, the safe reactivity management of the core is guaranteed. In France, all the ex-core neutron detectors of the nuclear reactor fleet are made by Rolls-Royce Civil Nuclear SAS. Since the 60’s, the company has an intimate knowledge and expertise in neutron detection.

Rolls-Royce has developed various technologies for neutron detection. The thesis focuses on one of the widely used neutron sensor type namely the boron coated compensated ionizing chamber for ex-core measurement. Boron coated detectors are used over the whole range of neutron flux magnitude. In this MSc project, a study has been carried out with a neutron CC80-detector, which corresponds to an intermediate range neutron channel (between $10^2$ and $10^{10}$ n/s/cm$^2$).

More specifically, a characterization of the boron coating in the ionization chamber CC80 has been performed at one of the Rolls-Royce facilities in order to reduce the failing rate of the production. Numerous experiments were undertaken and the CC80-detector went through various characterizing tests. This study answered many questions about the coating process. The process of each experiment consisted in changing parameters in the fabrication process and then measuring the response of the detector under irradiation. The obtained qualitative results can potentially improve the production line.

In the first experiment, the contribution of the two different electrodes in the detection process was highlighted. Secondly, the boron coating was characterized with different coating surfaces in order to establish a correlation between the coating surface and the detector sensitivity. Last but not least, different boron concentrations were used in order to investigate the relationship between the boron concentration and the detector sensitivity.

Through this thesis, an overview of Rolls-Royce and its neutron detection technology will be exhibited. Then the detection process in neutron detectors will be explained afterwards. Eventually, the experiments and the results will be revealed.
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I - ROLLS-ROYCE CIVIL NUCLEAR SAS AND THEIR NEUTRON DETECTORS

HISTORY: A SUCCESS STORY

Created in 1960, Merlin Gerin cooperates with the French atomic center CEA (Commissariat à l’Energie Atomique et aux Energies Alternatives) on neutron instrumentation. They investigate civil nuclear technology and submarine nuclear propulsion. In 1970, Merlin Gerin buys the CEA boron coated ionization chamber patent and is in charge of neutron detection and control systems for the French nuclear plants development. Since the 1970’s, they use these sensors in various reactor types: gas cooled reactor with graphite moderation UNGG (Bugey 1), fast neutron reactor (Phénix), PWR (Fessenheim 1 and other French PWR). In the 1980’s, they sign their first international contract for their instrumentation and control sector: neutronic detectors and boron meters for Doel 1 reactor (Belgium). In 1984, they install the first integrated digital protection system (SPIN) in the world in Paluel 2 reactor (France).

In 1992, Schneider Electric buys the Merlin Gerin’s activities. One year earlier, the company signed the first long term contract (Pérennité) with EDF (Electricité de France) for the French nuclear reactors fleet. In 1993, the business crosses borders and helps for the first criticality of Daya Bay 1 (China) providing control rods system, neutron instrumentation, neutron detectors and boron meters. In the 1990’s, the SPIN technology is enhanced and is spread all through the French reactors.

In 2003, Data Systems & Solutions takes over the business. In this period, the instrumentation and control (I&C) modernization project starts at Dukovany nuclear reactors (4 VVER- 440 type reactors) in Czech Republic. In 2006, the company launches the modernization of the 900 MWe French fleet (34 reactors) refurbishing the control rods system and in-core instrumentation system modernization. The year after, pressure transmitters and temperature probes are integrated to the technical range.

In 2009, the business moves finally to Rolls-Royce. In 2011, the new project of modernization of the safety I&C systems occurs for 20 French reactors. In 2012, the first criticality is reached in Ningde 1 reactor (China) using Rodline Technology for control rods system. In 2014, the safety authority in the US NRC approves the spinline technology. In the same year, they participate to a modernization of Loviisa nuclear reactors (2 VVER-440 types reactor) in Finland. In 2015, Rolls-Royce provides boronmeters to 34 nuclear reactors in France.

In 2018, Rolls-Royce Civil Nuclear SAS employs about 500 people in Meylan (France) and tends to expand its technology worldwide. Rolls-Royce nuclear technology is implemented in 200 reactors in 20 countries.
**IMPORTANCE OF NEUTRON DETECTORS**

Neutron detectors are the sensors that give an electrical signal proportional to the thermal neutron flux magnitude. Based on these measurements, the control system evaluates the instant power of the reactor core continuously in time. The control system relies on these readings in order to maintain the reactor core in safe and stable state. Neutron detectors have two global functions:

- **Control function**: core power monitoring, measuring the power distribution, monitoring of the response time, etc.
- **Protection function**: preventing all abnormal situations such as triggering core shutdown in case of fast increase of neutron population, fuel protection like maximal temperature of the cladding, burnup rate, …

Therefore, neutron detection devices are essential for the nuclear power plant operation.

**NEUTRON DETECTION SYSTEM FOR NUCLEAR POWER PLANTS**

Through the history of the company, it is clear that Rolls-Royce has developed plenty of techniques for nuclear industries. From now, we will focus only on neutron detection devices (the historical technology of Merlin Gerin).

There are two main types of neutron detection: in-core (RIC in French) and ex-core (RPN in French and NIS in English for “Neutron Instrumentation System”). The NIS is designed to monitor the neutron flux, the variation and distribution of the instantaneous power. This system is used for various reactors around the world: PWR (France and China), VVER (Russia), research reactor (France) and submarine propulsion (France).

The measurement principle of NIS is a boron coated ionization chamber. Those detectors lie around the reactor vessel. The following figure shows the location of the NIS. Therefore water (inside the vessel), steel (vessel) and air (outside the vessel) are shielding the neutrons between the detector and the nuclear core.
The NIS must fulfill measurement criteria over the whole magnitude range of thermal neutron flux. It is a difficult task to fulfill for just one detector because the neutron flux monitored by the NIS varies from 0 to $5 \times 10^{10}$ n/s/cm², that is to say from the startup to the full power operation until the shutdown. So to monitor the neutron flux over this wide range, three types of detectors are adopted in the NIS:

- Source range channel (CNS in French)
- Intermediate range channels (CNI in French)
- Power range channels (CNP in French)

Depending on the reactor status (startup, power production, shutdown, core loading), different detector types must be used. The following graph illustrates that.

The left axis shows the thermal neutron flux (n/s/cm²). And the percentage of the rated power of the reactor is shown on the right axis. The readout is given in pA, not in units of
neutron flux. Indeed, a detector does not measure a neutron flux, rather it gives the number of counts per second for CNS (cps) or an electric current in ampere for CNI and CNP (A). For confidentiality, specific values are not given here.

CNS detectors are typically used during reactor startup and shutdown. CNS detectors are used while there is fuel inside the core; so operators use the CNS for the fuel loading as well. During the slow ramping up, a threshold is reached (P6 threshold). This threshold means that the detection channel switches from CNS to CNI. The CNS is then deactivated (the polarization voltage of the detectors is switched off) because the electrodes can be damaged at high neutrons flux. After this stage, the CNI must remain active: during the ramping up and during the full power operation as well. The second threshold (“Upper limit of gamma disturbance”) stands for the minimum neutron flux detectable by the CNP. For the full power the CNP are switched on while the reactor is inside the power range. This is the monitoring process for the reactor divergence.

For a 900 MWe reactor unit, there are 4 CNP, 2 CNI and 2 CNS. For a 1300 MWe unit, they install 4 CNP 4 CNI and 4 CNS.

