



Radiation effects on polymers for coatings on copper canisters used for the containment of radioactive materials

Aba Mortley*, H.W. Bonin, V.T. Bui

Department of Chemistry and Chemical Engineering, Royal Military College of Canada, P.O. Box 17000 Station Force, Kingston, ON, Canada K7K 7B4

ARTICLE INFO

Article history:

Received 9 July 2007

Accepted 10 January 2008

PACS:

28.41.Kw

61.82.Pv

83.80.Va

ABSTRACT

The present work proposes applying polyurethane coatings as an additional barrier in the design of Canadian nuclear waste disposal containers. The goal of the present research is to investigate the physico-mechanical integrity of a natural castor oil-based polyurethane (COPU) to be used as a coating material in pH–radiation–temperature environments. As the first part to these inquiries, the present paper investigates the effect of a mixed radiation field supplied by a SLOWPOKE-2 nuclear research reactor on COPUs that differ only by their isocyanate structure. FTIR, DSC, DMA, WAXS, and MALDI are used to characterize the changes that occur as a result of radiation and to relate these changes to polymer structure and composition. The COPUs used in the present work have demonstrated sustained physico-mechanical properties up to accumulated doses of 2.0 MGy and are therefore suitable for end-uses in radiation environments such as those expected in the deep geological repository.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

In Canada, the proposed method for the ultimate disposal of spent nuclear reactor fuel and high-level radioactive waste consists of burying the radioactive waste deep underground within granitic rock formations referred to as plutons. These plutons are commonly found in the Canadian Shield [1]. The basis for the disposal concept is the multi-barrier approach, which has been successfully implemented in the design of the CANDU nuclear reactor. The actinides and the fission products, both intensively radioactive at the time of fuel discharge from the reactor's core, are contained within the fuel matrix and the cladding of the fuel rods. The discharged fuel bundles are stored for several years in the spent fuel bay at the nuclear generating station in order to allow them to cool down both radioactively and thermally.

The Canadian concept for a deep geological repository (DGR) for used fuel is comprised of a system of multiple barriers that include the used CANDU reactor fuel, the container, the buffer, the sealing systems, and the Geosphere [1]. In the Canadian multi-barrier approach for used nuclear fuel disposal, the bundles are left intact when retrieved from the spent fuel bay, and placed within a container specifically designed to keep the fuel bundles indefinitely. Inside the container the fuel bundles are surrounded by a filler material. Glass beads, a molten, low melting point metal, such as lead; and an internal structural support, such as an array of carbon steel tubes have been suggested as filler materials to occupy the

empty space between the fuel bundles [1]. The research team at the Royal Military College of Canada (RMC) has proposed sintered thorium dioxide (ThO_2) as a filler material because the purpose of the ThO_2 is threefold: it serves as a heat conducting material to keep the temperature of the bundles and the container walls to acceptable values; it shields the container walls from the radiation emitted by the radioactive material; and it offers yet an additional barrier opposing the escape of radioactive material in the event of a breach in the fuel cladding [2,3].

The container walls serve as a fourth barrier, since the container is designed to be leak-tight, and to resist the effects of radiations from the fuel bundles stored in the container. In addition to the effects of radiation, the container must also resist temperature effects and the chemical aggression from the surrounding alkaline or acidic groundwater. The change in pH is due to the presence of calcite in the surrounding groundwater. Over time, the calcite precipitates into surrounding rock fractures and calcium exchanges for sodium in the clay minerals resulting in a shift in the pH from 8.4 in higher concentrations of calcite to ~6.8 after its removal [1,4,5]. Once placed in the cavities of the DGR, buffer materials made of clay would surround the container. The same materials would be used to backfill the galleries and the mine shafts once the disposal facility is filled up to capacity. The backfill represents the fifth barrier, while the 500–1000 m thick granite rock of the pluton is the sixth barrier against the eventual displacement of the radioactive fission products and actinides towards the biosphere [1,4,5].

The present work is concentrated on the design of the storage container, which must absolutely maintain its integrity for at least

* Corresponding author.

E-mail address: aba.mortley@rmc.ca (A. Mortley).

500 years. The material proposed for the fabrication of the container is copper, more specifically, oxygen-free phosphorous doped copper. The main cause of failure of copper is corrosion, which in the context of the DGR is at its most aggressive in the warm oxidizing period during the early stages of emplacement (<100 years) [6]. The simultaneous exposure of the container's walls to the ionizing radiation field emitted by the spent nuclear bundles, the relatively high temperatures caused by the residual heat produced by the spent nuclear fuel, and the chemical aggression from the groundwater that would be in contact with the copper would all challenge the container's integrity.

At RMC, research has been carried out on the merits of replacing the copper material with polymer based materials for the fabrication of the container. Already, several polymers have demonstrated their qualities that would be well suited for such an application [7–12]. However, if the concerns about corrosion could be brushed aside for copper, this metal has many outstanding properties which justify that its consideration be maintained as a candidate material for the fabrication of the container walls. The present research thus aims at looking at the merits of coating the copper walls with a suitable polymer that would act as an additional physical barrier. It is anticipated that the polymer would provide an arduous pathway for groundwater movement towards the container walls thereby reducing the exposure time of the copper walls to the harsh oxidizing environment during the early emplacement phase. Consequently, the polymer may reduce the corrosion rate and increase the lifetime of the metal container, and thus the isolation of the used nuclear fuel.

