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The environment of Fe$^{3+}$/Fe$^{2+}$ cations in a sodium borosilicate glass

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The neutron diffraction isotopic substitution technique is employed to investigate the environment of Fe$^{3+}$/Fe$^{2+}$ cations in a sodium borosilicate glass matrix of composition $0.210\text{Na}_2\text{O} \cdot 0.185\text{Fe}_{3}\text{O}_3 \cdot 0.605\text{SiO}_2$. The neutron diffraction data were obtained using the D4c diffractometer at the Institut Laue-Langevin (ILL; Grenoble, France), and were recorded for three samples; the base glass, the base glass incorporating natural Fe$^{3+}$ (12 mol%) and a similar glass containing Fe$^{3+}$ enriched in $^{57}$Fe. The data are Fourier transformed to yield the real-space total correlation function, $T(r)$, and the first co-ordination shells of the Fe$^{3+}$/Fe$^{2+}$ cations are investigated via a peak fit to the isotopic difference correlation function $\Delta T_{Fe}(r)$. It is concluded that the iron is mainly present as Fe$^{3+}$ cations, both tetrahedrally and octahedrally co-ordinated by oxygen atoms, plus a small fraction ($0.07\pm0.01$) of Fe$^{2+}$ cations in octahedral co-ordination. The Fe$^{3+}$ tetrahedral fraction is $0.45\pm0.10$, and appears to exist as Fe$^{3+}$ structural units incorporated into the network of silicate chemical groupings, with their negative charge being balanced by Na$^{+}$ network modifying cations. The remaining Fe$^{3+}$ cations (fraction $0.48\pm0.10$) are thought to be predominantly octahedrally co-ordinated and associated with BO$_3^{3-}$ orthoborate anions in FeBO$_3$. 

N.B. Characters highlighted in red need a bar over the top.
chemical groupings, which become non-stoichiometric due to the reduction of some of the Fe$^{3+}$ cations to Fe$^{2+}$.

Footnote

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1. Introduction

A detailed knowledge of the environment of transition metal and rare earth cations in conventional network glasses is extremely important for a number of reasons. They are added to such glasses to provide specific properties for chosen applications, e.g. desired colouring, and are also important components of the nuclear waste that is incorporated into borosilicate glasses for immobilisation/storage. In each case the important properties, for example laser line shape or the leachability of highly radioactive waste, depend on their detailed structural environment.

The present study forms part of a programme to investigate the environment of transition metal and rare earth cations incorporated into borosilicate glasses that model those employed by BNFL for the vitrification of nuclear waste. NMR, Raman and Mössbauer spectroscopy data have already been recorded by Holland and co-workers(1–3) for a 0·103Li$_2$O.0·106Na$_2$O.0·186B$_2$O$_3$.0·605SiO$_2$ base glass containing equal amounts of Li$_2$O and Na$_2$O, to which has been added up to 12 mol% Fe$_2$O$_3$. They reported the presence of both tetrahedral Fe$^{3+}$ and octahedral Fe$^{2+}$, with the latter fraction decreasing from ~0·22 in a glass with 2·4 mol% Fe$_2$O$_3$ to ~0·12 in the 12 mol% Fe$_2$O$_3$ glass. Raman spectroscopy showed that the fraction of Si$^{[3]}$ silicon species decreased from 0·23±0·03 to 0·18±0·03 on adding 12 mol% Fe$_2$O$_3$ to the base glass, and this was accompanied by a reduction in cationic conductivity and an increase in corrosion resistance. Reference 3 also includes a review of previous NMR studies of borosilicate glasses used for the immobilisation of nuclear waste.

Fe$_2$O$_3$ is a typical nuclear waste component from the transition metal oxides and, in this paper, the neutron diffraction isotopic substitution technique is used to investigate the environment of Fe$^{2+}$/Fe$^{3+}$ cations in a borosilicate glass that also includes 12 mol% Fe$_2$O$_3$. However, the Li$_2$O in the above base glass has been replaced by Na$_2$O, to avoid the high neutron absorption cross-section of $^6$Li, the modified base glass composition being 0·210Na$_2$O.0·18511B$_2$O$_3$.0·605SiO$_2$. This same modified base glass similarly features in an accompanying study(4) of the environment of a representative rare earth (Dy$^{3+}$) cation, following the addition of 13 mol% Dy$_2$O$_3$.

The neutron diffraction experiment employs the first-order difference between samples containing natural Fe and Fe enriched in $^{57}$Fe, as in a similar investigation(5) of the environment of the same cations in a soda–lime–silica glass. The Fe$^{2+}$ cation fraction is determined by Mössbauer spectroscopy, and the distribution of basic structural unit species in the base glass is investigated by magic-angle-spinning (MAS) NMR spectroscopy, supported by thermodynamic modelling based on the model of associated solutions(6). The use of both NMR spectroscopy, via the model of Dell et al(7) (Section 1.1), and thermodynamic modelling in unravelling the complexities of neutron diffraction data for sodium borosilicate glasses has already been addressed in a series of papers(8–10) discussing the structure of four glasses of composition 2Na$_2$O.2B$_2$O$_3$.SiO$_2$, Na$_2$O.B$_2$O$_3$.SiO$_2$, ...
Na$_2$O.B$_2$O$_3$.6SiO$_2$ and Na$_2$O.B$_2$O$_3$.8SiO$_2$, to which the reader is directed for more detailed information.

1.1. Chemical nanoheterogeneity

An extremely important aspect of the structure of multicomponent glasses is that they exhibit chemical nanoheterogeneity in the form of composition fluctuations. In the case of alkali borosilicate glasses, this nanoheterogeneity involves silica-rich and alkali borate-rich regions and hence it is important to determine whether the transition metal and/or rare earth cations are associated with the silicate or borate component, since the latter is likely to be much more easily leached. It should be emphasised that these fluctuations are not phase separation, but rather represent compositional fluctuations that define the chemical structure of the glass, and are in excess of those expected for a network characterised by a spatially random distribution of borate and silicate basic structural units.

On the basis of $^{11}$B NMR data, Dell et al(7) have proposed a model for the chemical structure of sodium borosilicate glasses, based on the parameters

$$R = x_{Na_2O}/x_{B_2O_3}$$ (1)

and

$$K = x_{SiO_2}/x_{B_2O_3}$$ (2)

where $x_{Na_2O}$, $x_{B_2O_3}$ and $x_{SiO_2}$ are, respectively, the mole fractions of Na$_2$O, B$_2$O$_3$ and SiO$_2$. According to their model, which is limited to $K \leq 8$, the chemical structure is defined by four regions incorporating the following chemical groupings:

1. \{R < \frac{1}{2}\}: Na$_2$O–B$_2$O$_3$+SiO$_2$

2. \{\frac{1}{2} \leq R \leq (\frac{1}{2}+K/16)\}: Na$_2$O.2B$_2$O$_3$(sodium diborate)+Na$_2$O.B$_2$O$_3$.8SiO$_2$("reedmergnerite")+SiO$_2$

3. \{\frac{1}{2}+K/16 \leq R \leq (\frac{1}{2}+K/4)\}: Na$_2$O.2B$_2$O$_3$+xNa$_2$O.B$_2$O$_3$.8SiO$_2$

and

4. \{\frac{1}{2}+K/4 \leq R \leq (2+K)\}: Na$_2$O.2B$_2$O$_3$+2Na$_2$O.B$_2$O$_3$(sodium pyroborate)+2·5Na$_2$O.B$_2$O$_3$.8SiO$_2$+Na$_2$O.SiO$_2$(sodium metasilicate).