![FIGURE 3: TYPICAL DETECTORS CONFIGURATION FOR A 1300 MWE REACTOR USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR](image)

Concerning the signal processing line, Rolls-Royce manufactures cables and other digital equipment (cabinets), which however lies outside the scope of this MSc thesis.

**NEUTRON DETECTORS TECHNOLOGIES IN THE NIS**

**SOURCE RANGE CHANNEL CNS**

Due to the weak value of the neutron flux (1 to $10^4$ n/s/cm$^2$), the suitable detector is a boron coated proportional counter working with impulsion for the electric signal. This detector is composed of an electrode (metallic thread) lying in the middle of a metallic cylinder (the second electrode). This thread collects the detection signal. A boron coating lies on the inner
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surface of the cylinder. The detector is filled with a mixture of argon and carbon dioxide. The addition of CO₂ implies the increase of electrons velocity and so enhances the response time (shorter).

In this detector type, the number of collected charge is superior to the number of created ions (a typical multiplication factor is around 400). This phenomenon is also called avalanche. The auto-amplification of the signal enables to measure very low flux.

The signal amplitudes of impulsions coming from the electrons implied by α and Li particles are markedly superior to the amplitudes of impulsions coming from γ particles. The principle of the detector signal is thus:

- Compensation of γ radiation by removing impulsions inferior to a certain threshold (discrimination threshold).
- Counting of non-removed impulsions

The CNS measuring range corresponds to the neutron flux produced by a reactor during the fuel loading and unloading, the reactor startup and shutdown; that is to say from 0 to 10⁵ n/s/cm². Rolls-Royce typically suggests CPNB44 for such measurements.

**Intermediate range channel CNI**

For this type of detector, a γ compensated ionization chamber is used. Those chambers work with electric current. Polarization voltage, which is the voltage across the detectors electrodes, has almost no influence on the output current. Actually, there is an influence for low voltages (2 volts). However during operation the voltage is so high that a plateau is reached and the electric current remains approximately constant.

The γ-particles are removed from the measurement. CNI detectors work with electric current (so impossible discrimination). The γ-radiation perturbs the detectable thermal flux between 10² and 5.10⁶ n/s/cm². The intermediate range channel can detect flux from 2,2.10² n/s/cm² up to 5.10¹⁰ n/s/cm². The CNI measuring range corresponds to the startup up to 30% of the rated power of the reactor.

The CNI system and CNS system lies in the same envelopes (CCA) and in the same wells around the core. The CNI detectors monitor the middle of the core whereas the CNS detectors collect data in the last quarter of the core (cf figure 4). The CC80 is a type of CNI detector. The following experiments will be performed with a screwable version of a CC80.
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FIGURE 4: SKETCH OF CROSS-SECTIONAL VIEW OF NEUTRON DETECTORS DISPOSITION AROUND THE CORE USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR

POWER RANGE CHANNEL CNP

CNP detectors are based on the same technology as the CNI chambers: boron coated ionization chambers filled with argon, nitrogen and helium. The output is an electrical current. The ratio gammas/neutrons of the nuclear core at this flux power level is very low, hence the fact that the $\gamma$ signal can be neglected. In this case, there is no need to use detectors with compensated chambers.

The CNP measuring range corresponds to the full reactor core power operation. The detection of the thermal flux is limited to the range between $5.10^2$ n/s/cm² and $5.10^{10}$ n/s/cm².

For 900 MW reactors, CNP system has only 2 sections: high section and low section which enable to provide information on the neutron flux distortion. For 1300 MW reactors, there are 6 section in one CNP system. With this design, more accurate information are obtained on the axial neutron flux distribution.

Detectors are placed in wells around the reactor pressure vessel. The CNP has its own wells unlike CNS and CNI that lie together in the same wells. The CNP monitors all the height of the core.

In Rolls-Royce, those products are long chambers and called CBL 10,15 or 60.

To verify the symmetry, 4 detectors are located in 4 equidistant points around the core.
FIGURE 5: A CNP DETECTOR, AS LONG AS THE HEIGHT OF A NUCLEAR PRESSURE VESSEL
USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR

DETECTORS LIFETIME

The detector lifetime, whatever its type, is obviously much less than the reactor lifetime. Spare detectors or spare parts are always needed for maintenances. Electricity de France (EDF), the operator of the French reactor fleet, has a stock of detectors ready to be installed.

PROPORTIONAL COUNTERS (CNS)

For CNS detectors, the lifetime is between 15 and 20 years. Multiplication phenomenon is characteristic of the CNS. This happens in the ionizing gas. The purity of the gas is essential. The presence of oxygen or moisture can create heavy negative ions which block the multiplication phenomenon. This leads to a high decrease of the multiplication factor which eventually modifies the detectors features. This mechanism is probably responsible of the high failing rate on CPNB 42 counters initially set on 900 MW French PWR.

IONIZATION CHAMBERS (CNI/CNP)

The lifetime of CNI and CNP detectors is about 15 to 30 years. The limiting factor for the lifetime of those detectors is the degradation of the boron coating. Boron is the “fuel” of those detectors: it is the consumable part (cf annex 2). However the input quantity of boron
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is not determining. Physico-chemical reactions occur on the interface metal/gas which leads to a loss of conductivity (creation of boron nitrates and boron oxides). Moreover, radiations damage highly the coating quality. However the speed of those reactions is rather low and those modifications can be detected plotting the saturation curve, hence the replacement of CNI and CNP before they are out of order. It is better for the operator to have prevention policy instead of having a real functioning problem.

Ionization chambers are sturdier than proportional counters. Degradation due to the gas quality happens normally before spending all the boron of the coating.

**CONSEQUENCES OF MAINTENANCE**

For quality monitoring purpose, saturation curves measurements are performed periodically for CNI and CNP and discrimination curves for CNS. This measuring method is rather reliable for ionization chambers since the degradation has a slow pace. However, regarding the source counters (CNS), the degradation is quite fast and the acquisition of discrimination curves remains impossible during the nuclear plant operation. This monitoring is not as efficient as expected.

In other words, it is still useful to prevent defects and change detectors during unit outage before severe degradation instead of replacing them during operation time.
II - IONIZATION CHAMBER PRINCIPLES AND PHYSICS

As said previously, neutron detectors are one of the main sensors to operate a nuclear power plant. There are different types of neutron detectors technologies but we will focus mainly on ionization chambers. First of all, let’s focus on a global detector group: the gaseous ionization detectors.

GASEOUS IONIZATION DETECTORS

At first glance, the principle seems quite simple. The point of gaseous ionization detectors is to ionize the gas inside the detector in order to collect electrons and ions so that an electric signal can be created. Thanks to a ionizing particle (α,β,γ), gas particles of the detectors are ionized, that is to say split into ions and electrons. Ions and electrons have a good mobility in a gas, they can move easily. An electric field is applied within the gas chamber through two electrodes, an anode (highest potential +V₀) and a cathode (lowest potential). It allows the collection of electrons on the anode and the collection of ions on the cathode.

This type of detector is usually cylindrical but it can vary. On the picture below, we can observe the irradiating particle (blue line) ionizing the detector gas into ions (green dots) and electrons (red dots). In other words, the ionizing particle loses a part of its energy in the gas. This energy is used to ionize the gas.