The field of natural based polymers is a very active one, as industry strives to replace conventionally produced petroleum based polymers with biopolymers (natural polymers). The complex structure of the castor oil based polyurethanes (referred to in this document as COPU) provides an interesting backdrop for a variety of applications. The uniqueness of the castor oil component is that it imparts chain flexibility due to its long aliphatic chain component and more importantly it assumes several roles that promote crosslinking, which results from its tri-functional nature and proton donor ability. The present work considers the use of COPU as a coating material for the metal containers suggested for the storage of used nuclear fuel. Castor oil-based polyurethanes are chosen for this application because of its flexibility and impact resistance, important factors in the handling and transportation of the used fuel container. Epoxies for example, are known to be radiation resistant, but they are susceptible to brittle fracture. The formation of microcracks in the polymer coating can severely affect the protective function of the coating. The implication of this proposition is that the polymer will be subjected to a combined radiation–temperature–pH environment. The goal undertaken in the present work is to investigate the radiation effects provided by the mixed ionizing radiation on natural castor oil based polyurethanes. The properties and effects imparted by different isocyanate structure on the physico-mechanical performance of the COPU as a function of accumulated dose are analyzed.

A literature research has revealed many valuable works performed on the physico-mechanical properties of castor oil-based polyurethanes; and the effects of chain extenders, isocyanate structure, and hard-to-soft ratio [13–16]. However, no research has been performed on the study of the radiation effects on natural castor oil-based polyurethanes. In this work, the physico-mechanical behaviour of the COPUs was monitored by means of Fourier transform infrared spectroscopy (FTIR), dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), wide angle X-ray spectroscopy (WAXS), and matrix-assisted laser desorption/ionization (MALDI) spectroscopy.

2. Experimental

2.1. Materials

Castor oil, hexamethylene diisocyanate (HMDI), and 2,4-toluene diisocyanate (TDI) were obtained from Sigma-Aldrich Company, Inc. and were used as received. The equivalent weight per hydroxyl group for castor oil was 345 g and per NCO group were 84 g and 87 g for hexamethylene diisocyanate and 2,4-toluene diisocyanate, respectively.

2.2. Sample preparation

The samples were prepared by simultaneously introducing a predetermined amount of castor oil and isocyanate corresponding to a fixed NCO/OH ratio of 1.5 into a round-bottom flask. The round-bottom flask was then placed in an oil bath for even heat distribution. The mixture was stirred vigorously under reflux, with a Teflon-coated magnetic stir bar, and heated to approximately 65 °C for at least one hour to form the urethane prepolymer. After mixing, the blend was poured into moulds designed according to the tensile dumbbell shape prescribed by ASTM D638-96 [17]. To produce bubble-free samples, the moulds were degassed under reduced pressure, 76 mmHg (10.13 kPa), and heated to 65 °C for 30 min. Then the blends were cured in the moulds at 100 °C for 9.5 h.

2.3. Irradiation conditions

The samples were irradiated in the mixed radiation field provided by a SLOWPOKE-2 nuclear reactor. At the irradiation site, the mixed field comprised of 87% electrons, 9% gamma photons, 3% recoil protons and 1% fast and thermal neutrons. The samples were positioned at 32 cm in the radial direction from the reactor centre at mid-core height. At this position, the dose rate was determined to be 37 kGy h⁻¹ ±28% [18]. In the present work, the COPU sample names are reported as COPU suffixed first by H or T to represent HMDI or TDI, and followed by a number that represents the total accumulated dose in MGy; i.e. COPUH0, COPUT0, etc. Previous experiments not reported in the present paper illustrated an increasing trend in the tensile strength and the modulus values of COPUs subjected to radiation [20]. Based on the tensile tests it was shown that below an accumulated dose of 1.0 MGy there was a steady increase in the COPUs mechanical strength properties, with increasing dose. Then, above 1.0 MGy the response of the COPU to higher radiation doses reached a plateau. As expected, with the increase in mechanical strength, there was a slight drop in the ductility reflected in the decrease in the maximum strain, with increasing dose up to a dose of 1.0 MGy. After 1.0 MGy, the maximum strain remained at a constant value [19]. The decrease in ductility was not considered significant, as the long chain aliphatic structure of the polyol component, which is responsible for the COPUs ability to change conformation when deformed, is only slightly affected by increasing dose. The microphase structure of polyurethane allows for the formation of more hard segments such as additional urethane and allophanate linkages, with increasing radiation. This causes an increase in mechanical properties, while only slightly compromising the ductility of the polyol soft segment. Therefore, the present work focused on the effects of two accumulated doses at the two extremes of the dose spectrum at 0.5 MGy and 2.0 MGy [19].

2.4. Characterization

In the present work, five samples were tested at each trial to ensure the reproducibility and reliability of the test samples and the results.

FTIR analysis was performed on a Perkin Elmer Spectrum GX FTIR Spectrometer with a PIKE MIRacle ATR sampling accessory. The IR data were collected using the attenuated total reflectance (ATR) technique with a single bounce Ge crystal. Since the IR intensity can be dependent on sampling depth in the ATR measurement, all FTIR-ATR spectra were corrected for quantities analysis using the software attached to the spectrometer.

DSC analysis. Differential scanning calorimeter data were obtained on a TA instruments Q100 series. Runs were performed on polymer samples of about 10 mg at a heating rate of 5 °C/min. The gas-cooling accessory was used to provide an experimental range that began at –100 °C and spanned to 100 °C. Two consecutive cycles were run on each sample. The midpoint of the slope change of the heat capacity plot of the second scan was taken as the glass transition temperature.

DMA analysis. DMA data were collected on the TA instruments Q800 DMA series using a single cantilever clamp setting. The multifrequency mode at a temperature ramp of 15 °C/min, over a temperature range of –100 °C to 100 °C was used.

WAXS analysis. WAXS spectra were collected using a Thermo ARL Scintag X1 with a germanium monochromatic CuK α ($\lambda = 1.5406 \text{ \AA}$) radiation in a transmission mode. A curved position sensitive detector in the 2θ range from 2° to 50° at a step size of 1° was used.

