The development of neutron radiography and tomography on a SLOWPOKE-2 reactor

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Abstract

Development of neutron radiography at the Royal Military College of Canada (RMC) started by trying to interest the Royal Canadian Air Force (RCAF) in this new non-destructive testing (NDT) technique. A Californium-252 based device was ordered and then installed at RMC for development of applicable techniques for aircraft by the first author. A second and transportable device was then designed, modified and used in trials at RCAF Bases and other locations for one year. This activity was the only foreign loan of the U.S. Californium Loan Program. Around this time, SLOWPOKE-2 reactors were being installed at four Canadian universities, while a new science and engineering building was being built at RMC. A reactor pool was incorporated and efforts to procure a reactor succeeded a decade later with a SLOWPOKE-2 reactor being installed at RMC. The only modification by the vendor for RMC was a thermal column replacing an irradiation site inside the reactor container for a later installation of a neutron beam tube (NBT). Development of a working NBT took several years, starting with the second author. A demonstration of the actual worth of neutron radiography took place with a CF-18 Hornet aircraft being neutron and X-radiographed at McClellan Air Force Base, Sacramento, CA. This inspection was followed by one of the rudders that had indications of water ingress being radiographed successfully at RMC just after the NBT became functional. The next step was to develop a neutron radioscopy system (NRS), initially employing film and then digital imaging, and is in use today for all flight control surfaces (FCS). With the third author, a technique capable of removing water from affected FCS was developed at RMC. Heating equipment and a vacuum system were utilized to carefully remove the water. This technique was proven using a sequence of near real time neutron images obtained during the drying process. The results of the drying process were correlated with a relative humidity gauge and an NDT technique that could be performed at Canadian Forces (CF) Bases was developed. In order to determine the structural integrity of the component having undergone this water removal, further research was required into the effect of water inside composite honeycomb structures. This need has led to the present development of neutron tomography on the reactor at RMC, which is capable of determining the exact location of water ingress inside composite components. This technique has been successfully applied to coupons as well as to complete rudders.

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1. Introduction

The development of a neutron radiography capability at the Royal Military College (RMC) on behalf of the Royal Canadian Air Force (RCAF) started with a connection with a RMC staff member, A. Nellestyn, to a colleague at McMaster University, A.A. Harms. Funding was obtained from the Department of National Defence (DND) to acquire a one mg Californium-252 source in an exposure device to demonstrate neutron radiography’s applicability to aircraft structures. Such a device, shown in Figure 1, was installed at RMC in a small laboratory several years later by the first author, L.G.I. Bennett. It was also used in an undergraduate laboratory course for future officers. Although various items related to airframes could be radiographed, the restrictions in object size as well as accessibility for the air force demanded a more portable device with a stronger neutron output.

With the first author’s involvement with the Californium-252 Loan Program operated by the U.S. Department of Energy (DOE), the only foreign loan of Cf-252 was arranged for one-year in the late 1970’s [1,2]. To move the 2 mg source from Savannah River, GA, to Canada, the exposure device would also have to be a licensed shipping container. Gamma Industries of Baton Rouge, LA, provided such a unit along the lines of a gamma camera in that the moderator/collimator was separate from the shielded container. It was delivered to the Non-Destructive Testing Section at CFB Trenton where it was mounted on an engine carrier. In Figure 2 can be seen the crank out handle in front of the container along with the dismounted collimator. It was demonstrated as a transportable device to various interested researchers from the Department of National Defence (DND) and elsewhere (Royal Canadian Navy, Royal Canadian Mounted Police, and a munitions company) as it was moved to as far East as Montreal, Quebec, by road and as far West as Esquimalt, British Columbia, by air.
Although a successful year-long demonstration, the relatively low intensity and thus long exposure times using conversion screens and radiographic film was not convincing. In addition, the short half-life of Cf-252 and the consequential changing intensity and continuing cost of replacing it every two half-lives, approximately five years, was also a burden. However, the author was also aware of Atomic Energy of Canada Limited’s (AECL) development of a small, affordable research reactor that could possibly provide an option. An experiment conducted by the author and staff at the AECL reactor with a temporary beam tube and an ASTM indicator indicated that neutron radiography was possible. Installation and commissioning of a reactor at RMC would occur a decade later in a new science and engineering building in 1985.