Due to mobility difference, electrons are collected faster on the anode than ions on the cathode. The drift velocity is therefore higher for electrons than ions under an even electric field. Just as a reminder, the drift velocity is the velocity of the particle towards the electrode. According to [2] and [7], the relation between the drift velocity u, the mobility μ, the electric field E and the gas pressure P can be described as below:
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\[ u = \frac{\mu E}{p} \]

The mobility \( \mu \) depends on the mass \( m \) and on the charge \( e \) of the particle but also on the pressure and the density of the gas (the mean time \( \bar{\tau} \) between 2 collisions):

\[ \mu = \frac{e \bar{\tau}}{m} \]

If the anode thread has a radius \( a \) and the cathode has a radius \( b \), the electric field at a distance \( r \) from the anode is [1]:

\[ E(r) = \frac{V_0}{r} \frac{1}{\ln(b/a)} \]

Once the charges are collected with the electrodes, an electric signal is created. The number of created pairs (electron-ion) is proportional to the deposited energy by the particle inside the detector. Indeed, the number of created pairs is equal to:

\[ n_0 = \frac{\Delta E}{W} \]

Where \( \Delta E \) is the deposited energy created by the ionizing particle (eV) and \( W \) the mean energy for ion-electron pair creation (eV). You can notice that this formula is independent from the particle type. However, the resulting electric signal is not proportional to the deposited energy, it depends on the electric field.

The observed signal relies a lot on the electric field applied inside the detector. The phenomena inside the detector will change according to the applied voltage. A pattern of a gaseous ionization detector is showed on the following figure. This curve describes how a gaseous ionization detector reacts in function of the applied voltage.

- **FIGURE 7**: NUMBER OF IONS COLLECTED VERSUS ELECTRIC FIELD APPLIED IN GASEOUS IONIZATION DETECTORS, TAKEN FROM [7]
First of all, no charge is collected when voltage is zero because the electron-ion pairs recombine directly after splitting. The coulombic attraction of the two opposite charges is stronger than the applied voltage. By increasing the polarization voltage $+V_0$ just a bit, some coulombic interactions become weaker than the applied electric field. Thanks to this process, some electrons and some ions are collected. The ones which are not collected recombine rapidly. So increasing the voltage expands the number of collected charges and rises the output detector current. There is no practical application to this situation.

Beginning with a certain voltage, all the created charges are collected. Because of this situation phenomenon, there is no need to further increase $V_0$. A detector operating in this region, collecting ions and electrons produced from a direct radiation, is an ionization chamber. The electric signal is very low in this type of detector: hundreds of pA.

If the voltage $V_0$ rises again, the electric field is strong enough to accelerate electrons until they can ionize other gas molecules. Electrons from primary ionizations can give new electrons from a second ionization and so on and so forth: it is an avalanche effect called the Townsend discharge. The number of pairs in the avalanche is proportional to the number of primary electrons. Therefore the collected signal is still proportional to the deposited energy in the gas. The signal is amplified. It this region (III), a detector is called proportional counter. Since the electric field is more powerful next to the anode, the closer we are to the anode the more avalanches there is [2].

If the polarization voltage $V_0$ of the electrodes increases to the point of crossing the region of limited proportionality, the amount of ionizations created during the avalanche is so important that the space charges distort the electric field on the anode. Proportionality is lost: the signal is no more proportional to the deposited energy in the ionizing gas. No detector operates in this area.

When the voltage increases, the energy becomes so important that discharges occur in the gas. This discharge is due to ultraviolet radiations emitted during molecules deexcitation.
Those radiations create more ionizations. The signal is saturated by the same amplitude. The **Geiger-Müller counter** detector is used in this area. This region is characterized by a little plateau. This detector is really sensitive.

After region V, a constant discharge occurs and it must be avoided as it damages the counter. It is nonetheless the principle of a spark chamber though, which is used for cosmic radiation.

Despite the fact that there are various operation areas for a gaseous ionization detector, no universal detector operates properly all over the voltage range. Every type of gaseous ionization detector has its own features: geometry, gas, materials,...

**IONIZATION PHENOMENA IN GASES**

**IONIZATION MECHANISMS**

A charged particle can lose energy in matter in two ways: excitation and ionization [1].

The excitation of an atom X (X→X*) is a resonant reaction and requires the exact amount of energy to be transferred. In this reaction, neither electrons nor ions are created. However sometimes, an excited molecule or atom is likely to participate in further ionization reaction.

For an ionization (X + p → X⁺ + p + e⁻, with p a charged particle), an energy threshold is to be reached. The electrons and ions created by an incident radiation are named primary ionization. An energy surplus might be given to the resulting electron. This electron will imply new ionization if it has enough energy for this reaction (bigger than the ionization energy threshold).

A second mechanism of ionization in gases is the Penning Effect. In some atoms, metastable states are excited and they are unable to deexcite to the ground state by the emission of a photon. In this case, deexcitation may occur through a collision with another atom which will be ionized through this process. This mechanism happens usually with noble gas: Ne⁺ + Ar → Ne + Ar⁺ + e⁻. The Penning Effect is more likely to happen with Penning mixtures. A Penning Mixture is a mixture of noble gas. The first excited state of the noble gas is very high compared to the ionization potential of the quench gas. The predominant noble gas can ionize the quench gas just by energy transfer through collisions (Penning Effect).

A third mechanism of ionization in noble gases is molecular ions formation. In this process, a positively charged particle interacts with a neutral one to form a molecular ion: He⁺ + He → He₂⁺
Recombination and electron Attachment

The creation of electron-ion pairs is essential for particles detectors. It is important to have enough time to collect the ions and electrons. Two processes will block the collection otherwise: recombination and electron attachment.

Recombinations occur for electron-ion pairs but for ion-ion pair as well. Recombination is driven by the coulombic interaction, although this one needs to be larger than the electric field applied between the electrodes. After the recombination, a photon is emitted.

\[ X^+ + e^- -> X + h\nu \]
\[ X^+ + Y^- -> XY + h\nu \]

Electron attachment is an electronic capture by electronegative atoms. A negative ion is created:

\[ e^- + X -> X^- + h\nu \]

Therefore, the presence of electronegative atoms hinders charge. Pairs undergo electron attachment before reaching the electrodes. This is why electronegative atoms must be avoided in the detector gas (O\(_2\), H\(_2\)O, ...). Unlike electronegative gases, noble gases have no electron affinity and are promoted for the detectors.

IONIZATION CHAMBER FOR NEUTRONS DETECTION

For neutron detection, ionization chambers are fostered. The neutron is a neutral particle unlikely to ionize at thermic level (25 meV) hence neutrons are more difficult to detect directly as compared with charged particles; further their path of motion is only weakly affected by electric and magnetic fields. That’s why boron is used for neutron detection. Boron-10, \(^{10}\)B is an isotope of boron element. \(^{10}\)B is stable but present in small quantity in the earth crust (20% abundance). \(^{10}\)B is very interesting in nuclear engineering as it is a very strong neutron absorber for thermal energies (25 meV). The nuclear reaction involved is:

\[ ^{10}_5B + ^0_1n = ^4_2\alpha + ^7_3Li \]

After this reaction the \(\alpha\), the ion \(^7\)Li\(^{3+}\) can ionize the gas inside the detector. We finally obtain detectable particles. To be more accurate, two reactions are actually possible [3]. A reaction with a probability of 6% also emits an energy of 2.79 MeV. This energy excess will be spread to the two resulting particles through kinetic energy.
There will be a further understanding of the crucial importance of this step to cross the potential barrier of the boron coating. The second reaction, with a probability of 94%, emits 2.31 MeV of energy and a γ of 0.48 MeV.

Now the question is: how to place the boron inside the detector? Gaseous boron detectors are not used anymore since they are very unstable and very complex. Solid boron coating detectors are the adequate solution. Usually, a boron coating lies in the inner part of the detector, towards the ionization chamber. It is to be notice that this type of detector only perceives thermal neutron. Obviously, the emerging neutron flux from a nuclear core is spread out over a wide range of energy. A neutron thermalizer, like polyethylene, is commonly used. The neutron flux is shifted to thermal energy and more neutrons can be detected.