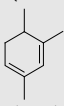
MALDI analysis. The MALDI spectra were acquired using a Voyager-DE STR, MALDI TOF instrument from Applied Biosystems. The Voyager DE-STR MALDI TOF instrument was operated in the reflectron mode. The accelerating voltage was 20 kV. The COPUs were dissolved in a THF/chloroform mixture at 10 mg/mL. The matrix solution was prepared by dissolving 0.5 μL polymer solution (polymer in THF/chloroform (v/v, 1:1) with 0.5 μL DHB matrix (160 mg/mL in THF). The mixture was deposited on a MALDI target. When the co-crystallation was formed, the samples were analyzed by MALDI MS with a nitrogen laser (337 nm).

3. Results and discussion

3.1. FTIR

Two types of castor oil-based polyurethane specimens were produced, differing only in their isocyanate structure. The two types of isocyanate structures were provided by an aliphatic HMDI and an aromatic TDI. Both types of castor oil-based polyurethanes displayed typical polyurethane spectra. Table 1 assigns the functional groups associated with the various frequencies derived from the spectrum of the different COPUs (Fig. 1).

Table 1
Band assignment for the COPU specimens

Frequency, cm^{-1}	Assignment
3321	ν (N–H) bonded in TDI
3311	ν (O–H) bonded in TDI in HMDI
3000	ν (C–H) sp^2 CH stretch from the C=C bond in the castor oil and the C=C bond in the aromatic group of TDI
2920	ν (C–H) in CH_2 groups
2851	
1727	ν (C=O) in TDI
1713	In HMDI
1600	δ (C=C) in TDI benzene ring and in castor oil
1533	δ (N–H) bending
1061	ν (C–O–C)
875	 γ (CH) due to 1,2,4-substituted ring in TDI
811	
729	δ (C–H) rocking band due to long aliphatic chains of castor oil

^a ν = stretching, δ = in plane bending, and γ = out of plane bending.

The FTIR spectra can be used to give a qualitative comparison of the functional groups present in the COPUs. As the accumulated dose on the COPUs increased, there was no change observed in the FTIR spectra. This was because the rearrangement of the structure due to chain scission or recombination may have changed the quantity of functional groups present, but did not change the type of functional groups observed by FTIR analysis.

3.2. DMA and DSC

The dynamic mechanical properties for a series of castor oil polyurethanes based on HMDI and TDI with a NCO/OH ratio of 1.5 are presented in Figs. 2–4. The maximum values of the storage and loss modulus were lower ($\sim \times 2$) for the COPUT samples than for the corresponding COPUH samples. In the glassy region, there were two drops in the storage modulus of the COPUT samples versus one drop in the COPUH and several maxima exhibited in the loss and $\tan \delta$ graphs of the COPUT specimens. The different trends between the COPUH and the COPUT samples could be attributed to the different diisocyanate structures.

The aliphatic diisocyanate provides a hard segment structure that is in line with the long chain aliphatic structure of the castor oil. As such, the COPUH demonstrated a higher storage modulus than the corresponding COPUT because the aliphatic chains could store energy through various conformational arrangements more easily than the COPUT containing a rigid aromatic group. The two drops exhibited in the storage modulus of the COPUT were due to secondary transitions that occurred at low temperatures. The occurrence of secondary transitions in the COPUT was supported by the T_g , β , and γ peaks in the loss modulus and the $\tan \delta$ graphs of COPUT in Figs. 3 and 4. The glass transition temperature coincided with the second drop in the storage modulus. The second transition β peak was associated with the Schatzki [21] crankshaft mechanism corresponding to the first drop in the storage modulus. The secondary transitions obtained from DSC and DMA measurements for the COPU are shown in Table 2.

The glass transition temperature derived from the DSC measurements indicated a single transition, which confirmed that both the COPUH and the COPUT samples consisted of an amorphous structure. The DSC thermograms are illustrated in Fig. 5. The T_g s derived from DSC occurred at lower values than those derived from the peak temperatures of $\tan \delta$ in the DMA measurements (Fig. 4). DMA measurements characterize the dynamic mechanical properties that rely strongly on the changes in the relaxation time of the polymer and are therefore well suited for secondary transition measurements. However, DSC gives a more accurate indication of first order transitions, which usually produce an instantaneous large step change in the enthalpy (heat flow). With secondary transitions, the step changes are smaller and occur over a longer time frame and, therefore, the glass transition temperature is much less distinct when measured with DSC.

In terms of structural differences, the T_g s extrapolated from both DSC and DMA experiments showed that the aromatic based polyurethanes exhibited a higher glass transition temperature than the aliphatic based ones. The T_g could be used to reflect the polymers' ability to undergo significant backbone movement and is affected by flexibility and intermolecular forces. As such, the more flexible aliphatic COPUH, which can easily undergo conformational changes, had a lower T_g whereas the aromatic COPUT had a higher T_g due to the stiffness and inflexibility imparted by the aromatic ring structure.

With respect to the effects of ionizing radiation on the COPU, there were slight differences observed between the unirradiated sample and the samples exposed to radiation. The COPU based on the aliphatic isocyanate showed a decrease in its T_g values and the COPU based on the aromatic isocyanate exhibited an in-