2. SLOWPOKE-2 Neutron Source

The SLOWPOKE-2 was designed by AECL as a simple, safe, and affordable neutron source for universities and hospitals for neutron activation analysis (NAA) and radioisotope production. Because of its simplicity and relative accessibility, it also became a useful tool for reactor familiarization for visitors and students. It was never intended for extracting a neutron beam for radiography and was too weak for neutron scattering.

The challenges to extracting a neutron beam from a SLOWPOKE-2 reactor start with the relatively low neutron flux available, $1 \times 10^{12} \text{n cm}^{-2} \text{s}^{-1}$, at a full nominal power of 20 kW, inside the annular reflector just beyond the core where the inner irradiation sites are located. In fact, most of the time, the reactor is operated at half that value, adequate for its main application of NAA. Accessibility is restricted due to the reactor core being at the bottom of a sealed reactor container extending about 5 m, under water, in a narrow and deep, vertical pool (Figure 3). There is also no possibility for a horizontal beam port underground. Although the reactor itself was safe due to the sufficient depth of water for shielding the core, careful planning would be required to extract a neutron beam in an area not designed for shielding.
Realizing the restrictions in accessibility, the only possible arrangement for a neutron beam tube (NBT) would have to be vertical and tangential to the reactor core in the reactor pool. Several fortunate circumstances would allow this solution. First, RMC is located on a peninsula near the St. Lawrence Seaway with a controlled water level, unlike other SLOWPOKE installations with lower water tables. All previous SLOWPOKE installations required a permanent shielding of concrete over the pool, in case of loss of water shielding. Secondly, the RMC concrete pool was roughly surfaced on the interior, meaning that a stainless steel lining had to be installed, rather than the pool simply painted. As well, the concrete reactor pool remained empty for 10 years since its construction until installation of the reactor, i.e. no hydrostatic balance existed, indicating good integrity. RMC requested consideration of the additional lining and the high water table in the site licence, which was approved, allowing for an open reactor pool and access for the NBT.

Thirdly, for future refuelling, the reactor container is located in one half of the pool, which allowed for the NBT to be in the other half of the reactor pool. To offset the limited neutron flux, AECL was requested to install a thermal column between the beryllium annular reflector and the reactor container wall in an outer irradiation site facing the open half of the pool. In Figure 4, the shim tray on top of the reactor core and the thermal column are shown. Filled with heavy water and covering and angle of 45°, this thermal column provided a thermal neutron flux almost three times higher [3]. After the permanent NBT was installed following the prototype experimentation described in the next Section, it was made neutrally buoyant and moveable hydraulically. It could thus be moved next to the thermal column for exposures and away by relaxing it so that it floated vertically, to act as a simple shuttering mechanism. The radiation levels would decrease to near background when not in use and the reactor room could thus be accessible for other uses.
2.1. Prototype NBT

With easy access to the reactor pool, the second author, W.J. Lewis, performed a series of experiments to determine the best arrangement of shielding and NBT diameters for the maximum thermal neutron output [4]. Since the NBT would be tangential to the reactor core, both neutron and gamma radiation would penetrate the NBT above an aperture and would have to be shielded. Two limitations existed, one being the flange just above the core, which impeded adding shielding there. It also increased the angle from vertical from the reactor container and towards the top of the pool wall (Figure 3). The other limitation was the amount of shielding that could be added before affecting the neutral buoyancy of the NBT, as it was only suspended from the I-beam.