The Na$_2$O.2B$_2$O$_3$ chemical groupings involve equal numbers of BO$_3$ and BO$_4$ basic structural units, where O represents a bridging oxygen atom, but these do not necessarily combine to form diborate superstructural units, whilst the so-called “reedmergnerite groups” comprise a BO$_4^-$ tetrahedron linked to four SiO$_4$ tetrahedra plus an Na$^+$ network-modifying cation, yielding the composition Na$_2$O.B$_2$O$_3$.8SiO$_2$. Note, however, that this is not the composition (Na$_2$O.B$_2$O$_3$.6SiO$_2$) of the compound reedmergnerite. The xNa$_2$O.B$_2$O$_3$.8SiO$_2$ and 2·5Na$_2$O.B$_2$O$_3$.8SiO$_2$ chemical groupings consist of “modified reedmergnerite groups” with extra Na$^+$ network-modifying cations associated with nonbridging oxygen atoms on the silicate (SiOO$^-$) tetrahedra surrounding the central BO$_4^-$ tetrahedron. Of particular interest, in respect of the incorporation of the Fe$_2$O$_3$ into the present base glass, are the pyroborate (B$_2$O$_5^{4-}$) anions in the 2Na$_2$O.B$_2$O$_3$ chemical groupings in Region 4, as will become apparent in Section 4.3.

2. Experimental procedure

2.1. Sample preparation
The base glass, of composition 0·210Na2O·0·18511B2O3·0·605SiO2, was prepared using boric acid enriched (99·27%) in 11B, to avoid the high neutron absorption cross-section of 10B. Powdered sodium carbonate, enriched boric acid and silica were tumbled for approximately 2 h, and then heated with the furnace to 1350°C, in air in a platinum–rhodium (~10% Rh) crucible, at a rate of 300°C/h. The sample was quenched to the vitreous state in water and dried overnight in a drying oven, before being powdered. The enriched 57Fe isotope was the same as that in Table 2 of Ref. 5, and has a neutron scattering length of (0·284±0·010)×10−14 m, compared to (0·945±0·002)×10−14 m for NATFe. A full set of neutron scattering lengths is given in Table 1, together with the atom fractions, x, for both the base and Fe2O3-containing glasses. Similar quantities of the two Fe2O3-containing samples were prepared simultaneously, in the same furnace, to ensure that they were identical except for the different Fe isotopic compositions. High purity NATFe2O3 and 57Fe2O3 (12 mol.%) were mixed with the base glass (88 mol%) and heated with the furnace to 1350°C at a rate of 10°C/min, and then held at 1350°C for 1 h, before quenching into water and drying overnight. The atomic number densities, ρ°, of the base and Fe-containing glasses were determined from helium pycnometry to be 0·08116±0·00006 and 0·07821±0·00002 atom Å−3, respectively.

2.2. Experimental techniques

Neutron diffraction patterns were recorded for the base glass and the Fe2O3-containing samples using the D4c diffractometer[12,13] on the high-flux reactor at the Institut Laue-Langevin, at an incident wavelength of 0·5021±0·0001 Å. The data reduction closely followed that of Ref. 5, and is illustrated for the NATFe-containing sample in Figure 1, which shows the raw diffraction pattern (points) plus cubic spline fit (solid line), the corrected, normalised diffraction pattern, I(Q) (solid line) and the nuclear + paramagnetic self-scattering, I(NP)(Q) (dashed line), and the interference function, Qi(Q). The magnetic form factor, fM(Q), for the Fe3+ cations was generated from the coefficients tabulated by Brown.[14] The experimental techniques and data reduction for the Mössbauer spectroscopy and 29Si MAS NMR spectroscopy were the same as those in Ref. 5. Fits to the Mössbauer spectrum were carried out using two different methods. The first fitted two Lorentzian doublets for Fe3+ and one for Fe2+, as shown in Figure 2(A). The second used the extended Voigt-based fitting (xVBF) method: one doublet was fitted for Fe3+ and one for Fe2+, as shown in Figure 2(B). The Fe2+ fractions obtained from these fits (Lorentzian fit, 0·072±0·020; xVBF fit, 0·083±0·020) agree well within the fitting uncertainty, and can be compared to the value of 0·115±0·005 reported by Parkinson et al[1] for their glass in which half of the Na2O has been replaced by Li2O (cf. Section 1). The small measured differences in iron redox between the present fits and those reported by Parkinson et al[1] can be attributed to differences in alkali oxide constituents, melting times and/or melting temperatures. The atom fractions in Table 1 and the value of ρ° for the Fe-containing samples include allowance for the Fe2+ content.

11B MAS NMR spectra were obtained for the base glass at 14·1 T using a Bruker 600 MHz Avance II+ spectrometer operating at 192·3 MHz. A 4 mm Varian T3 probe was used with MAS frequency 12 kHz; pulse width 1 µs (~π/12) and pulse delay 4 s. The 11B MAS NMR spectrum was referenced against solid BPO4 taken as −3·3 ppm with respect to the primary reference Et2O:BF3, and peak fits were performed using the program DMfit2009.[15]

2.3. Thermodynamic modelling

Given the complexity of the interpretation of both the neutron diffraction and MAS NMR data, a thermodynamic modelling study was undertaken to predict the distribution of the basic structural
unit species in the base glass, using the model of associated solutions.\(^6\) Calculations of the chemical structure (Table 2) were performed in the same way as those for the sodium borosilicate system in Refs 9 and 16–18, and the resulting distribution of structural unit species is given in Table 3. The thermodynamic modelling data in Table 3 are presented in two different ways, \emph{viz.} separate fractions for the borate and silicate structural units, as normally quoted in NMR studies, and the combined fractions, which more accurately represent the overall structure. \{See, for example, Equations (24) and (26) of Ref. 17.\}

It is important to note that the derivation of the chemical structure (equilibrium fractions of the various chemical groupings) in Table 2, via the model of associated solutions,\(^6\) is entirely rigorous, in that it does not involve any adjustable parameters, being solely defined by the minimum Gibbs free energy for the system as a whole. The conversion of the chemical structure in Table 2 into the structural unit fractions of Table 3 is based on the assumption that the short-range structures of the chemical groupings (i.e. the structural units present) are similar to those of the corresponding crystalline phases.