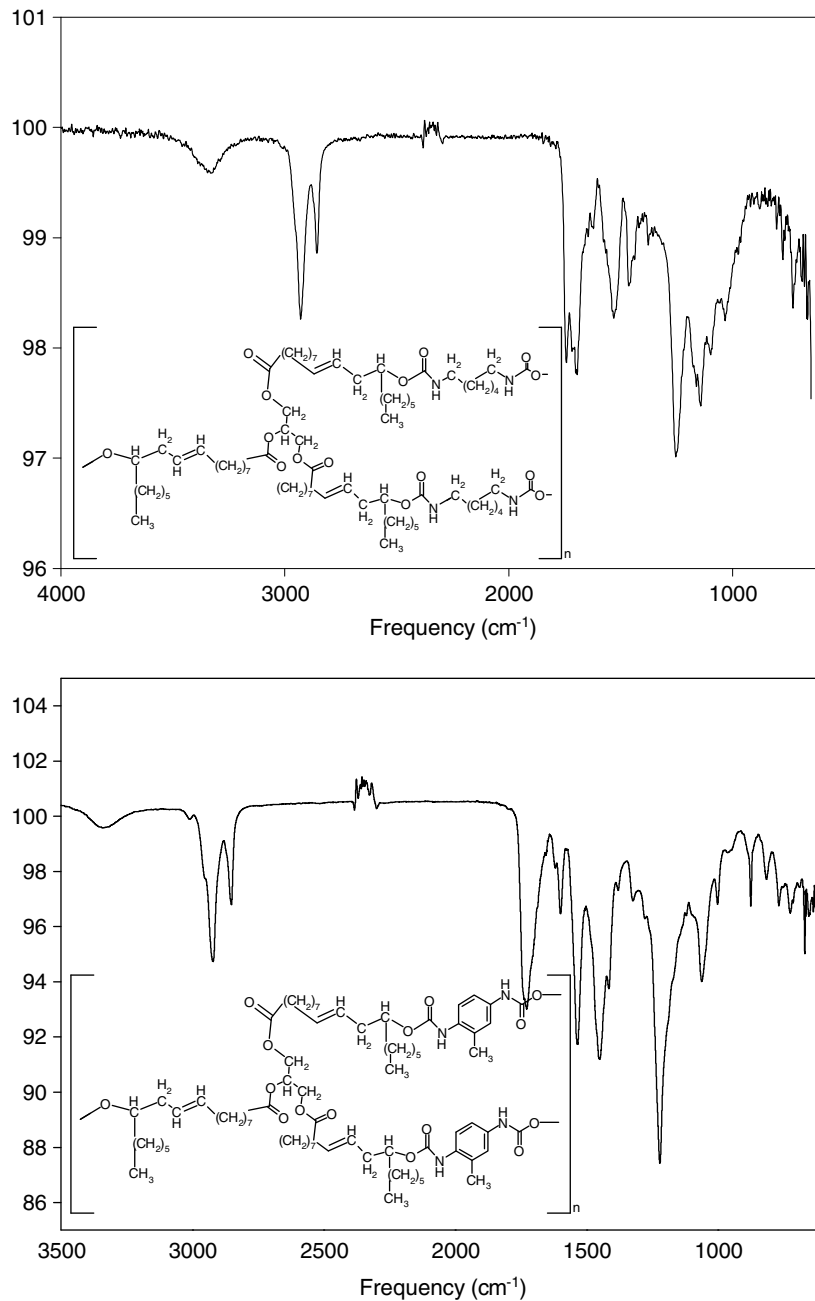


Fig. 1. Typical FTIR spectra for COPU specimens. Top: COPUH; Bottom: COPUT.

crease in its T_g values. The aforementioned trend could be explained by changing structural effects resulting from radiation exposure. Radiation affects polymers through two competing effects: crosslinking leading to bond formation and chain scission leading to bond reduction. The decreasing T_g values of the aliphatic polymer suggested an increase in the polymer's flexibility and fluidity and therefore indicated some possible rearrangement caused by chain scission within the polymer network structure. The aromatic ring could provide radiation protection to the polyurethane, thus the geminate pairs formed during the radiation driven process reacted to give additional crosslinks that imparted stiffness to the polymer network, thereby increasing its T_g .

The changes experienced by the polymers COPU as a function of accumulated dose reflected in their T_g s and dynamic mechanical

properties were small ($\Delta T_g < 3^\circ\text{C}$ for COPH and $\Delta T_g < 9^\circ\text{C}$ for COPUT using $\tan \delta$ values). The small differences were accounted for by the highly networked structure provided by the long aliphatic soft segment imparted by the castor oil. The radiation doses provided in the present work were not large enough to supply sufficient energy to cause multiple fragmentations along the backbone of the chain. As a result, the competing crosslinking and chain scission reaction were such that neither reaction dominated in the COPUs. For degradation to occur, free radical segments formed upon radiation should ideally be separated from the polymer network. The highly networked COPU structure can impart only limited mobility on these free radical segments resulting in a more probable geminate pair recombination reaction as the radicals may find escape difficult due to the cage formed by the surrounding matrix.

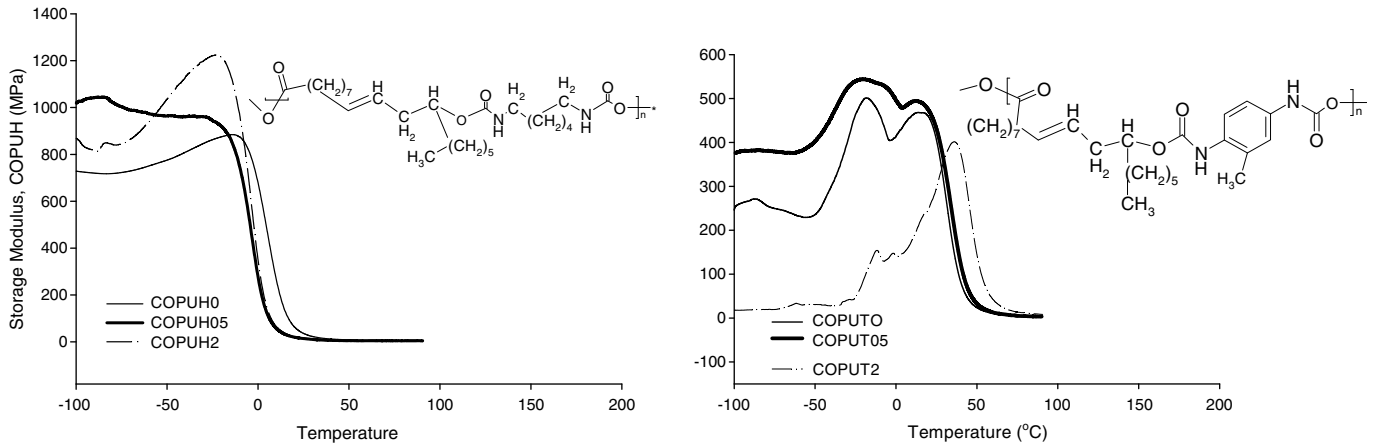


Fig. 2. Storage modulus graphs of COPUs.