Other technologies can be used for neutron detection with various reactions: $^3\text{He} (n,p)^3\text{H} \rightarrow ^{10}\text{B}(n,\alpha)^7\text{Li} \rightarrow ^{235}\text{U}(n,f)$. The idea is basically the same: convert the neutron in a detectable particle. It was customary to use helium detectors before, but a shortage of $^3\text{He}$ occurred and $^{10}\text{B}$ neutron detectors became the standard [5], because they are cheap and efficient.

**IONIZATION CHAMBER FOR NEUTRON DETECTION: ROLLS-ROYCE CC80**

Among the different types of Rolls-Royce’s neutron detectors, we can find the CC80. The coming experiments are based on this detector. The CC80 is a CNI (intermediate range neutronic channel). Its design is a bit different from the standard ionization chamber, as seen previously. The CC80 neutron detector has a cylindrical shape. On figure 11, you can...
see a cross section of the detector going from the center of the cylinder to the exterior. “CC” stands for “Compensated Chamber” and 80 refers to the diameter of the detector.

FIGURE 10: DISMANTLED CC80
USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR

The detector is composed of three electrodes:

- A first cathode +HT. A voltage of 600 V<sub>DC</sub> is applied to this electrode (named saturation voltage). It is boron coated towards the inside of the detector

- An anode S. This electrode is to collect the signal of the whole detector. It is boron coated towards the exterior of the detector. The voltage here is the potential reference.

- A second anode –HT. This electrode has a compensation voltage of -50 V<sub>DC</sub> and no boron lies on the surface. This anode is used for the compensated chamber: it subtracts the γ radiation signal

All the inside of the CC80 is filled with a special gas mixture. The gas composition is undisclosed for confidentiality. The gas proportions are chosen in order to get the optimized conditions for the Penning Effect.

FIGURE 11: SKETCH OF A ROLLS-ROYCE CC80, IT REPRESENTS THE HALF OF THE CYLINDER SHAPE
USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR
Why is there this setup?

The CC80 is placed around the core vessel. It undergoes neutron and gamma flux. For a medium power range, the neutron flux is not very high so detectors are sensitive to gamma flux as well. Therefore we need to subtract the gamma flux to the general flux.

Thus the first chamber, the boron coated one between the +HT and S electrodes, acts for detecting neutrons and gammas radiation. The signal electrode receives electrons coming from gas, triggered by the α and the ion \(^{7}\text{Li}^{3+}\) which are created by the neutron-boron reaction \((^{10}\text{B} + ^{1}\text{n} \rightarrow 4\Phi + ^{7}\text{Li})\). However the signal electrode receives also electrons coming from ionizations caused by gamma radiation. So the first chamber creates an electric signal caused by neutrons and gamma radiation.

The second chamber, the non-coated one between the S and –HT electrodes, only detects gamma through ionizing process. Indeed, the neutron flux can’t involve ionization, because this chamber is not boron coated. Since the electric field is in the opposite direction (towards the –HT electrode), the second chamber gives the opposite charge of the first chamber caused by gamma radiation.

Eventually, this process yields to an electric signal proportional to the neutron flux. This detector works thanks to a differential measurement: the first chamber measures the total flux (neutrons+gammas) and the second ones subtracts the measure of gammas. You only end up with a signal measuring neutron flux.
III - NEUTRONIC SENSITIVITY OF BORON COATING

The purpose of the following experiments is to characterize the boron coating on the electrodes of ionization chambers. Several ionization chambers will be assembled and only the surface and the mass of the boron coating will vary. After being assembled, the detector will undergo an irradiation test in order to study its sensitivity response.

Obviously, those test detectors won’t be produced in the same way as the standard industrial ones which are sealed, welded and impossible to be taken apart. For this experiment, a “screwable” detector was used so the same body can serve several times and does not seal the configuration of each electrode. This product is named CC80 dévissable. (CC80 is the type of detector and “dévissable” stands for “screwable”)

The first experiment consists in three tests with different batches of electrodes in order to study the contribution of the +HT and S electrodes in the detection process. Those measurements enable to compute the thickness of the boron coating.

The second experiment includes different coating surfaces for the electrodes. Anodes and cathodes were coated on various surfaces to investigate the link between the coating surface and the detector sensitivity.

The third experiment focuses on the influence of boron surface concentration on the detector sensitivity. Plenty of electrodes were coated, assembled and tested under irradiation. This stage involves several preparations and solutions. This experiment highlights the Wall Effect phenomenon. It occurs when a layer, crossed by a particle flux, is so thick that the spectrum of a particle flux is widened.

MANUFACTURING PROCEDURE AND TESTING

Before presenting the experiments and the results, it may be interesting to mention how a detector is assembled. For just one test, it is a whole and tiresome process.

Boron coating

First of all, the signal and +HT electrodes undergo a passivation, made by the supplier. The passivation aims to clean the electrode surface in order to enable a good grip of the boron coating on the surface. We can coat the raw electrodes once their quality and their conformity have been verified. An operator, expert in boron coating, undertakes this stage. A meticulous and confidential procedure is to be respected during the boron coating.
Electrodes baking

After coating, the electrodes must undergo a thermal cycle (around 8 hours) to ensure the integrity of the boron coating.

CC80 assembly

Afterwards, the electrode is inserted inside the CC80. This part requires calm and precision in order not to damage the boron coating when inserting the electrodes. Final step, the lid is screwed.

Total clean-up and gas filling

The CC80 must be cleaned up after all these stages. That would deteriorate the gas mixture and consequently worsen the detection. A thermal cycle, a pump and a molecular pump insure a vacuum around $10^{-7}$ mbar to prevent air and moisture from remaining in the detector. Finally, the detector is filled with a special gas composition with a precise pressure.

Electrical testing

Three tests are important to check the electrical features through the cables.

At first hand, all the electrode cables must endure a dielectric test. If there is no discharge, it validates the conformity of the assembly.

At second hand, an insulation resistance test is performed to verify the contact between the critical parts of the detector.

Finally, the capacity between each electrode has to reach a certain value established in the procedure. The detector is a big capacitor because of the electrodes and the gas mixture. Therefore, it must be insured that the discharge of such a capacitor is not bigger than expected.

Irradiation test

After all those intermediary stages, the detector can finally undergo the main test: neutron irradiation. The irradiator gives the electrical response under a neutron flux. It characterizes the functional features of the detector.
CONTRIBUTION OF THE ELECTRODES +HT AND S AND CALCULATION OF THE BORON COATING THICKNESS

The contribution of the +HT coating and the S (signal) coating on the detector sensitivity were at first a question to deal with. The investigation focused on coating just one electrode (+HT or S) and leaving the other one untouched. Thereby, three detectors have been assembled: +HT0&S1, +HT1&S0 and +HT1&S1. +HT0 is the bare electrode and +HT1 is the coated one, same naming for the S0 and S1. The coating concentration is exactly the same for all the electrodes. In standard conditions, the saturation voltage (+HT) is 600 V and the compensation voltage (-HT) is -200 V. The results of the sensitivity are in the chart below.