The series of experiments involved using various combinations of diameters of commercially available plastic tubing up to 13 cm and several metres long with selections of neutron and gamma ray shielding (Figure 5). The tubing had to be connected in a waterproof manner each time and would only last for a few exposures before the radiation produced cracking and thus water leakage. Film exposures with ASTM devices were used to indicate improvements in successive arrangements.
2.2. Permanent NBT

With the experimentation on the prototype NBT providing a basis for a design of a permanent NBT, funding was sought for a permanent neutron imaging system (NIS) from DND and approved. Commissioning of this NBT took some time until satisfactory images were obtained. Successive experimentation [5-7] as before rather than calculations such as MCNP were not deemed useful due to the complex nature of the arrangement of the shielding and the NBT. Aside from configuring the shielding on the floating NBT as before, the main contribution was from a lining of neutron shielding material in the section just above the aperture.

![Diagram of the permanent neutron beam tube](image)

Figure 6 Sketch of the permanent neutron beam tube in the exposure position next to the reactor container

In Figure 6 is shown a cross section of the NBT in the reactor pool. Initially, only the bottom shielding box was installed, as the expected parts were thought to be long and thin such as a helicopter blade. It had configurable sides, two of which had sliding doors, which were matched to allow for passage of such a long item. As large flight control surfaces from the CF-18 Hornet were starting to be the main item
radiographed, the awkward and time consuming addition of temporary shielding to this shielding box became prohibitive. The bottom shielding was reconfigured, and the middle and upper shielding boxes were then added, with accommodation for a CCD camera. Semi-conformable shielding from the middle, shielding box allowed for partial coverage of the part. The image head, for either a film cassette or scintillation screen, could be lowered onto the part’s surface. A computer-controlled X-Y positioning system was installed for inspecting each of the six, per side, flight control surfaces of the CF-18 in accordance with the reproducibility requirements of the inspection technique. These components of the NIS are shown in Figure 7.

3. Flight Control Surfaces

The main application of neutron radiography for the RCAF became inspection of water ingress into the flight control surfaces of the CF-18 Hornet, specifically, the moveable parts such as ailerons and rudders [8-10]. With a double tail, there are two rudders on this aircraft and it is these rudders that have departed this aircraft in flight, e.g. two for the RCAF and 15 for the U.S. Navy (Figure 8).
It appeared that water was entering the rudders at the hinges and grounding straps, due to difficulties with the sealant at these penetrations. Concentrations of moisture would migrate to adjacent areas and weaken the adhesive bond between the aluminium honeycomb interior and the graphite epoxy surfaces. When this problem arose, all available and current NDT techniques were tested, with the conclusion that neutron radiography was the most sensitive [11]. The vertical orientation of the NBT at RMC was an advantage for inspections of FCS since water collected at the bottom of the honeycomb cells when the part was laid horizontally. A composite film image of a rudder with water ingress in the honeycomb cells is shown in Figure 9. As experience was gained with the CCD camera, the inspection procedure developed into a digital scan of the flight control surface, most of which are larger than the rudder, followed by film techniques, which had better resolution at the time [12-21]. Experimentation at other facilities with higher neutron beam intensities, such as at Pennsylvania State University, confirmed the imaging quality and also provided some insight into the movement and effect of the water ingress. Additional research into designing a water gauge and probability of detection (POD) studies on the NDT techniques used were also carried out (22, 23).

3.1. Water ingress solution

For the RCAF to be able to have their aircraft available and safe, neutron radiography was used to provide information on the extent of the water ingress problem due to its unique sensitivity to water. However, as indicated above, small portable neutron sources are not adequate for feasible neutron radiography, especially for large surfaces. Even the NBT for the reactor at RMC was compromised in its output intensity in that the coverage at the output end was made large enough (56 cm diameter) for a standard X-ray film in either orientation. Although a reactor can provide greater neutron intensity, it is not transportable like a source and thus other techniques were required at the Base level where the aircraft are located. Infrared thermography was developed as an indication of water ingress on an intact aircraft. If indications were found, the flight control surface would be removed and X-radiographed at the Base. If further investigation were warranted, the part would be packaged and shipped to a DND laboratory for C-scan ultrasonic inspection to determine if disbonds were present and to RMC for further water detection.