3. Results

3.1. Neutron diffraction

The corrected, normalised diffraction patterns, \(I(Q)\), for all three samples are shown in Figure 3, and the data were Fourier transformed \((Q_{\text{max}}=23.4 \text{ Å}^{-1})\) to give the corresponding real-space total correlation functions, \(T(r)\). The correlation functions for the two \(\text{Fe}_2\text{O}_3\)-containing glasses are shown in Figure 4, together with their difference,

\[\Delta T(r) = x_{\text{Fe}}\Delta T_{\text{Fe}}(r)^* \quad (3)\]

where \(\Delta T_{\text{Fe}}(r)\) is the \(\text{Fe}--\text{Fe}--\text{X} \ (\text{X}=\text{Na}, \text{B}, \text{Si} \text{or O})\) difference correlation function, and that for the base glass is in Figure 5, which also includes the \(\text{Fe}--\text{Fe}--\text{X}--\text{X}\) difference correlation function, \(\Delta T_{\text{X}}(r)\). The difference, \(\Delta T(r)\), between \(\Delta T_{\text{X}}(r)\) and the correlation function for the base glass, also plotted in Figure 5, provides information on the modification of the base glass structure as a result of the introduction of the \(\text{Fe}_2\text{O}_3\) (see Section 4.3). Comparing to the base glass (Figure 5), the contribution from the \(\text{Fe}--\text{O}\) bonds can be clearly seen on the high-\(r\) side of the first \((\text{B}--\text{O}+\text{Si}--\text{O})\) peak in \(T(r)\) for the \(\text{Fe}_2\text{O}_3\)-containing samples in Figure 4.

3.2. Base glass

The composition of the base glass yields values for \(R\) and \(K\) of 1.14 and 3.27, respectively, which locates it in Region 3 of the Dell \emph{et al.}\(^7\) model, and leads to a chemical structure of the form

\[\chi_D(\text{Na}_2\text{O}.2\text{B}_2\text{O}_3) + \chi_R(x\text{Na}_2\text{O}.\text{B}_2\text{O}_3.8\text{SiO}_2) = 0.42(\text{Na}_2\text{O}.2\text{B}_2\text{O}_3) + 0.58(2.05\text{Na}_2\text{O}.\text{B}_2\text{O}_3.8\text{SiO}_2) \quad (4)\]

in which \(\chi_D=0.42\) and \(\chi_R=0.58\) are the fractions of the sodium diborate and “modified reedmergnerite” chemical groupings. The results of the thermodynamic modelling have already been given in Tables 2 and 3 (Section 2.3), and present a much more complete picture of the overall structure than that of the Dell \emph{et al.}\(^7\) model, which only considers the borate subnetwork. Thus, in addition to \(\text{Na}_2\text{O}.2\text{B}_2\text{O}_3\) and \(\text{Na}_2\text{O}.\text{B}_2\text{O}_3.6\text{SiO}_2\), the former reveals significant fractions of \(\text{Na}_2\text{O}.\text{B}_2\text{O}_3.2\text{SiO}_2, \ \text{Na}_2\text{O}.2\text{SiO}_2\) and unreacted \(\text{SiO}_2\) (Table 2), together with minor fractions of \(\text{Na}_2\text{O}.3\text{B}_2\text{O}_3, \ \text{Na}_2\text{O}.\text{B}_2\text{O}_3, \ 3\text{Na}_2\text{O}.8\text{SiO}_2, \ \text{and Na}_2\text{O}.\text{SiO}_2\). Note that the “modified reedmergnerite”

\(^*\Delta T_{\text{Fe}}(r)\) and \(\Delta T_{\text{X}}(r)\) are defined in Ref. 5.

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\(x_D\) and \(x_R\) represent the fractions of the sodium diborate and “modified reedmergnerite” chemical groupings, respectively.
(Na₂O·B₂O₃·8SiO₂) composition of the Dell et al. model is required to compensate for the absence of Na₂O·2SiO₂ and unreacted SiO₂, and that the thermodynamic modelling indicates the presence of two sodium borosilicate chemical groupings, reedmergnerite (Na₂O·B₂O₃·6SiO₂) and danburite (Na₂O·B₂O₃·2SiO₂).

As demonstrated by the thermodynamic modelling, more than two silicon species are expected for the base glass because of the possibility of Si–O–B linkages, in addition to the formation of nonbridging oxygen atoms. Therefore, a simulation of the ²⁹Si NMR peaks was undertaken, based on the predictions of the Dell et al. model and the thermodynamic modelling, plus evidence from the ¹¹B NMR spectroscopy. Figure 6 shows the ²⁹Si spectrum obtained from the base glass accompanied by the Gaussian lines used to fit the spectrum to contributions from Si⁴(₄B) and Si⁳ species. Both of these species are approximately axially symmetric and therefore each centreband has associated spinning sidebands. Fitting of the sidebands to two contributions could only be achieved by constraining their half-widths to be close to those of the centre bands. The fitted peak parameters are summarised in Table 4.

The ¹¹B spectrum (Figure 7) is typical of spectra reported for glasses of similar composition; i.e. with similar values of R (1·14) and K (3·27). The two peaks in the spectrum are from boron nuclei in 4-coordinated (~0 ppm) and 3-coordinated sites (~17 ppm). The fraction, x₄, of the boron atoms that are 4-fold co-ordinated can be obtained by integrating the area under the B⁴ peak and taking its ratio to the area under the entire central (½↔½) spectrum. However, the area under the 3-coordinated boron B³ peak has to be corrected for loss of signal into the satellite transitions. At high fields and rapid rotation, this correction is small (~4%) and a final value of 0·75±0·04 is obtained for x₄. The Dell et al. model predicts that

x₄=½+K/16=0·704

(5)

for this composition. There are in fact several contributions to the B⁴ and B³ peaks. In their studies of similar sodium borosilicates, Du & Stebbins fitted peaks to sites corresponding to B³_ring, B³_non-ring and B⁴ with different numbers of next-nearest neighbour silicon atoms, namely B⁴(B,3Si) and B⁴(4Si). In the case of the B⁴ peak manifold, the values of the quadrupole coupling constant, C_Q, are small, and the individual peak line shapes can be approximated as Gaussian–Lorentzian, with the Gaussian:Lorentzian ratio fixed at 0·7. Two peaks were used to simulate the B⁴ contribution. The values of C_Q for the B³ peaks are typically ~2·5 MHz, and thus the B³ manifold must be simulated using two quadrupole line peak shapes, with asymmetry parameter, η, fixed at 0·2, representing B³_ring and B³_non-ring. Table 5 presents the results of this peak fitting. The parameters shown are reasonable consistent with those from Du & Stebbins, given that their nearest sodium borosilicate composition to the current study has K=4 and R=0·75.

There are five possible contributions to the first peak in T(r) for the base glass, viz. from B–O and B–O− bonds for trigonal boron atoms, from B–O bonds for tetrahedral boron atoms, and from Si–O and Si–O− bonds, where O− represents a negatively-charged nonbridging oxygen atom. The situation is further complicated by the systematic variation of the bond lengths both within borate and silicate basic structural units, and when borate structural units are incorporated into superstructural units, as discussed in Refs 10, 21 and 22. The extent of this variation can be seen from Table 6, which shows the average bond lengths for independent borate and silicate structural units, calculated from the data for crystalline B₂O₃, SiO₂, alkali borates, alkali silicates and reedmergnerite in Table 2 of Ref. 10. Hence there are too many overlapping peaks to extract meaningful bond lengths, root mean square (RMS) bond length variations and co-ordination numbers for each contribution. It was
therefore decided to perform a two-peak fit, to provide a guide as to the changes in the structure of the base glass occurring on the introduction of the Fe2O3.