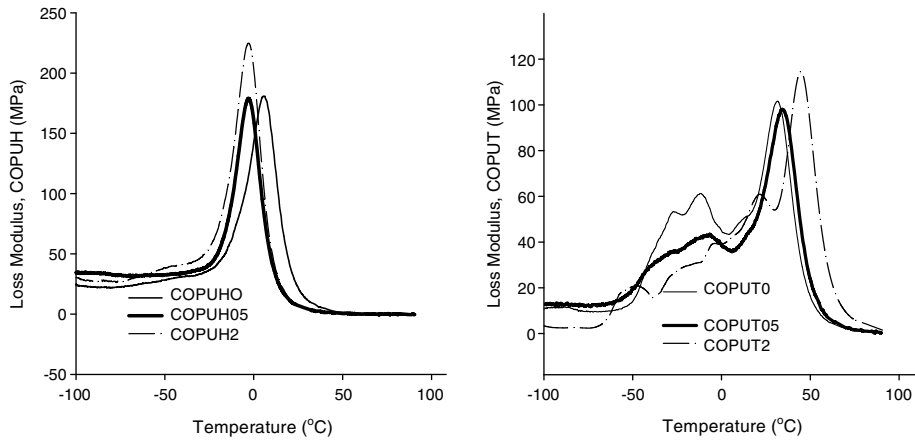


Fig. 3. Loss modulus graphs of COPUs.

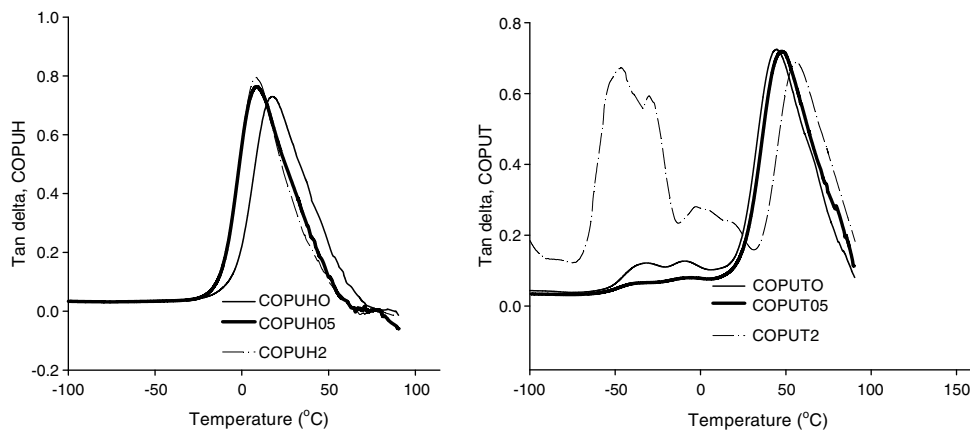


Fig. 4. Tan delta graphs of COPUs.

3.3. WAXS

The results of the WAXS diffraction patterns (Fig. 6) complemented the DSC data, which showed that there were no crystalline structures in the COPUs and therefore the COPU consisted only of an amorphous structure. The WAXS spectra show two broad peaks that were analogous to the peaks exhibited by the pure castor oil

sample. The spectra consisted of two broad peaks that were found in the regions $2\theta = 5.5^\circ$ and 19.4° .

3.4. MALDI

The MALDI mass spectra of the COPUs are illustrated in Fig. 7. Castor oil consists of a mixture of a di- and tri-glycerol at 30%

Table 2
Secondary transitions of COPU

Sample	DSC		DMA	
	T_g (°C)	T_g (°C)	β (°C)	γ (°C)
COPUH0	-21.27	11.10	-	-
COPUH05	-22.39	8.18	-	-
COPUH2	-21.25	8.21	-	-
COPUT0	10.44	44.36	-9.45	-31.87
COPUT05	14.47	46.51	-7.60	-40.28
COPUT2	14.90	53.12	2.5	-44.87

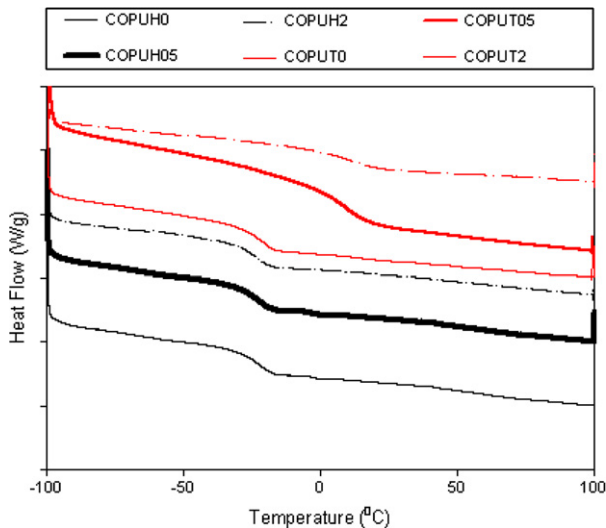


Fig. 5. DSC thermograms.

and 70%, respectively; therefore the molecular weights derived in the mass spectrum were an averaged weight between the fragments produced by the di and tri-components.