<table>
<thead>
<tr>
<th>Electrode batch</th>
<th>HT0&amp;S1</th>
<th>HT1&amp;S0</th>
<th>HT1&amp;S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (pA)</td>
<td>730</td>
<td>765</td>
<td>1030</td>
</tr>
</tbody>
</table>

We primarily observe two different values for HT0+S1 and HT1+S0. There is a gap of 35 pA. This variation can be explained by the different sizes of the electrodes. Indeed, HT electrode, which has a bigger diameter than the S electrode, has therefore more surface to get the neutron flux; it triggers more nuclear reactions (Boron +neutron). Moreover, the boron layer in HT0+S1 has one more shielding layer: the gas. The gas obviously absorbs neutrons even if it has a low cross section (cf Annex 1). Those two assessments confirm the bigger sensitivity of HT1+S0 compare to HT0+S1.

The second analysis to underline is that the overall signal is different from the sum of the two signals coming from the two coated electrodes. Of course, when HT is coated with boron, it is shielding the flux for the second boron coating and the S electrode. The S electrode is thus not receiving the same flux than the previous configuration (HT0+S1) and does not provide the same amount of current. If HT1 is still contributing to the same amount of current than for the configuration HT1+S0 (because HT1 sees the same flux than previously), then HT1 provides 765 pA to the overall signal. The remaining signal (1030-765=265 pA) is given by the coated S electrode.

This reasoning assumes that the detection process is linear; that is to say, based on the superposition principle. In other words, we assume the response of HT1+S0 is equal to the sum of the response of HT1+S0 and to the response of HT0+S1.

This linearity assumption can be of course tackled with the fact that the collected signal is not exactly proportional to the deposited energy given by the neutron flux. Each model has its own faults, but let’s simply focus on our model.

We will foresee how we can compute the coating thickness by using this flux differentiation.
The saturation curves were plotted on the figure above. We can notice the three different thresholds that correspond to the values 730 pA, 765 pA and 1030 pA. It is peculiar to notice that the saturation curve starts from a lower value than usual when only +HT is coated. This phenomenon can be explained by the fact that the electrons emitted thanks to +HT coating cannot reach the signal electrode when there is no applied voltage. Without a substantial polarization voltage, the scattering electrons created by the +HT coating are lost into the ionized gas. On the other hand, the electrons created by the S coating are closer to the signal electrode. No huge value for +HT voltage is required to collect them. The beginning of the saturation curve [0 V;0.4 V] of HT1+S1 is entirely due to the contribution of the S electrode.
**Calculation of the coating thickness**

Thanks to the previous experimental result, and using a simple model, it is possible to assess the thickness of the boron coating. This thickness has remained unknown in Rolls-Royce because it is very difficult to measure without damaging the coating and using a cheap device. They only have a clue of the boron coating thickness. The model used is represented below. More details are shown in the annex 1 for the cross sections and the flux attenuation.

![Neutron flux direction](image)

**FIGURE 15: SKETCH OF THE CC80 MODEL
USED BY PERMISSION OF ROLLS-ROYCE CIVIL NUCLEAR**

The flux attenuation depends on the media the neutrons have to cross. The media are characterized by a total macroscopic cross section: $\Sigma_{tot}$. The total flux attenuation for the entire system is given by:

\[
\varphi_1 = (e^{-L_{env}\Sigma_{tot,thermal}(Al)} \cdot e^{-L_{gas1}\Sigma_{tot,thermal}(gas)} \cdot e^{-L_{+HT}\Sigma_{tot,thermal}(Al)}
\]
\[
\cdot e^{-d\Sigma_{tot,thermal}(B)} \cdot e^{-L_{gas2}\Sigma_{tot,thermal}(gas)}
\]
\[
\cdot e^{-d\Sigma_{tot,thermal}(B)} \cdot e^{-L_{S}\Sigma_{tot,thermal}(Al)}
\]
\[
\cdot e^{-L_{gas3}\Sigma_{tot,thermal}(gas)} \cdot e^{-\frac{L_{-HT}\Sigma_{tot,thermal}(Al)}{2}})^2
\]

With $L_{env}$ (4.9 mm) the width of the detector envelope, $L_{gas1}$ (3.6 mm) the length between the envelope and the electrode +HT, $L_{+HT}$ (2.5 mm) the width of the aluminum electrode +HT, $d$ the width of the boron layer, $L_{gas2}$ (4.3 mm) is the length between the +HT electrode and the signal electrode and $L_{S}$ (2.1 mm) the width of the S electrode.

In this expression, all the exponentials correspond to the half of the system. A square is added at the end of the formula, to take into account the other symmetrical part of the system.

This attenuation equation of the CC80 is valid only in the HT1+S1 configuration. For the two other configurations, one exponential must be removed: $e^{-d\Sigma_{tot,thermal}(B)}$, with $d$ representing the thickness of a boron layer. For the HT1+S0 configuration or the HT0+S1
configuration, only 2 layers of boron lie in the detector (thickness of 2$d$ instead of 4$d$). Hence the attenuation of the signal coming from S1, in the configuration of HT1+S1, which is due to the presence of boron on the +HT electrode. It gives:

\[ e^{-2d \Sigma_{\text{tot.thermal}}^{(B)}} = \frac{\text{contribution of } S \text{ electrode signal with } + \text{HT shielding in } HT1 + S1}{\text{contribution of } S \text{ electrode signal with no shielding in } HT0 + S1} = \frac{265 \text{ pA}}{730 \text{ pA}} \]

\[ e^{-2d \Sigma_{\text{tot.thermal}}^{(B)}} = 0.363 \]

This yields to:

\[ d = (3.6 \pm 0.58) \mu m \]

This is of course a basic model of the reality. The cylindrical shape is not taken into account, as well as the exact neutron flux direction in real conditions.

As a summary, we can compute the boron coating thickness by using the superposition principle and by performing 3 measurements (HT1+S1, HT1+S0 and HT0+S1). In Rolls-Royce facilities, it has been always assumed that the thickness of the boron layer was about the range of a micrometer. From now, they have a genuine value based on their own experiments and a really simple model.

**VARIATION OF COATING SURFACE**

The second experiment deals with the coating surface. The surface of boron coating applied to the both electrodes was changed to quantify the contribution of the boron surface on the neutronic sensitivity. A coating of the +HT and S electrodes with the half, the third, the fourth and the eighth of the initial surface is necessary to begin this experiment. The figure below is a picture of the different S electrodes.
It is essential to mention that those electrodes were coated with the same boron concentration. The coated surfaces were centered in the middle of the electrode.

The pattern of this curve is obviously linear. This means that the geometry, and primarily the length of the boron coating, is very crucial for the sensitivity of the detector. The longer the detector is, the more sensitive it becomes.

It is difficult to assess the accuracy of this graph as the genuine coating surface might not be exactly as indicated. Before coating, pencil marks were drawn on the electrodes to respect the coating surface. However, while coating, the operator might inadvertently coat the
Characterization of boron coating in ionization chambers

boron a bit outside of the drawn marks. Therefore it is likely to find uncertainties on coating surfaces.

Rolls-Royce could use this graph in the future when developing new detectors to assess the length of a new manufactured detector in order to get a certain amount of the output current.

**VARIATION OF DEPOSIT CONCENTRATION**

The purpose is to understand the correlation between the boron concentration on the electrodes surfaces and the detector sensitivity under irradiation. To reach this goal, several electrodes pairs (+HT and S) were coated with different concentrations. The range of boron surface concentrations is from 0.1 mg/cm² until 1.6 mg/cm². All those electrodes were inserted inside the CC80 dévissable. It helps the influence of the envelope to stay constant through all the tests. The gas pressure remained equal for all the experiments.

The following figure illustrates the plotted curve of the output current of the detector against the boron coating concentration.