The two-peak fit to the base glass is shown in Figure 8(A), and the peak parameters are summarised in Table 7. However, whilst the lower-\(r\) peak from this fit will be dominated by B–O and B–O\(^{-}\) bonds, and the higher-\(r\) peak by Si–O and Si–O\(^{-}\) bonds, peak overlap/intermixing means that these peaks cannot be ascribed to a particular bond type, which means that the uncertainties in the individual peak parameters are irrelevant, and hence are not quoted in Table 7. It is important to note that the fit involves two symmetric peaks, whereas the peaks arising from the borate and silicate basic structural units will certainly not be symmetric, due to the presence of more than one type of bond in each case. The quality/accuracy of the fit is given by the \(R_\chi\) factor (Table 7), and can be seen from the peak fit residual {Figure 8(A)}. For convenience, henceforth the lower-\(r\) peak will be referred to as the B(O) peak and the higher-\(r\) peak as the Si(O) peak, even though there is almost certainly some intermixing. No attempt was made to fit the second peak in \(T(r)\), which includes contributions from Na\(^{-}\)-O bonds to nonbridging oxygen atoms, Na\(^{+}\) distances and O–O distances within the various borate and silicate structural units. The results of the two-peak fit will be discussed in Section 4.3, together with a similar fit to \(\Delta T_X(r)\) {Figure 8(B)}.

### 3.3. Fe–Fe+Fe–X correlation function

As in Ref. 5, the calculation of the difference, \(x_{Fe} \Delta T_{Fe}(r)\), between the correlation functions for the \(^{57}\text{Fe}\)-containing samples included a small (~2%) renormalisation of the diffraction pattern for the \(^{57}\text{Fe}\)-containing glass, due to the extremely large uncertainty (30%; cf. Table 2 of Ref. 5) on the total scattering cross-section for the \(^{57}\text{Fe}\) isotope. The Fe–Fe+Fe–X correlation function, \(\Delta T_{Fe}(r)\), is non-zero after the first (Fe–O) peak, suggesting that there is no well-defined cut-off distance for the first Fe(O) co-ordination shell. The peaks at \(\sim 3.25\) and \(\sim 4.4\) Å are mainly due to Fe–B/Si/Na and Fe–(2)O interactions, respectively. A 2-peak fit (Figure 9 and Table 8) to the first Fe–O peak gives a total co-ordination number, \(n_{Fe(O)}\), of 4.88±0.20, the increased uncertainty being due to that on the neutron scattering length for the \(^{57}\text{Fe}\) isotope of \(\pm 0.01 \times 10^{-14}\) m (Table 1). The average Fe–O bond lengths, \(r_{Fe-O}\), are 1.895 Å {between tetrahedral (1.85 Å) and either 5-fold (1.94 Å) or octahedrally (2.00 Å) co-ordinated Fe\(^{3+}\) – see Table 1 of Ref. 5} and 2.182 Å {\(\text{cf.}\) 5-fold (2.06 Å) and octahedrally (2.14 Å) co-ordinated Fe\(^{2+}\) cations}, respectively, the root mean square (rms) bond-length variations, \(<u_{Fe-O}^2>^{1/2}\), being 0.079 and 0.041 Å.

The 2-peak fit in Figure 9 does not include all of the area between the first and second peaks, as may be seen from the peak-fit residual. This extra area may include contributions from longer Fe–O bonds, Fe–Fe and/or Fe–X distances. As in Ref. 5, therefore, a further fit was performed, adding an extra broad \(<u_{Fe-O}^2>^{1/2}=0.2\) Å peak at 2.48 Å, such that the low-\(r\) tail of the peak at \(\sim 3.25\) Å reduced smoothly to zero at \(\sim 2.55\) Å. The assignment of at least part of this extra area to longer Fe–O bonds is consistent with the longest Fe–O bond length of 2.537 Å (octahedral Fe\(^{3+}\) cations) in iscorite (\(\text{Fe}_7\text{SiO}_{10}\)),\(^{23}\) whilst the total area corresponds to an increase in the total average Fe(O) co-ordination number to 5.34. The Fe(O) co-ordination number was also estimated from the integrated area under \(r \Delta T_{Fe}(r)\), assuming that all of this area is due to Fe–O bonds (\(\text{cf.}\) Ref. 5). The running co-ordination number from 1.5 Å to \(r\) is shown in Figure 10, as a function of \(r\). The minimum in \(r \Delta T_{Fe}(r)\) is at \(\sim 2.46\) Å; and the average co-ordination number for the range 1.50–2.46 Å is 5.00.

### 3.4. Fe–Fe+X–X correlation function
The Fe–Fe+X–X first-order difference correlation function, \( \Delta T_X(r) \), is plotted in Figure 5, divided by the base glass fraction (0.88). This is to allow subtraction of the base glass correlation function to give the curve denoted \( \Delta T(r) \), which can be interpreted in terms of the change in the structure of the base glass caused by the introduction of Fe\(_2\)O\(_3\). As in the case of \( \Delta T_{Fe}(r) \), it was necessary to apply the same correction to the magnitude of the correlation function for the \(^{57}\)Fe-containing sample. The Fe–Fe+X–X correlation function shows the first peak in \( T(r) \) for the Fe-containing glass without interference from the Fe–O peak, and so a two-peak fit {Figure 8(B)} was performed, similar to that for the base glass, the parameters being given in Table 7.

4. Discussion

4.1. Structure of base glass

Denoting the overall structural unit fractions in the base glass as \( x_{B4}, x_{B3}, x_{B2}, x_{Si4}, x_{Si3} \), and \( x_{Si2} \), where the subscript indicates the network-forming cation plus the number of bridging oxygen atoms, the total number of negative charges per composition unit (c.u.) is equal to the number of Na\(^+\) cations per c.u.:

\[
2x_{Na2O} = x_{B4} + x_{B2} + x_{Si3} + 2x_{Si2} = 0.420 \quad (6)
\]

The \(^{11}\)B NMR data indicate that the fraction of the boron atoms, \( x_4 \), that are tetrahedrally coordinated is

\[
x_4 = x_{B4}/2x_{B2O3} = 0.75 \pm 0.04 \quad (7)
\]

This is slightly higher than the value (0.72 \pm 0.03) obtained from the thermodynamic modelling, and higher than predicted by the Dell et al\(^7\) model, but there is no evidence for the existence of BOO\(^-\)\(_2\) basic structural units within the experimental uncertainty. It is also higher than the 0.69 \pm 0.04 observed for the waste-form glass in which half of the Na\(_2\)O is replaced by Li\(_2\)O\(^3\), although this reflects the findings of the study by Zhong et al\(^{24}\) that \( x_4 \) is significantly smaller (typically 25% less for the present values of \( K \) and \( R \)) for lithium borosilicate as compared to sodium borosilicate glasses.