The COPUT and COPUH structures showed a bell shaped distribution with a bias towards the low molecular weight components. The most abundant peaks at molecular masses of 1108 and 1114 for the COPUH and COPUT samples respectively were due to a frag-

ment composed of the castor oil linked to three isocyanate groups from HMDI and TDI, respectively, produced as a result of the proposed fragmentation pattern illustrated in Fig. 8. This fragmentation pattern was due to scission of the alkyl-substituted carbon adjacent to the urethane linkage and cleavage at the C–N heteroatom bond in the hard segment of the urethane group (Fig. 8). In the COPUH and COPUT mass spectra series, mass spectral peaks differed by 142 and 149 for the COPUH and COPUT specimens and were attributed to their isocyanate hard polyurethane component. The series of lower intensity peaks can be classified as various short chain fragments of the soft castor oil component attached to isocyanate hard component. The MALDI spectra suggested that, in the presence of high-energy radiation, the COPU would cleave at the carbonyl group ester (C–O) linkage to produce isocyanate fragments.

3.5. Long-term performance

The present work is concerned with ensuring minimal contact between the surrounding groundwater and the metal wall of the container in the DGR through the implementation of a physical polymer barrier. As such, the lifetime of the polymer material in simultaneous radiation–temperature–pH environments must be investigated.

The present research investigates one of these conditions, the radiation effects on COPUs subjected to high doses over short times. The maximum predicted dose rate at the surface of the used fuel container within the DGR environment is 0.908 Gy/h at the beginning of the dwelling time of the container within the DGR [3]. The dose rate gradually decreases with time such that the total expected dose on the metal wall of the container over its lifetime of 500 years is 6.262 MGy [3]. If the thorium dioxide filler suggested by the RMC research team were used instead of the glass beads as the filler material within the container, then the total expected dose experienced on the metal container wall over its lifetime in the DGR would be 0.289 MGy [3,4].

Based on the preliminary results derived from the present research the COPUs withstood the accelerated dose rate of 37 kGy/h such that there were minimal changes in the polymer's properties up to an accumulated dose of 2.0 MGy. Therefore based on these experimental findings the COPUs can be considered as suitable materials in their application as a coating material for the

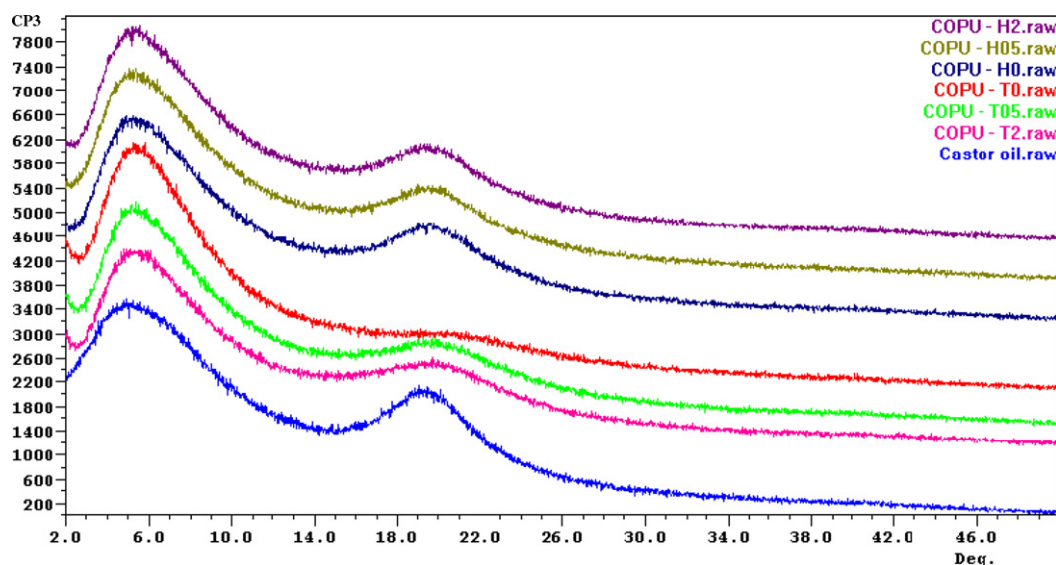


Fig. 6. WAXS diffraction patterns of COPU.

