Ultrasonics 57 (2015) 1–10

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Radiation endurance of piezoelectric ultrasonic transducers – A review

A.N. Sinclair [a,*], A.M. Chertov [b,1]

[a] Department of Mechanical and Industrial Engineering, University of Toronto, Ontario M5S 3G8, Canada
[b] Institute for Diagnostic Imaging Research, University of Windsor, Ontario N9A 5R5, Canada

ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 28 October 2014
Accepted 30 October 2014
Available online 20 November 2014

Keywords:
Ultrasonic NDT
Piezoelectric transducers
Nuclear reactor inspection
Radiation endurance
Transducer failure

ABSTRACT

A literature survey is presented on the radiation endurance of piezoelectric ultrasonic transducer components and complete transducer assemblies, as functions of cumulative gamma dose and neutron fluence. The most extensive data on this topic has been acquired in CANDU electrical generating stations, which use piezoelectric ultrasonic transducers manufactured commercially with minor accommodation for high radiation fields. They have been found to be reliable for cumulative gamma doses of up to approximately 2 MegaGrays; a brief summary is made of the associated accommodations required to the transducer design, and the ultimate expected failure modes.

Outside of the CANDU experience, endurance data have been acquired under a diverse spectrum of operating conditions; this can impede a direct comparison of the information from different sources. Much of this data is associated with transducers immersed in liquid metal coolants associated with advanced reactor designs. Significant modifications to conventional designs have led to the availability of custom transducers that can endure well over 100 MegaGrays of cumulative gamma dose.

Published data on transducer endurance against neutron fluence are reviewed, but are either insufficient, or were reported with inadequate description of test conditions, to make general conclusions on transducer endurance with high confidence. Several test projects are planned or are already underway by major laboratories and research consortia to augment the store of transducer endurance data with respect to both gamma and neutron radiation.

Contents

* Corresponding author. Tel.: +1 416 978 6953.
E-mail addresses: sinclair@mie.utoronto.ca (A.N. Sinclair), chertov@uwindsor.ca (A.M. Chertov).
[1] Tel.: +1 (519) 991 6546.

http://dx.doi.org/10.1016/j.ultras.2014.10.024
0041-624X/

1. Introduction

There is considerable demand for ultrasonic nondestructive evaluation (NDE) at locations where there are substantial radiation fields, e.g., periodic inspection of nuclear reactor components, or ultrasonic scanning for potential leakage sites on irradiated fuel assemblies. This raises the possibility of degradation or even complete failure of ultrasonic transducers. Much has been written about the effects of gamma radiation (and combined neutron and gamma radiation) on individual materials used in transducer components, such as the piezoelectric element. However, less has been documented regarding the precise failure mechanisms and projected lifetimes of entire transducer *assemblies*. Most of the literature on that topic tends to be in the form of isolated observations under unique operating conditions on various types of sensors and piezoelectric materials – some of the work in this area is briefly summarized in several technical articles, e.g., [1–9]. However, the limited extent of these transducer studies makes it difficult to get an overall picture of expected lifetime reduction of a transducer as a function of radiation dose. In addition, some of the relevant data have never been published in the open literature, but have been acquired through operational experience and kept as internal information at nuclear generating stations or research facilities.

In this review paper, we draw on operational experience to provide the link between studies on individual transducer component materials exposed to gamma radiation, and expected lifetimes of ultrasonic transducers. Experience at CANDU heavy-water moderated nuclear reactors is particularly useful, where extensive ultrasonic inspections are routinely performed of fuel channels and other reactor components during maintenance shutdowns, using a sophisticated robotic delivery system to enable remote scanning. In such instances where the nuclear reactor is shut down, the neutron flux is negligible and the effects of gamma radiation alone can be studied.

Other operational experience and research data include that acquired in liquid metal-cooled research reactors, [4,10–14], or current US government-sponsored programs on Advanced Sensors and Technologies in Nuclear Environments [7,15]. The total amount of data acquired under such conditions, in terms of number of irradiated transducers or total radiation dose, is far less than for CANDU reactor inspections, and many of the transducers have specialized designs to match unique operating environments. Under these conditions, it is difficult to draw definitive conclusions with a sound statistical basis.