If it is assumed that neither BOO\(^-\)\(_2\) nor SiO\(_2\)O\(^2-\) structural units are present, then the \(^{11}\)B NMR data yield

\[
x_{B4} = 2x_4x_{B2O3}/(2x_{B2O3} + x_{SiO2}) = 0.285 \pm 0.015 \quad (8)
\]

\[
x_{B3} = 2x_{B2O3}/(2x_{B2O3} + x_{SiO2}) - x_{B4} = 0.094 \pm 0.015 \quad (9)
\]

\[
x_{Si3} = 2x_{Na2O}/(2x_{B2O3} + x_{SiO2}) - x_{B4} = 0.146 \pm 0.015 \quad (10)
\]

and

\[
x_{Si4} = x_{SiO2}/(2x_{B2O3} + x_{SiO2}) - x_{Si3} = 0.475 \pm 0.015 \quad (11)
\]

A comparison of these structural unit fractions with those from the thermodynamic modelling in Table 3 reveals excellent agreement, well within their combined uncertainties. Thus approximately \( 2/3 \) of the Na\(^+\) cations are associated with BO\(_4\) tetrahedra, and \( \sim 1/3 \) are compensated by nonbridging oxygen atoms on SiO\(_3\) structural units. This is in accordance with the chemical natures of B\(_2\)O\(_3\) and SiO\(_2\), in that the alkaline oxide, Na\(_2\)O, preferably interacts with the more acidic B\(_2\)O\(_3\), rather than the less acidic SiO\(_2\).
The relative intensities (Table 4) of the two fitted peaks (including sidebands) in the $^{29}$Si spectrum in Figure 6 are consistent with the above values of $x_{Si3}$ (0·146) and $x_{Si4}$ (0·475), which correspond to approximate Si$^{[3]}$ and Si$^{[4]}$ fractions of 0·23 and 0·77, respectively. The chemical shifts observed are also close to the values reported in the literature. Si$^{[3]}$ is generally quoted as having a shift of about −90 ppm and Bunker et al.$^{(25)}$ reported a chemical shift of −105 ppm for Si$^{[4]}$(B,3Si) compared to −110 ppm for Si$^{[4]}$(4Si). Table 9 shows the results of calculating the average Si(B) co-ordination number using the thermodynamic prediction of the chemical groupings present, assuming that the Si$^{[4]}$ species in silica have zero boron next-nearest neighbours whilst those in the danburite and reedmergnerite groupings have the same $n_{SiB}$ as Si$^{[4]}$ in the crystals (3 and 4/3, respectively). It also assumes that any Si$^{[4]}$…B$^{[3]}$ next nearest neighbours can be neglected, i.e. that B$^{[3]}$ structural units are part of the borate network only. The peaks in the $^{29}$Si NMR spectrum of the base glass can then be assigned as follows: The peak at −88 ppm consists of the Si$^{[3]}$ contribution with Si$^{[2]}$ being too weak to discriminate. It is thought that the nonbridging oxygen on the Si$^{[3]}$ structural unit makes it unlikely that the negatively charged B$^{[4]}$ units would be a neighbouring unit, and so Si$^{[3]}$(B) can be neglected at this composition. The peak at −100 ppm in Figure 6 contains the Si$^{[4]}$ contributions from the chemical groupings indicated in Table 9, each of which provides a different value for $n_{SiB}$. There is insufficient information in the spectrum to be able to discriminate the individual contributions, but the centre of gravity of the peak can be estimated from the chemical shifts of the spectra of the pure chemical groupings, weighted by the relative abundances of their various Si$^{[4]}$ units. The relevant chemical shifts can be taken as −110 ppm for Si$^{[4]}$ in silica; −102 ppm for Si$^{[4]}$ in reedmergnerite {a mix of Si$^{[4]}$(B,3Si) and Si$^{[4]}$(2B,2Si)}, and −90 ppm for Si$^{[4]}$(3B,Si) in danburite. The values for reedmergnerite and danburite were determined for vitreous sodium preparations$^{(26)}$ of the two compounds, although these are not ideal analogues, since they contain ~30% B$^{[3]}$. The contribution from trisodium octasilicate is considered insignificant. The calculated centre of gravity of the composite peak is therefore at −101±2 ppm, consistent with the observed −100±1 ppm.

4.2. Fe$^{2+}$/Fe$^{3+}$ cation environment

The Mössbauer spectroscopy has confirmed that the iron in the present glasses is highly oxidised, such that the Fe$^{2+}$ fraction is only 0·072±0·020 (Lorentzian fit) or 0·083±0·020 ($x$VBF fit), with the large majority of the iron being present as Fe$^{3+}$. The Fe$^{2+}$ fraction has been calculated from the spectral areas, and assumes that the recoil-free fraction is the same for Fe$^{2+}$ and Fe$^{3+}$ cations in these glasses. The spectrum was satisfactorily fitted by both methods. The first used three Lorentzian doublets; one representing the Fe$^{2+}$ and two the Fe$^{3+}$ cations. The centre shifts (CS) obtained for the two Fe$^{3+}$ doublets are 0·13±0·02 and 0·35±0·02 mm s$^{-1}$. The first CS (fractional area 0·340) is nearer the lower boundary of the tetrahedral regime (0·10–0·35 mm s$^{-1}$ $^{(27)}$), and the second (fractional area 0·588) is at the upper boundary of the tetrahedral regime and close to the lower boundary for Fe$^{3+}$ in octahedral co-ordination (0·3–0·5 mm s$^{-1}$ $^{(27)}$). Quadrupole splitting (QS) and linewidth (LW) parameters for the two Fe$^{3+}$ doublets are (doublet 1) 0·96±0·02 and 0·19±0·02 mm s$^{-1}$, and (doublet 2) 0·96±0·02 and 0·24±0·02 mm s$^{-1}$, respectively. The CS, QS and LW for the Fe$^{2+}$ doublet are 0·95±0·02 mm s$^{-1}$, 2·16±0·02 mm s$^{-1}$ and 0·25±0·02 mm s$^{-1}$. The alternative fitting of the Mossbauer spectra, using extended Voigt-based fitting ($x$VBF), shown in Figure 2(B), involves two doublets, one for Fe$^{3+}$ and one for Fe$^{2+}$, the Lorentzian HWHM linewidths being 0·16 mm s$^{-1}$. The Fe$^{3+}$ doublet yields CS=0·26±0·02 mm s$^{-1}$, with sigma=0·11 mm s$^{-1}$; QS=0·94±0·02 mm.s$^{-1}$, with sigma=0·25 mm s$^{-1}$, and a fractional area of 0·9172. The Fe$^{2+}$ doublet has
CS = 0.82±0.02 mm s\(^{-1}\), with sigma constrained at 0·20 mm s\(^{-1}\), and a fractional area of 0·0828. Arguably, the quality of fit is greater for the xVBF model than the Lorentzian model. This is consistent with the presence of a distribution of co-ordination sites which can be better represented by an xVBF model. The fitted CS and QS parameters from the xVBF fit are consistent with a major proportion of Fe\(^{3+}\) cations occupying tetrahedrally-coordinated sites\(^{(27)}\), although the values of sigma also support the presence of some fraction of higher co-ordinated sites which can be expected to be 5- and/or 6-fold co-ordinated. For both the Lorentzian and xVBF models, the CS and QS for the fitted doublets, the relative doublet areas, and their associated linewidths combine to indicate a distribution of site parameters around an average co-ordination number for the Fe\(^{3+}\) cations of circa 5, and an average co-ordination number for the Fe\(^{2+}\) cations of \(~6\). These results are entirely consistent with those from the neutron diffraction data.