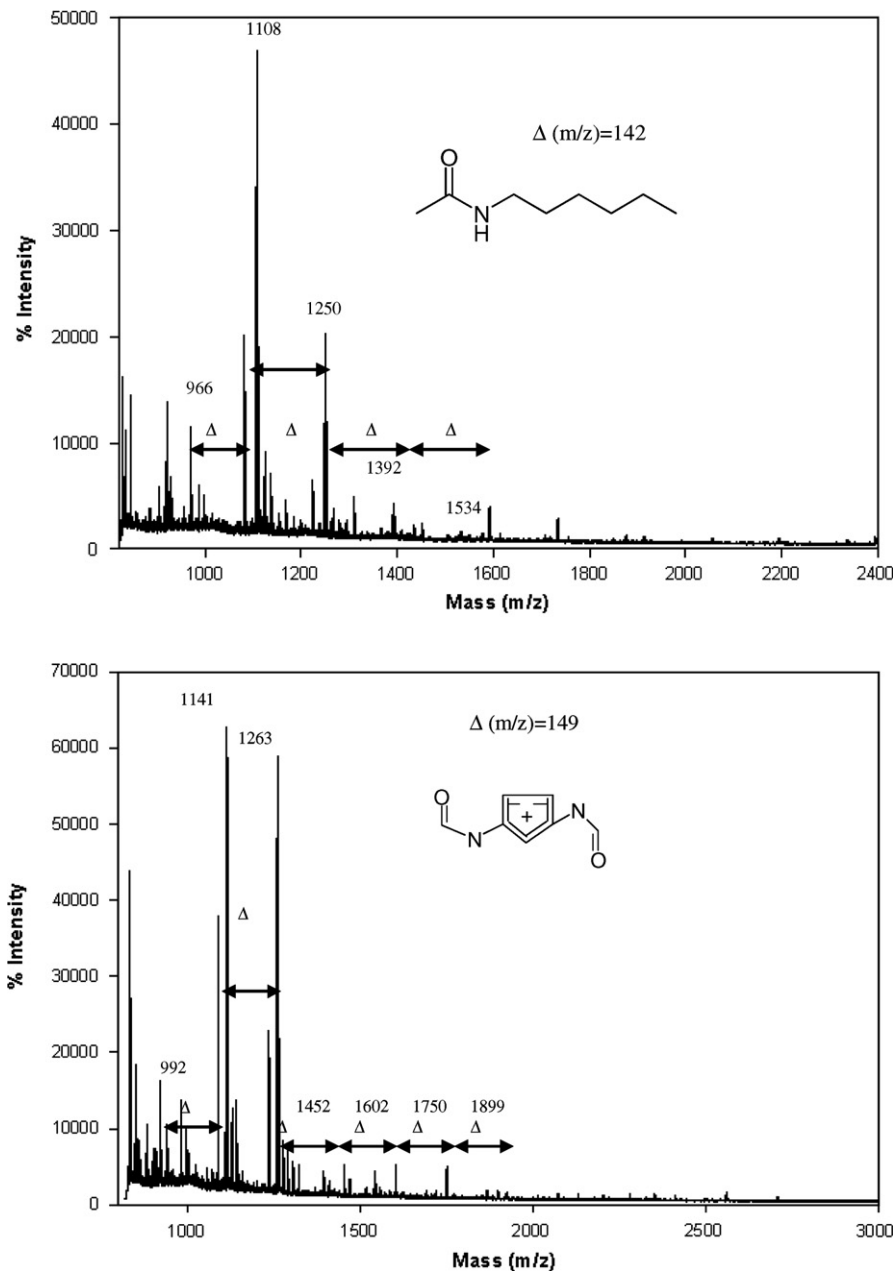


Fig. 7. MALDI MS of COPUs. Top: COPUH; Bottom: COPUT.

used fuel copper container walls, provided that ThO_2 is used as the filler material.

Ongoing research is aimed at determining the validity of transposing the results of the accelerated experimental conditions utilized in this work to more representative conditions of the container's lifetime in the DGR. The upcoming research investigates the individual and combined effects of radiation, temperature and varying pH environments on the COPU.

4. Conclusions

The goal of the present work was to investigate the radiation effects on the properties of elastomeric castor oil polyurethanes based on two isocyanate structures: an aliphatic HMDI and an aromatic TDI, using several investigation techniques. The steric impositions placed by the rigid structure of the aromatic ring in the hard

segment of the COPUTs lead to specimens that were less viscoelastic than the COPUH counterparts. The results retrieved from the analysis of the various data revealed an amorphous polymer whose properties ($\Delta T_g < 3^\circ\text{C}$ for COPH and $\Delta T_g < 9^\circ\text{C}$ for COPUT using $\tan \delta$ values) were only slightly altered by radiation. The indifference to the accumulated doses used in the present work (0.5 MGy and 2.0 MGy) was because the ionizing energy supplied to the COPU was below the energy threshold required to produce multiple bond scission that would otherwise lead to degradation. To that end, the competing crosslinking and chain scission reactions was such that no significant changes occurred in the COPU network as reflected by the DMA and DSC data. MALDI analysis revealed a network structure that could be decomposed by successive loss of the isocyanate hard segment upon exposure to aggressively harsh ionizing beam. Therefore, below and including an accumulated dose of 2.0 MGy, COPUs can be used in radiation environments.