Once the capability to detect water was optimized (24), the next step was to determine the best means of repairing the component to place it back in service, as these large items are expensive and spares are not readily available. Drilling out areas deemed to be affected by water ingress and patching with epoxy...
material is one solution, but this method is invasive and the mass of the flight control surface is increased. Instead, a method of drying the flight control surfaces, specifically the rudder, was developed using neutron radiography.

It was thought by the third author, P.C. Hungler, that utilizing heat, vacuum pressure and removing all hinges to open up water egress paths would draw the trapped moisture out of the honeycomb cells, as shown in Figure 10. In the experimentation, both coupons of honeycomb sections with known amounts of water and actual rudders were investigated. By placing the complete drying setup on top of the NBT, a series of “near real time” neutron images were obtained over a period of time, which revealed the movement of water out of the honeycomb cells. A successful drying procedure was developed using neutron imaging [25,26]. However, since neutron imaging is not available at the Base level, where the majority of aircraft maintenance is performed, the results from the drying procedure were correlated to a dew point meter. This meter measured the relative humidity of the air being removed from the vacuum bag which was wrapped around the rudder. A correlation between the percentages of relative humidity in the vacuum bag compared to different levels of moisture in the rudder as determined by neutron imaging was obtained. The RCAF now employs a Base level NDT technique based on the neutron imaging research at RMC, to remove any moisture detected in CF-18 flight control surfaces.

3.2. Structural integrity

The next stage in which neutron imaging can be of value is to determine the structural integrity of the rudders once the water has been removed and before they are placed back on the aircraft. There are two structural adhesive bonds used in the FCS that can be degraded by water ingress: the filet bond and the node bond. The filet bond is located between the aircraft skin and the honeycomb core as seen in Figure 11 a). The second adhesive bond is the node bond, which is formed during manufacturing of the honeycomb cells. Adhesive is placed at regular intervals along the length of the thin aluminum foil and, when it is stretched apart, it forms its honeycomb shape (Figure 11 b). Using 2D neutron radiography, it is possible to observe water movement within the honeycomb core at different orientations, which
provides some indications of which adhesive bonds have been degraded [27]. However, the exact location and position of moisture, which is essential information to determine structural degradation, is difficult to assess. The 3D images obtained from neutron tomography would enhance the capability to determine the contribution of each structural adhesive bond to water movement within the structure.

The neutron imaging system at RMC was modified by the third author to incorporate a neutron tomography system [28]. Due to the vertical orientation of the NBT, the tomography instrument has a horizontal axis of rotation. This set-up required a novel design as shown in Figure 12.

Following initial experimentation to show that the neutron tomography system was capable of producing tomograms, the system was optimized to improve the quality of the images produced and the spatial resolution of the system. Further modifications have been incorporated to enable limited angle
tomography of a complete CF-18 rudder to be carried out at RMC. The advances in neutron tomography at RMC have allowed the RCAF to better understand water movement and the level of structural degradation within the CF-18 rudders [29]. The neutron tomography instrument developed at RMC has also been used by other researchers for NDT inspections including investigations of archeological artifacts. In Figure 13, the sectioned view of a tomogram of an Ancient Egyptian bronze statue obtained at RMC for researchers at Queen’s University at Kingston is shown.

4. Conclusion

The investigation of neutron imaging, both radiography and tomography, has been purpose led by the maintenance requirements of the RCAF, specifically for its CF-18 fighter aircraft fleet. Development started with small neutron sources in different enclosures, which provided the impetus for adding a neutron radiography capability to a research reactor smaller than typically used for this technique. However, with certain attributes of this reactor along with the advancement from film to digital imaging, neutron imaging has been instrumental not only in the direct application as a NDT technique, but also as a research tool to investigate a repair technique for water removal as well as the structural integrity of the repaired component.

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References