The site distributions for iron in glasses have received considerable attention in the literature, but it is important to realise that such studies have considered a wide range of glass compositions, iron contents, and redox conditions, and so direct comparisons must be carried out with caution. Wilke et al\(^{(28)}\) have studied the Fe(O) co-ordination number for Fe\(^{2+}\) and Fe\(^{3+}\) cations in a wide range of minerals, and find that in the vast majority of cases these cations are in either 4- or 6-fold co-ordination. They do, however, quote one example for Fe\(^{2+}\) \{grandidierite; (Mg,Fe)Al\(_3\)(BO\(_4\))(SiO\(_4\))O\} and one for Fe\(^{3+}\) \{yoderite; (Mg,Al,Fe\(_8\))Si\(_4\)(O,OH)\(_{20}\)\} cations where the iron is 5-fold co-ordinated. On the other hand, there are several reports of 5-fold co-ordination in the vitreous state. For example, Rossano et al\(^{(29,30)}\) have employed a combination of EXAFS spectroscopy and molecular dynamics simulations to investigate the environment of the Fe\(^{2+}\) cations in vitreous CaO·FeO·2SiO\(_2\), and conclude that they occupy distorted sites, whose geometry varies continuously from a tetrahedron to a triangular bipyramid.

The work of Weigel et al\(^{(31,32)}\) on the structure of vitreous Na\(_2\)O·Fe\(_2\)O\(_3\)·4SiO\(_2\) has already been discussed in Ref. 5, where it is compared to that on a soda–lime–silica (0·127Na\(_2\)O·0·162CaO·0·711SiO\(_2\)) glass containing 12 mol\% Fe\(_2\)O\(_3\). Both studies conclude that the largest fraction of the iron is present as Fe\(^{3+}\) cations in tetrahedral co-ordination, but Weigel et al\(^{(31,32)}\) propose that the remaining Fe\(^{3+}/Fe^{2+}\) cations are in 5-fold co-ordination, whereas Wright et al\(^{(5)}\) find that they are in 6-fold co-ordination. A possible explanation of this discrepancy is given below. Weigel et al\(^{(33)}\) have also investigated a series of Na\(_2\)O·xFe\(_2\)O\(_3\)·(1–x)Al\(_2\)O\(_3\)·4SiO\(_2\) glasses in which Al\(_2\)O\(_3\) is progressively substituted for Fe\(_2\)O\(_3\), and reach the same conclusion as to the co-ordination state of the iron; i.e. 4- and 5-fold.

The 2-peak fit to the Fe–Fe+Fe–X difference correlation function discussed in Section 3.3 that the accuracy to which the Fe\(^{2+}/Fe^{3+}\) cation environments can be deduced is limited by the assignment given to the extra area between the first and second peaks in \(\Delta T_{Fe}(r)\). First, therefore, the 2-peak fit will be considered in isolation, and then the possible interpretations of this extra area. In analysing the co-ordination numbers in Table 8, it is important to understand that they are the co-ordination numbers averaged over all of the Fe atoms in the sample. The second peak from the 2-peak fit is at 2·182 Å, which is at a significantly higher \(r\) than the mean Fe\(^{2+}\)–O bond length (2·14 Å) for octahedral co-ordination in Table 1 of Ref. 5. If the assignment of this peak solely to Fe\(^{2+}\)–O bonds were correct, the Fe\(^{2+}\) cation fraction of 0·072 would yield an Fe\(^{2+}\)\(_2\)(O) co-ordination number of 8·1 (0·58/0·072), greatly in excess of the expected value of 6·0; i.e. this peak must also include a contribution from Fe\(^{3+}\)–O bonds. It can, however, be concluded that the vast majority of the Fe\(^{2+}\) cations are likely to be in octahedral co-ordination. The position of the first peak (1·895 Å) indicates that a significant fraction of the Fe\(^{3+}\) cations must be in tetrahedral co-ordination but, to extract their fraction, it is necessary to consider the total area under the two peaks,
which yields an overall average Fe(O) co-ordination number of 4·88. The remainder of the Fe$^{3+}$
cations may be in either 5-fold or 6-fold (octahedral) co-ordination. Assuming the latter leads to an
upper limit for the fraction of the Fe$^{3+}$ cations that are in tetrahedral co-ordination of 0·60.
Alternatively, in terms of the total Fe content, the overall fractions are: tetrahedral Fe$^{3+}$ 0·56;
octahedral Fe$^{3+}$, 0·37 and octahedral Fe$^{2+}$, 0·07. At the opposite extreme, it is possible to assume
that the remaining Fe$^{3+}$/Fe$^{2+}$ cations are 5-fold co-ordinated, as proposed by Weigel et al.$^{31,32}$
for vitreous Na$_2$O·Fe$_2$O$_3$·4SiO$_2$. In this case the overall average Fe(O) co-ordination number of 4·88
reduces the fraction of the Fe$^{3+}$ cations in tetrahedral co-ordination to only 0·12, which is much
lower than inferred by the Mössbauer data and the position of the first peak in the fit to $\Delta T_{Fe(r)}$.

To extract the total Fe(O) co-ordination number, Weigel et al.$^{32}$ fit three Gaussian peaks to the
real-space correlation function for their NATFe-containing sample (Ref. 32, Figure 2 and Table 4)
to extract an average Si–O bond length of 1·63 Å, and Fe–O distances of 1·87 and 2·01 Å, the
corresponding co-ordination numbers being 3·9, 3·2 and 1·0, respectively. However, the fit does not
include the real space peak function, $P(r)$, and hence the peak areas (co-ordination numbers) do not
include the satellite features on either side of the central maximum. Weigel et al.$^{32}$ also performed a
single-Gaussian fit to the first peak in $\Delta T_{Fe(r)}$, to yield an average Fe–O distance of 1·89 Å, and a
total Fe(O) co-ordination number of 4·3 (cf. 4·2 for the 3-peak fit). In this connection, it is
important to note that, whereas the latter peak appears symmetric, the corresponding peak in the
present study is asymmetric, having a tail to high $r$, with the result that the second fitted peak is also
moved to significantly higher $r$ (2·182 Å). This, together with the higher average Fe(O) co-
modation number of 4·88, compared to 4·2 for vitreous Na$_2$O·Fe$_2$O$_3$·4SiO$_2$,$^{32}$
again indicates a large fraction of 6-fold co-ordinated Fe$^{3+}$/Fe$^{2+}$ cations in the present glasses. In respect of the use
of EXAFS spectroscopy in studying the environment of cations with highly distorted first co-
ordination shells, it is also worth pointing out that EXAFS spectroscopy is much less sensitive to
broad distributions of inter-atomic distances than are diffraction techniques$^{34}$ and hence to the
presence of a high-$r$ tail, such as that in Figure 9.

The Fe$^{3+}$ tetrahedral fraction of 0·56, calculated assuming no 5-fold co-ordination, is clearly an
overestimate, given the high-$r$ tail of the first peak in $\Delta T_{Fe(r)}$ and the fact that $\Delta T_{Fe(r)}$ is non-zero
between the first and second peaks. The most likely scenario is that the remaining Fe$^{3+}$/Fe$^{2+}$
cations (i.e. excluding the tetrahedrally co-ordinated Fe$^{3+}$ cations) have a distorted octahedral first co-
nordination shell with at least some of the extra area from the 3-peak fit being due to long Fe$^{3+}$–O or
Fe$^{2+}$–O bonds. If all of the extra area is assigned to Fe–O bonds, and in the absence of 5-fold co-
nordination, the Fe$^{3+}$ tetrahedral fraction is reduced to 0·33 (octahedral Fe$^{3+}$, 0·60 and octahedral
Fe$^{2+}$, 0·07), but this is certainly an underestimate, since some of the extra area will be due to
interactions other than Fe–O bonds. Finally, the co-ordination number from the integrated area
under $r\Delta T_{Fe(r)}$ between 1·50 and 2·46 Å is 5·00 (tetrahedral Fe$^{3+}$ 0·50; octahedral Fe$^{3+}$, 0·43 and
octahedral Fe$^{2+}$, 0·07). Taken together, these thee estimates yield a "best" value for the average
Fe(O) co-ordination number of 5·1±0·2, leading to the following cation fractions: tetrahedral Fe$^{3+}$
0·45±0·10; octahedral Fe$^{3+}$, 0·48±0·10 and octahedral Fe$^{2+}$, 0·07±0·01.