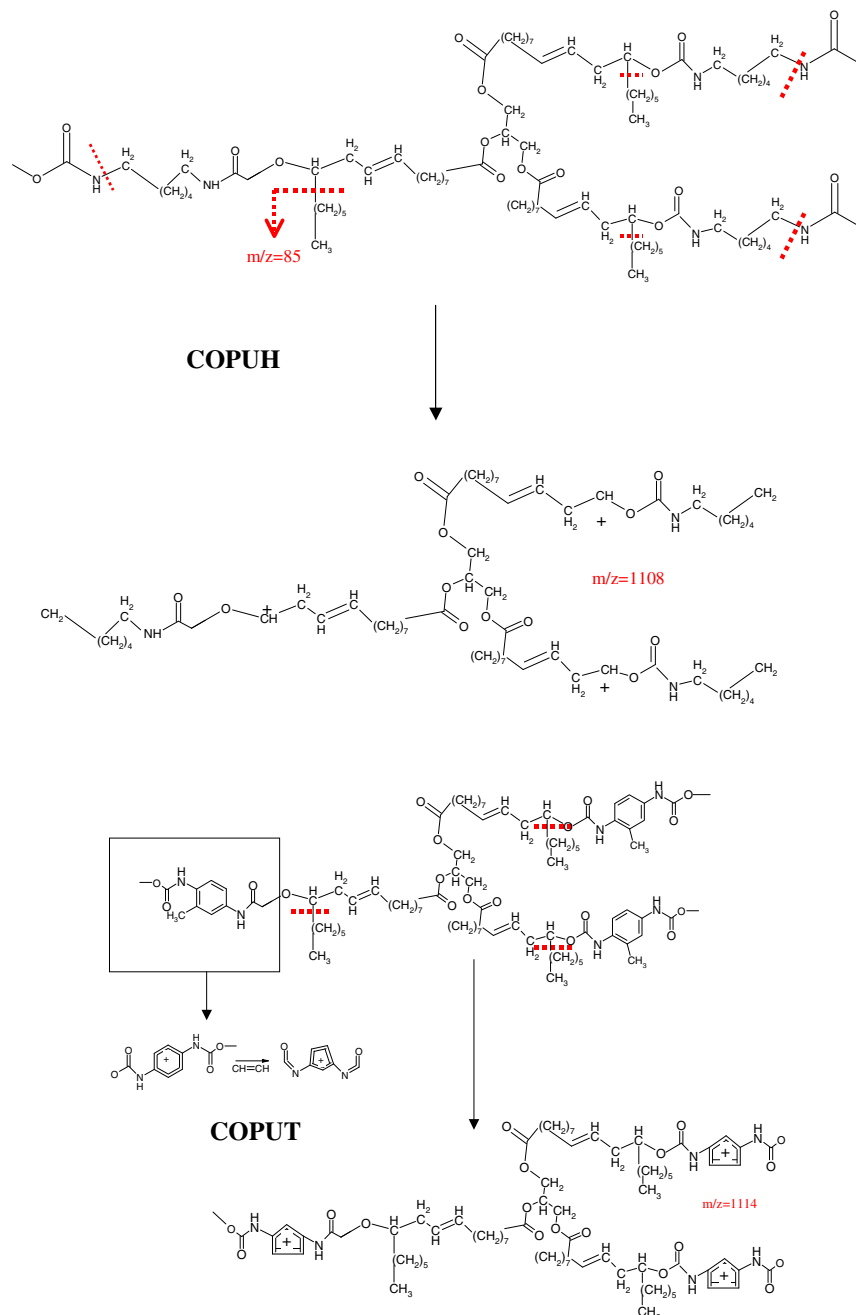


Fig. 8. Probable COPU fragmentation pattern. Top: COPUH; Bottom: COPUT.

Acknowledgements

The authors would like to acknowledge and thank the Natural Science and Engineering Research Council of Canada (NSERC) and the Defence Research Development Board (DRDB) for financial support of the research project. The support provided by Dr Yimin She at Queen's University MALDI facility, by Ms Kathy Nielsen and the staff of the SLOWPOKE-2 facility at RMC, and by Mr Bob Whitehead at the WAXS facility at RMC is well appreciated by the authors.

References

- [1] Atomic Energy Limited of Canada, Environmental Impact Statement on the Concept for disposal of Canada's Nuclear fuel waste, AECL-10711, COG-93-1, 1994.
- [2] H.W. Bonin, I. Miedema, V.T. Bui, in: Proceedings of the 23rd Annual Conference of the Canadian Nuclear Society, 2002.
- [3] I. Miedema, Application of advanced polymeric composites to spent nuclear fuel disposal containers, MSc. Thesis, Royal Military College of Canada, 2002.
- [4] Nuclear Waste Management Organization, Choosing a way forward. The Future Management of Canada's Used Nuclear Fuel. Final Study, 2005.
- [5] CTECH Radioactive Materials Management, Conceptual Design for a Deep Geological Repository for Used Nuclear Fuel, Annex 1, Metallurgical Aspects of Used Fuel Design, 2002.
- [6] D.W. Shoesmith, F. King, B.M. Ikeda, Mat. Res. Soc. Symp. Proc. 412 (1996) 563.
- [7] M. Walker, Polymeric Radioactive Waste Disposal Containers. An investigation into the application of polymers to house low and intermediate level radioactive waste, MSc. Thesis, Royal Military College of Canada, 2001.
- [8] O. Davey, T. Douglas, C. Duriez, B. MacGregor, Examination of the feasibility of using polymeric composites in the fabrication of a container for the long-term disposal of spent nuclear fuel, RMC-CEE-CME417-97-2, 1997.
- [9] C.A. McKenna, K.R. Hoffman, M.R. Dunning, Epoxy composite Container vessels for the long-term storage of spent nuclear fuel: Heat transfer effects and limitations, RMC-CEE_CM417-99-3, 1999.
- [10] L.L. Brown, H.W. Bonin, V.T. Bui, J. Nucl. Mater. 341 (2005) 115.

- [11] A. Mortley, Radiation effects on the properties of a polyurethane/epoxy graft interpenetrating polymer network. An investigation into the application of polymers in the fabrication of containers to store radioactive waste, MSc. Thesis, Royal Military College of Canada, 2005.
- [12] T.M. Liu, V.T. Bui, *J. Appl. Polym. Sci.* 56 (1995) 350.
- [13] Rajiv Kumar, S.K. Srivastava, G.N. Mathur, *Indian J. Technol.* 21 (1983) 517.
- [14] B.K. Kendaganna Swamy, Siddaramaiah, R. Somashekar, *J. Mater. Sci.* 38 (2003) 453.
- [15] T.M. Liu, V.T. Bui, *J. Appl. Polym. Sci.* 56 (1995) 350.
- [16] Z.S. Petrovic, D. Fajnik, *J. Appl. Polym. Sci.* 29 (1984) 1031.
- [17] An American Standard Test Method, Standard Test Method for Tensile Properties of Plastics, ASTM D638-96, 1996.
- [18] G.B. Lamarre, Experimental and Computational Determination of Radiation Dose Rates in the SLOWPOKE-2 Research Reactor at the Royal Military College of Canada, MSc. Thesis, Royal Military College of Canada, 1999.
- [19] A. Mortley, H.W. Bonin, V.T. Bui, *Nucl. Instrum. and Meth. B* 265 (2007) 98.
- [20] N.G. McCrum, B.E. Read, G. Williams, *An Elastic and Dielectric Effects in Polymeric Solids*, Wiley, NY, 1967. 28.
- [21] T.F. Schatzki, *J. Polym. Sci.* 57 (1962) 496.