There is the added possibility in some experiments to examine the effects of neutron radiation on transducer lifetimes. However, these data often feature a gamma–neutron mixture; some of these data correspond to an unknown elevated temperature, and the spectrum of neutron energies is generally not precisely described. This complicates the task of comparing results of different studies on neutron irradiation of piezoelectric transducers, and determining a precise correlation between cause and effect. The end result is a somewhat ambiguous overall picture of the relative effects of neutron radiation compared to gamma radiation on transducer lifetimes.

1.1. Scope of literature review

The scope of this review is as follows:

- Identify the most common failure mechanisms and associated cumulative radiation doses of individual ultrasonic piezoelectric transducer components in gamma fields. The review is limited to transducers containing conventional piezoelectric elements – composite piezoelectric elements are not included due to their vast number and frequent lack of detailed published information regarding their exact structure.
- Identify degradation and failure mechanisms of entire transducer assemblies in radiation fields, and associated dose levels.
- Describe minor modifications to commercial transducer manufacturing steps that have been adopted to improve gamma radiation resistance. Characterize operating experience and expected transducer lifetimes with such modified commercial transducers in contemporary electrical power generating stations.
- Review the published data regarding lifetimes of transducers and their components exposed to neutron radiation fields, or combinations of neutron and gamma radiation. The data are far less definitive than those corresponding to gamma irradiation, due to the limited amount of data, variety of test conditions under which measurements have been made, and lack of information regarding the role of neutron energy.

Note: The measurement unit for gamma radiation dose is the Gray, equal to 1 Joule of absorbed energy per kg of material; the data relevant to this literature review are generally in the Mega-Gray (MGy) range. Due to the very strong dependence of the attenuation coefficient for gamma rays on the atomic number Z of the target [16], the various components of a transducer will experience vastly different radiation doses that are difficult to estimate. It is therefore common practice [17] to express radiation dose in terms of the number of Grays that *would* be absorbed by light elements with atomic numbers similar to those of biological tissue. Materials used in such dosimeters include dyed polymethylmethacrylate [14], ferrous sulfate and sodium chloride mixed with sulfuric acid and water used in the Fricke dosimeter [18], silicon [19], and air [20]. The key point is that the *actual* energy absorption (plus associated heating effect) in a high-Z piezoelectric element such as PZT will be far higher than that indicated by the quoted nominal dose applicable to biological tissue. This can cause high temperature excursions that could damage a transducer. For perspective on the relative magnitudes of gamma radiation doses, a few key examples are shown in Table 1.

Neutron radiation exposure is usually expressed in terms of neutron *fluence*, equal to the cumulative track length swept out by neutrons per unit volume of material integrated over time. Neutron fluence is commonly expressed in the non-S.I. unit of cm^{-2}.

Table 1
Approximate gamma dose rates and cumulative doses [21–24].

Gamma radiation source	Dose rate (Gy/h)[a]	Cumulative dose in one year (Gy)
Interior of a commercial nuclear reactor, at full power	10^7	10^{11}
Interior of a commercial nuclear reactor, shutdown	0.5	4000
Adjacent to nuclear fuel in spent fuel storage ponds	10^3	10^7
Gamma doses to the human body		
Short-term dose yielding 50% death probability		2.5–5
Typical background radiation from rocks, cosmic rays	10^{-7}	10^{-3}
One full-body CT Scan		10^{-2}
Maximum legal dose to the public from non-medical nuclear activities (Canadian Nuclear Safety Commission regulations)		10^{-3}

[a] The *biological effect* of a dose of radiation is expressed in Sieverts, where 1 Sievert is equal to the dose (expressed in Grays) multiplied by a Quality Factor. The Quality Factor is 1 for gamma radiation, such that Grays or Sieverts are used interchangeably for gamma.