4.3. Modification of base glass structure

The effect of the addition of Fe$_2$O$_3$ on the structure of the base glass is best seen from the $\Delta T_X(r)$ —
base glass difference correlation function, $\Delta T(r)$ in Figure 5. The "reverse-curve" structure in the
region of the various boron–oxygen and silicon–oxygen bond lengths (maximum at 1·29 Å and
minimum at 1·54 Å), together with the peak fit parameters in Table 7, strongly suggest a reduction
in the fraction, $x_4$, of the boron atoms that are 4-fold co-ordinated, and an increase in the fraction of

\[ x_4 \]
trigonal borate structural units with nonbridging oxygen atoms. The minimum at 2·47 Å in $\Delta T(r)$ is also consistent with the conversion of BO$_4^-$ tetrahedra into trigonal borate structural units, in that it reflects the reduction in the number of intra-structural unit O–O distances. The O–O distance for a regular BO$_4^-$ tetrahedron, with a B–O bond length of 1·468 Å (Table 6) is 2·397 Å. The average co-ordination number for the B(O) peak is reduced from 3·89 to 3·43, and the average bond length from 1·477 to 1·427 Å. These bond lengths should be compared to the average value for BO$_4^-$ tetrahedra (1·468 Å) and those for the B–O and B–Ø bonds in trigonal borate structural units in Table 6. On the other hand, the smaller increase in the average bond length for the Si(O) peak, from 1·617 to 1·627 Å, suggests a slight increase in the number of Si–O relative to Si–Ø bonds, although this may be due to a change in the level of intermixing between the two peaks. The average Si–O and Si–Ø bond lengths in crystalline $\alpha$-Na$_2$O.2SiO$_2$ (35) and $\beta$-Na$_2$O.2SiO$_2$ (36) are 1·634 and 1·579 Å, respectively. It therefore appears that the modification of the base glass structure on the incorporation of the Fe$_2$O$_3$ mainly involves the replacement of the negatively-charged BO$_4^-$ tetrahedra with negatively-charged nonbridging oxygen atoms. This strongly suggests that the majority of the Fe$^{3+}$/Fe$^{2+}$ cations are associated with borate structural units; i.e. that they are predominantly to be found in borate chemical groupings.

The peak in $\Delta T(r)$ (Figure 5) at 2·99 Å is due to the O–O distances within the Fe$^{2+}$ and Fe$^{3+}$ co-ordination polyhedra. Assuming the Fe–O bond lengths for silicate systems in Table 1 of Ref. 5, and regular octahedral co-ordination of the oxygen atoms around the Fe$^{2+}$ and Fe$^{3+}$ cations, yields O–O distances of 3·03 and 2·83 Å, respectively, whereas regular FeO$_4^-$ tetrahedra give rise to an O–O distance of 3·02 Å. A guide as to the expected interatomic distance between the Fe$^{3+}$ cations and the negatively-charged nonbridging oxygen atoms on the triangular borate structural units can be gleaned from the crystalline structures of ferric orthoborate, FeBO$_3$ (or Fe$_2$O$_3$.B$_2$O$_3$), (37,38) and Fe$_3$BO$_6$ (3Fe$_2$O$_3$.B$_2$O$_3$). (39,40) Ferric orthoborate (37,38) has the calcite structure, consisting of Fe$^{3+}$ cations plus BO$_3^-$ orthoborate anions. The Fe$^{3+}$ cations are 6-fold co-ordinated with a single Fe–O distance of 2·028 Å, which for regular octahedral co-ordination yields an O–O distance of 2·87 Å, and the B–O bond length for the BO$_3^-$ anions is 1·379 Å (38). The structure of Fe$_3$BO$_6$ is based on BO$_4^-$ anions, and there are two Fe$^{3+}$ cations in the asymmetric unit, both of which are in (distorted) octahedral co-ordination. (39,40) The Fe$^{3+}$–O$^-$ distances for the first Fe$^{3+}$ cation range from 1·904 to 2·132 Å (mean 2·023 Å), and those for the second from 1·864 to 2·227 Å (mean 2·055 Å). (40) The B–O bond lengths for the BO$_4^-$ anions lie between 1·439 and 1·504 Å (mean 1·485 Å). (40)

No crystalline borate phases have been reported with tetrahedrally co-ordinated Fe$^{3+}$ cations; i.e. with a network incorporating FeO$_4^-$ structural units. A network with adjacent BO$_4^-$ and FeO$_4^-$ structural units is unlikely to be stable, since both structural units are negatively charged, and so there are two possible locations for the tetrahedrally co-ordinated Fe$^{3+}$ cations. Either the FeO$_4^-$ units are incorporated into a network of trigonal borate structural units, or they are present in silicate chemical groupings, as in the case of the tetrahedrally co-ordinated Fe$^{3+}$ cations in the soda–lime–silica glass of Ref. 5. In either case, the negative charge on the FeO$_4^-$ structural units must be balanced by a positively charged Na$^+$ network modifying cation. However, there appear to be no crystalline Na$_2$O–Fe$_2$O$_3$–B$_2$O$_3$ crystalline phases, which strongly suggests that the tetrahedrally co-ordinated Fe$^{3+}$ cations are almost certainly located in silicate chemical groupings. The slight increase in the average bond length for the Si(O) peak may be due to the replacement of Si–O bonds to nonbridging oxygen atoms with Si–Ø–Fe linkages to FeO$_4^-$ tetrahedra.
Given that the tetrahedrally co-ordinated Fe$^{3+}$ cations seem to be associated with silicate chemical groupings, combined with the fact that there are no known Na$_2$O–Fe$_2$O$_3$–B$_2$O$_3$ crystalline phases, leads to the conclusion that the Fe$^{3+}$ cations are most likely to be present in FeBO$_3$ chemical groupings; i.e. as octahedrally co-ordinated Fe$^{3+}$ cations associated with BO$_3^{3-}$ orthoborate anions. The boundaries between the FeBO$_3$ chemical groupings and the other chemical groupings that make up the borosilicate network would then involve BO$_2$Ø$_2^{−}$, BOØ$_2^{−}$ and possibly SiOØ$_3^{−}$ basic structural units. This association of the octahedrally co-ordinated Fe$^{3+}$ “network-modifying” cations with isolated BO$_3^{3−}$ orthoborate anions, rather than a borate network, is entirely consistent with the presence of B$_2$O$_5^{4−}$ pyroborate anions in Region 4 of the Dell et al$^{(7)}$ model; i.e. at the highest network-modifying cation content. As a result, the octahedrally co-ordinated Fe$^{3+}$ cations will be much more easily leached than those that are tetrahedrally co-ordinated, and incorporated into the network of silicate chemical groupings.