![Detector Sensitivity](image)

**FIGURE 18 : DETECTOR SENSITIVITY AS A FUNCTION OF BORON COATING CONCENTRATION**

The pattern is assimilated as a “bell curve”. For a certain boron coating concentration, there is an optimum of the output current value, that is to say an optimum of the detector sensitivity. This is due to the so-called “wall effect”.

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It may seem blatant the more boron atoms the more sensitive the detector becomes. Indeed, for any nuclear reaction, the total number of reactions per unit time and unit volume (reactions/s/cm³) for the thermal energy may be evaluated as:

\[ R = N \sigma \phi \]

N indicating the number density of atoms (atoms/cm³), \( \phi \) the thermal neutron flux (n/s/cm²) and \( \sigma \) the thermal microscopic cross-section for the nuclear reaction in question (barn or cm²). As a comment, the detectable neutrons by boron coated detectors have a thermal energy. The reaction rate increases as the boron coating concentration (g/cm²) rises, whereas the neutron flux and the microscopic cross section remain constant (regarding the Rolls-Royce irradiator). More and more boron atoms react, creating more lithium and \( \alpha \) particles, creating more electrons. The electric output signal of the detector is then amplified.

However, a threshold occurs. Since the boron concentration rises, the thickness of the coating also gets bigger. This creates a bigger potential barrier for the lithium and \( \alpha \) particles to cross. Those particles, coming from the nuclear reaction, are therefore trapped in the boron coating. That phenomenon yields to a decrease of the output signal of the detector although more boron lie on the electrodes surfaces.

This effect is well known in the neutron detection field. In Rolls-Royce facilities, it has been a while that the investigation has been achieved but never on a CC80. This Rolls-Royce investigation emphasizes the study made by McKinny, Anderson and Johnson in [5]. The optimum coating concentration is about the same than the one found inside Rolls-Royce facilities: 0.5 mg/cm².

Furthermore, coating concentration for Rolls-Royce detectors has never been set on the optimum concentration which is rather surprising. Indeed, the highest sensitivity is reached for a concentration equal to 0.5 mg/cm² while Rolls-Royce targets 1 mg/cm² in their industrial processes. An explanation would be the operation time of a nuclear core and the fact that boron is the limiting “fuel” for our detectors. As explained in Annex 2, boron is consumed over the years by neutrons. The amount of 1 mg/cm² is enough to use the detector for 35 years with the maximal fluence, corresponding to the initial lifetime of a nuclear power plant. The value 1 mg/cm² was set to optimize the sensitivity as well as the detector lifetime, knowing the maximal fluence it could withstand.

As it is an experimental study, it is relevant to highlight that the roughness is a determining criteria during the boron coating process. It is important for the operator to smoothen the surface at the end of the process since a considerable variation of the coating might influence the detector sensitivity [5].
Wall effect

As previously stated, the wall effect takes place when the boron coating thickness is more important than the added amount of boron. An optimal concentration occurs and adding more boron would not enhance the sensitivity of the detector since the Lithium and α particles cannot go through the thickness of the boron layer. This is a limiting factor for our detector sensitivity.

The reaction of $^{10}$B and $^1n$ creates a $^7$Li and $^4$α emitted in opposite direction in the coating with energies of 840 keV respectively 1470 keV in 96% of reactions. If the two emitted particles have opposite directions, one will go towards the aluminum wall and the other will go toward the ionizing gas. Before reaching it, this particle will have to cross a certain distance within the boron coating. Depending on its energy and on the crossed path in the boron coating, the particle might or might not penetrate the gas and release its energy left through a ionizing process.

In [5], McKinny, Anderson and Johnson did a really interesting study on the spectrum of a $^{10}$B lined proportional counter. The figure below exhibits the wall effect perfectly well. The $^7$Li is emitted, for 96% of reactions, with a maximum energy of 840 keV. A peak corresponding to this energy should be formed. It is not the case. Lithium particles will just scatter in the boron coating and so will lose energy before reaching and ionizing the gas. Counts for all energies under 840 keV, corresponding to the lithium particles less energetic, are observed. The least energetic particles correspond to the ones travelling longer in the coating. Hence the pattern of the spectrum: the pick at 840 keV is widened towards lower energy levels. The severe decrease of the spectrum around 840 keV means that lithium particles are not produced beyond that energy. Besides, the same explanation is found for the other part of the spectrum, corresponding to α particles. 1470 keV could have formed a peak in the spectrum but the scattering effect of α in the boron coating widen the α spectrum. Therefore, we can notice counts of α particles under 1470 keV. From 0 to 840 keV the α spectrum and Li spectrum are overlapped. The sudden decrease of the spectrum around 1470 keV means that no more particles are created with this amount of energy.

![Graph showing the spectrum of a B-10 lined proportional counter.](image)

**FIGURE 19: SPECTRUM OF A B-10LINED PROPORTIONAL COUNTER, TAKEN FROM [5],**
Unfortunately, it is impossible to replicate this experiment inside Rolls-Royce facilities since they don’t have a multi-channel analyzer. Thanks to this spectrum, you can observe how efficient your coating is to detect neutrons. For instance, as showed below, it was monitored with two spectra for a standard and a thin coating. It enables to integrate the number of counts detected all over the energy spectrum, perceive and deduce the real sensitivity of your detector. Indeed, our experiments were based on current measurements. Although, it remains impossible for us to see the spectrum range of our detection.

By the way, it is also interesting to spot that the two peaks (840 keV and 1470 keV) reappear on the thin coating spectrum.

**FIGURE 20: SPECTRUM OF TWO DIFFERENT BORON COATED DETECTORS, TAKEN FROM [5], COPYRIGHT © 2013 IEEE**
CONCLUSION

It is essential that neutron detectors provide reliable data as long as nuclear power safety is concerned. This MSc study meets the quality policy of Rolls-Royce’s nuclear instrumentation.

Using a specific neutron detector prototype, the author performed three major experiments. The sensitivity of the “CC80 dévissable” has been correlated with the surface and the concentration of the boron coating. The linearity pattern of the sensitivity as a function of the coating surface is consequently revealed. Moreover, an optimum boron concentration to maximize the sensitivity was found.

All along this research investigation, the quality of detectors was checked in order to fulfill customers’ requirements. The experimental results enable Rolls-Royce to design new detectors and find new ways of manufacturing.

Based on these results, the nuclear industry could manufacture more sensitive neutron detectors thus contributing to enhance global nuclear safety.

As a logical continuation, it may be recommended a further study on the influence of the gas pressure inside compensated ionization chambers. It is also a critical part during the manufacturing process. Therefore, there is a genuine interest for this investigation in order to strengthen safety requirements.
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ANNEX

ANNEX 1: CROSS SECTIONS AND NEUTRON FLUX ATTENUATION OF THE SYSTEM

In nuclear engineering, boron is famous for being a neutron absorber. Its neutron capture cross section is very high for thermal neutrons.

The macroscopic cross sections of our system were computed below, thanks to reference [4] data:

\[
\begin{align*}
\Sigma_{\text{tot, thermal}} (B) &= 1383 \text{ cm}^{-1} \\
\Sigma_{\text{tot, thermal}} (\text{Gas}) &= 0.175 \text{ cm}^{-1} \\
\Sigma_{\text{tot, thermal}} (\text{Stainless Steel}) &= 1.735 \text{ cm}^{-1} \\
\Sigma_{\text{tot, thermal}} (\text{Al}) &= 0.267 \text{ cm}^{-1}
\end{align*}
\]

The cross section of the stainless steel was determined with this configuration: 69% Iron, 17% Chromium, 12% Nickel and 2% Molybdenum.

\[
\Sigma_{\text{tot, thermal}} (\text{Stainless Steel}) = 0.69\Sigma_{\text{tot, thermal}} (\text{Fe}) + 0.17\Sigma_{\text{tot, thermal}} (\text{Cr}) + 0.12\Sigma_{\text{tot, thermal}} (\text{Ni}) + 0.02\Sigma_{\text{tot, thermal}} (\text{Mo})
\]

The cross section of the gas was evaluated with the microscopic cross sections of the gas components, remained secret.

FIGURE 21 : NEUTRON CAPTURE CROSS SECTION FOR B^{10}, TAKEN FROM [3]
Characterization of boron coating in ionization chambers

As a reminder: \( \Sigma_{\text{tot, thermal}} = \frac{\sigma \rho N_A}{M} \), with \( \sigma \) the microscopic cross section at thermal level (barn), \( \rho \) mass density (g/cm\(^3\)), \( M \) the molar mass (g/mol), \( N_A \) the Avogadro number (mol\(^{-1}\)).

Those cross sections are computed for thermal neutrons. We can obviously observe that boron cross section is the biggest one since it is a strong neutron absorber. Due to this huge value, it is more likely that neutrons get absorbed by boron in our system.

The mean free path is 5.71 cm for the gas \( \lambda = \frac{1}{\Sigma_{\text{tot, thermal}} \text{(gas)}} \) and the gas space between the two electrodes is 4.8 mm. Therefore, only a small average of collision happens in the gas in between the electrodes. Just as a reminder, the mean free path is the average distance between two collisions involving the neutron and particles of the scattering medium.

For our experiments, the “CC80 dévissable” is in aluminum just like commercial detectors. Rolls-Royce used to exploit a stainless steel shell before but neutrons scattered worse in it since stainless steel absorbs neutrons better than aluminum. Indeed, the macroscopic cross section is bigger than the aluminum one.

Eventually, we can evaluate the neutron flux attenuation.

To simplify the system for this evaluation, the neutron flux was placed perpendicular to the detector, assimilated as 7 distinct aluminum blocks. This sketch represents the model.

![Figure 22: Sketch of the CC80 model](image)

After crossing the detector envelope, the aluminum electrodes, the first boron coating and the first gas gap, the attenuation of the neutron flux becomes:

\[
\phi_1 = e^{-L_{\text{env}} \Sigma_{\text{tot, thermal}} \text{(Al)}} \cdot e^{-L_{\text{gas}1} \Sigma_{\text{tot, thermal}} \text{(gas)}} \cdot e^{-L_{+HT} \Sigma_{\text{tot, thermal}} \text{(Al)}} \cdot e^{-d \Sigma_{\text{tot, thermal}} \text{(B)}}
\]

\( L_{\text{env}} \) (4.9 mm) the width of the detector envelope, \( L_{\text{gas}1} \) (3.6 mm) the length between the envelope and the electrode +HT, \( L_{+HT} \) (2.5 mm) the width of the aluminum electrode +HT, \( d \) the width of the boron layer. It was hard to assess accurately the width of the boron deposit inside Rolls-Royce facilities. In this thesis, the coating thickness was computed...
Characterization of boron coating in ionization chambers

experimentally: 3.6 µm. Let’s take this value and a bigger one to simulate heavy and thick coating: 3.6 µm and 10 µm.

\[ \varphi_1 (3.6 \text{ µm of boron}) = 46.7\% \]
\[ \varphi_1 (10 \text{ µm of boron}) = 19\% \]

If the boron layer is about 3.6 µm, 46.7% of the neutron flux will reach the second chamber. If the boron layer is about 10 µm, only 19% of the neutron flux will reach the second chamber.

After the second chamber, the flux attenuation is:

\[ \varphi_2 = \varphi_1 \cdot e^{-L_2 \Sigma_{\text{total,thermal}}(\text{gas}) \cdot e^{-d\Sigma_{\text{total,thermal}}(\text{Boron}) \cdot e^{-L_S \Sigma_{\text{total,thermal}}(\text{Aluminum})}}} \]

\( L_{\text{gas}2} \) (4.3 mm) is the length between the +HT electrode and the signal electrode and \( L_S \) (2.1 mm) the width of the S electrode. For the two extreme values of boron coating width, the flux attenuation is:

\[ \varphi_2 (3.6 \text{ µm of boron}) = 24\% \]
\[ \varphi_2 (10 \text{ µm of boron}) = 4\% \]

The aim of those compensations is just to inform. You can continue the flux attenuation computation until the last layer of the detector.
ANNEX 2: A THOUGHT ABOUT THE AMOUNT OF BORON ATOMS ABLE TO REACT

It is normal to wonder the lifetime of the coating knowing the flimsy amount of boron in the coating (1 mg/cm²). The boron coating is the sensitive and consumable part of the detector. The detection will happen while there are boron atoms within the coating. This raises a question: considering the boron concentration and a standard flux coming from a nuclear core, how long can the boron coating last?

To answer this question, we assume that the detector is barely based on just one boron coating with a concentration of 1 mg/cm². The concentration of atoms is given by:

\[
N = \frac{m N_A}{M} = \frac{1 \text{ mg/cm}^2 \cdot 6.02 \cdot 10^{23} \text{ mol}^{-1}}{10.8 \text{ g/mol}} = 5.57 \cdot 10^{19} \text{ atoms/cm}^2
\]

Let’s state that an average neutron flux received by the neutron detection system is about 5.10^10 neutrons/cm²/s for 100% of the rated power output. The required time to trigger all the possible reactions with boron atoms, considering only neutron capture, will be:

\[
t = \frac{5.57 \cdot 10^{19} \text{ atoms/cm}^2}{5.10^{10} \text{ neutrons/cm}^2/\text{s}} = 35 \text{ years}
\]

Surprisingly, this time roughly corresponds to the operation time (full power) of a typical nuclear power plant. Neutron detectors ought to be functional during the reactor life. Therefore, detector coating lifetime and nuclear power plant lifetime are matching.

To tackle this problem, we could have used the mean fluence around the reactor pressure vessel. Knowing that the fluence (over the reactor lifetime) must be, at least, equal to the amount of boron atoms, it would have led to the boron density 1 mg/cm². By the way, the order of magnitude of a fluence received by neutron detectors is about 10^{18} neutrons/cm².

Actually the detector would have obviously failed before this time (35 years). In reality, the limiting factors are the gas quality (absence of humidity and electronegative gases) and the boron coating quality (coating grip and purity).
ANNEX 3: ROLLS-ROYCE IRRADIATOR

The irradiator inside Rolls-Royce facilities is composed of a high density polyethylene block. It has a volume of 1 m$^3$ and it is made for thermalizing the neutrons. This entire block is surrounded by cadmium plates, a very strong neutron absorber, with a thickness of 1 mm. Those plates are here to shield and protect humans and facilities from residual neutrons which could scatter out of the irradiator. There are two lateral cavities to insert the detectors during the tests. Between those cavities, five neutrons sources stand along the cavity of the detector. The neutron sources are made with Americium and Beryllium compounds. They are placed into five different wells evenly distant. The high density polyethylene and the gap between the sources provide a uniform flux of thermal neutrons in the detector cavities.

The purpose of the irradiator is to check the features of any detectors which could be manufactured in Rolls-Royce facilities. The only way to verify that a neutron detector is functioning properly is by using a neutron source. During the test, a detector is inserted inside one of the cavities and an operator checks the electronical output signal in order to measure the sensitivity of the detectors and to verify that the detection range is fulfilled. Those ranges are fixed by Rolls-Royce and customers (like EDF).

In order to provide reliable verifications, operators must know the exact value of the neutron flux inside the cavities. Calibrations are made regularly to figure out this value.

The presence of a detector inside the irradiator modifies the neutron flux. Therefore it can be useful to define two different sensitivities of a detector. In this way:
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\[
Detector \ sensitivity \ in \ a \ disturbed \ flux \quad = \quad \frac{output \ signal}{mean \ flux \ crossing \ the \ detector \ surface}
\]

Each detector has its own sensitivity and does not depend on its environment.

\[
Detector \ sensitivity \ in \ an \ undisturbed \ flux \quad = \quad \frac{output \ signal}{mean \ flux \ in \ the \ detector \ cavity \ without \ the \ detector}
\]

This sensitivity depends on the type of detector and on its environment as well. We used this sensitivity in an undisturbed flux all along this study.

N.B.: notions of sensitivity and electric output signal are mixed up since they are correlated. When talking about “detector sensitivity”, it is a misuse of language. It should be called “detector output signal”. However the mean neutron flux is assumed to be even all along the experiment period. Those terms are thus equivalent.

Americium-Beryllium source

AmBe source is a neutron source. It is composed of Americium-241 and Beryllium-9 and commonly used in industrial radiation processes. The source is usually into sealed pellet, welded with stainless steel. Its lifetime is about 10 years.

\(^{241}\text{Am}\) is a \(\alpha\) emitter, one of the most widespread \(\alpha\) source. \(^{241}\text{Am}\) has a half-life of 432 years. 85\% of the time, the \(\alpha\) particle is emitted with a kinetic energy of 5.485 MeV. This decay
leads to neptunium-237. The $^{237}$Np itself is a $\alpha$ emitter with a half-life of 2.14 million years. The $^{237}$Np, when created, is also in an excited state. It emits a $\gamma$ radiation with an energy of 59.54 keV.

The $\alpha$ particles emitted from $^{241}$Am is captured by $^9$Be. This nuclear reaction leads to a neutron and $^{12}$C.

To sum up, the process is:

\[
^{241}_{95}Am \rightarrow \frac{4}{3}\alpha + ^{237}_{93}Np
\]

\[
\frac{4}{3}\alpha + ^{9}_{4}Be \rightarrow \frac{1}{3}n + ^{12}_{6}C
\]

The average neutron energy is 4.2 MeV, but neutrons energy can reach until 11 MeV. The speed of this nuclear process is entirely defined by the decay of $^{241}_{95}Am$. It is important to obtain chemically a homogeneous medium as $\alpha$ particle stops really fast in matter. This source is passive, so there is no need to monitor anything. However it is impossible to stop the source emitting neutrons.

In addition with that, a tiny amount of neutrons is created through two other reactions:

\[
^1_0n + ^9_{4}Be \rightarrow 2 \times ^1_0n + 2 \times \frac{4}{3}\alpha \ (Q = -1.57 \text{ MeV})
\]

\[
\gamma + ^9_{4}Be \rightarrow ^1_0n + 2 \times \frac{4}{3}\alpha \ (Q = -2.0 \text{ MeV})
\]

Those two reactions are endothermic. They are anecdotic though.

In Rolls-Royce irradiator, there are 5 neutron sources. Their features are:

- 2 neutron sources with an activity of 111 GBq and a neutron flow of $7,2.10^6$ neutrons/second
- 2 neutron sources with an activity of 37 GBq and a neutron flow of $2,2.10^6$ neutrons/second
- 1 neutron sources with an activity of 37 GBq and a neutron flow of $2,3.10^6$ neutrons/second

**Neutrons thermalization**

After being created, neutrons are thermalized thanks to the high density polyethylene (HDPE). The chemical formula of HDPE is $(C_2H_4)_n$. Its mass number $A$ is 28. In this case (for heavy targets with $A>10$), the average logarithmic energy decrement per collision $\xi$ can be assessed by:
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\[ \xi = \frac{2}{A + \frac{2}{3}} = 7\% \]

A neutron loses, on average, 7\% of its energy when colliding with a HDPE molecule. The number of collisions \(N\) in order for the neutron to be thermalized is:

\[ N = \ln \left( \frac{E_f}{E_i} \right) = \ln \left( \frac{0.025}{4 \times 10^6} \right) = 7 \]

On average, 7 collisions are required for the neutrons to reach thermal energy from 4 MeV in HDPE. Those collisions are only enabled by scattering reactions. Only the hydrogen scattering cross section must be taken into account for the computation of the mean free path:

\[ \lambda = \frac{1}{\rho \sigma_s} = \frac{1}{\rho \sigma_s} = \frac{M}{(\sigma_{s,H}^4 * \rho_{HDPE} + \sigma_{s,C}^2 * \rho_{HDPE})N_A} = 1.83 \text{ cm} \]

With \(\rho_{HDPE} = 0.95 \text{ g/cm}^3\), \(\sigma_{s,H} = 20 \text{ barn}\) and \(\sigma_{s,C} = 4.8 \text{ barn}\)
ANNEX 4: RADIATION PROTECTION

It is interesting, and even more crucial, to make an assessment of the radiation dose received while using the irradiator.

Three different radiations are emitted from the source:

- $\alpha$ from $^{241}$Am
  This is the primary radiation emission of the entire process. But this one does not get out of the steel envelope. It is not a problem in normal operation.
- $\gamma$ from $^{241}$Am (60 keV) and from the reaction of $\alpha$ on Be (>1MeV)
  It is not negligible because the total emitted dose is roughly even to the neutron dose.
- Neutrons from Be
  Neutrons are the main radiation coming from the sources. The mean energy is 4.2 MeV. The spectrum shifts towards thermal energy due to HDPE presence.

The associated irradiation risks are neutrons and $\gamma$ in standard operation. In case of the failure of the envelope source, there will be a risk of contamination and irradiation (neutron, $\gamma$ and $\alpha$).

Investigation was made inside Rolls-Royce for their irradiator. Of course, it is indisputably a very broad topic: one annex is not enough to describe all the radiation protection. We will nevertheless try to display the main results.

Measurements can be carried out in the whole space around the irradiator. We will only focus on 2 extremum situations. The first one defines the position of the operator while inserting the detector inside the irradiator. The second one indicates the place of a bare person standing outside the irradiation room, 1 meter from the 30 cm concrete walls.

The dose rate for the operator, when opening the cavity to insert the CC80, is 85 $\mu$Sv/h for neutron radiation and 10 $\mu$Sv/h for $\gamma$ radiation. The time spent in that location is around 1 to 2 minutes maximum. Those dose rates concern a whole body.

The dose rate for the standing persons outside the room is inferior to 1 $\mu$Sv/h for both neutron and $\gamma$ radiation. It is so small that it makes it difficult to measure accurately the dose taken in this location.

As far as the the operator is concerned, we can go a bit further. A detailed assessment, knowing the operation and the time standing in precise location, gives a dose rate of 1.7 $\mu$Sv for a global working session in the irradiator room using the small irradiator’s cavity (used for CC80). On an average, an operator can take a dose up to 378 $\mu$Sv if we take into account
both cavity and all types of controls during an entire year. This is significantly low compared to annual dose naturally taken: about 2 mSv.

Operator must absolutely adopt a good behavior when working inside the irradiator room. For instance, they must wear their dosimeters and not look inside the cavities, they have to minimize their time in the irradiator room, they must lock the room after working inside and so on and so forth.