Finally, the question arises as to the location of the octahedrally co-ordinated Fe$^{2+}$ cations. The only crystalline ferrous borate phase known to the authors is the pyroborate, Fe$_2$B$_2$O$_5$, which is isostructural with triclinic Mg$_2$B$_2$O$_5$, Mn$_2$B$_2$O$_5$ and Co$_2$B$_2$O$_5$.$^{(41)}$ The structure of Mg$_2$B$_2$O$_5$.$^{(41)}$ is formed from Mg$^{2+}$ cations and B$_2$O$_5^{4−}$ pyroborate anions, with two symmetrically-distinct Mg$^{2+}$ cations octahedrally co-ordinated by oxygen atoms. One Mg$^{2+}$ cation has six nonbridging oxygen atom neighbours, whereas the first co-ordination shell of the second includes five nonbridging and one bridging oxygen atom (the central oxygen atom of the pyroborate anion). Unfortunately, however, structural parameters (Fe–O distances) have not been reported for Fe$_2$B$_2$O$_5$, but the existence of this crystalline phase does suggest that the Fe$^{2+}$ cations are associated with independent borate (pyroborate and/or orthoborate) anions. One possibility is that disorder within the FeBO$_3$ chemical groupings leads to non-stoichiometry, with some of the Fe$^{3+}$ cations being replaced by Fe$^{2+}$ cations.

4.4. Comparison with vitreous Na$_2$O–CaO–Fe$_2$O$_3$–SiO$_2$.$^{(5)}$

It is interesting to compare the effect of the added Fe$_2$O$_3$ on the structure of the present sodium borosilicate glass with that on the structure of the soda–lime–silica glass in Ref. 5. The $\Delta T_X(r)$ – base glass difference correlation functions, $\Delta T(r)$, for the two glasses are shown in Figure 11, and $\Delta T_{Fe}(r)$ in Figure 12. Whilst the peak positions and structure in $\Delta T(r)$ at higher $r$ (Figure 11; $r>4$ Å) are remarkably similar, two important differences are worthy of note in respect of the present glasses: First, the structure in $\Delta T(r)$ around the first peak in $T(r)$ for the corresponding base glass is considerably more pronounced, reflecting the much greater change in the distribution of basic structural unit species; i.e. the conversion of negatively-charged BO$_4^{−}$ tetrahedra into triangular borate structural units with nonbridging oxygen atoms. Second, the average density contribution to $\Delta T(r)$ is negative, whereas it is positive for the soda–lime–silica glasses. This is consistent with the fact that, for the sodium borosilicate glass, the average atomic number density decreases from 0.08116 to 0.07821 atoms Å$^{-3}$ on the addition of Fe$_2$O$_3$ but, for the soda–lime–silica glass,$^{(5)}$ it increases from 0.07278 to 0.07497 atoms Å$^{-3}$.

A much better guide as to the effect of the addition of Fe$_2$O$_3$ on the vitreous network is to consider the average network number density $\rho_{N°}$, which is the average number of network structural units (s.u.) per unit volume. In both cases, $\rho_{N°}$ decreases with the incorporation of the Fe$_2$O$_3$, as expected; i.e. the network expands to accommodate the Fe$_2$O$_3$. For the sodium borosilicate glass, it decreases by 19.7%, from 0.02348 to 0.01886 s.u. Å$^{-3}$, and for the soda–lime–silica glass it decreases by 16.5%, from 0.01823 to 0.01522 s.u. Å$^{-3}$. (Note that these network number densities do not include
the FeO₄− tetrahedra incorporated into the network of the Fe₂O₃-containing glasses.) A possible explanation for the slightly larger reduction for the present glasses is that the replacement of 4-connected BO₄− tetrahedra by trigonal borate structural units with nonbridging oxygen atoms leads to a more open (less compact) network.

The Fe−Fe+Fe−X correlation function, ∆T_Fe(r), which mainly consists of Fe−X interactions, is also very similar to that for the Na₂O−CaO−Fe₂O₃−SiO₂ glass in Ref. 5, as may be seen from Figure 12. However, again there are some significant differences when the present Na₂O−Fe₂O₃−B₂O₃−SiO₂ glass is compared to vitreous Na₂O−CaO−Fe₂O₃−SiO₂:

1. The first (Fe−O) peak is at slightly lower r, with an increased area, but the peak widths are very similar, reflecting the lower Fe³⁺ fraction and the fact that the octahedrally co-ordinated Fe³⁺/Fe²⁺ cations are now incorporated into borate chemical groupings.

2. The maximum of the peak between 3·0 and 3·5 Å, which mainly involves Fe−Na, Fe−B and Fe−Si distances, is at lower r, and the peak has an increased width, due to the presence of Fe−B interactions.

3. The {predominantly Fe−(2)O} peak at 4·4 Å is also broader, with the suggestion of a low-r shoulder, although the position of the maximum is exactly the same (4·41 Å), as a result of the wider range of Fe³⁺ cation environments.

4. The average density contribution to ∆T_Fe(r) is larger, due to the combined effect of the higher atomic number density, ρ°, and the different neutron scattering lengths, [ ], for the constituent atoms.

All of these differences can be accounted for by the fact that the Fe³⁺/Fe²⁺ cations are now present in both borate and silicate chemical groupings, rather than just silicate chemical groupings, as in the case of the Na₂O−CaO−Fe₂O₃−SiO₂ glass.(5)

5. Conclusions

It can therefore be concluded that the present data for the Fe₂O₃-containing Na₂O−¹¹B₂O₃−SiO₂ glasses are consistent with a fraction of 0·45±0·10 of the iron being present as network-forming FeO₄− tetrahedra, each associated with an Na⁺ network-modifying cation. The remaining iron is most likely to be predominantly in octahedral co-ordination, and exists as both Fe³⁺ (0·48±0·10) and Fe²⁺ (0·07±0·01) network-modifying cations. However, the presence of a minor fraction of 5-fold co-ordinated Fe²⁺ and/or Fe³⁺ network-modifying cations cannot be eliminated.

The chemical nanoheterogeneity of borosilicate glasses may be thought of as consisting of a transition from B₂O₃ regions containing boroxol groups, through borate regions containing superstructural units such as triborate, pentaborate and diborate groups, followed by borosilicate regions with 4-membered rings similar to those in danburite and reedmergnerite, then silicate regions involving Si[3] and Si[4] basic structural units, and finally to SiO₂ regions with only Si[4] units. The presence and relative dimensions of these various regions depends on the overall composition and thermodynamic balance. In the case of the sodium borosilicate glass in this study, the thermodynamic modelling predicts the absence of B₂O₃ chemical groupings, but that 25% of the boron atoms are present as B[3] and 20% as B[4] in borate groupings, and that the remaining 55% are involved in borosilicate groupings, which is consistent with the ¹¹B NMR data. The model also predicts that 45% of the silicon atoms are present as Si[4] in borosilicate groupings, 23% as Si[3] units and 1% as Si[4] in silicate groupings, and 31% as Si[4] in SiO₂ groupings. This is similarly consistent with the ²⁹Si NMR data. (Note, however, that this comparison of the thermodynamic
modelling and NMR data ignores the presence of the \( \text{BOO}_2^- \) and \( \text{SiO}_2\text{O}_2^2- \) basic structural units predicted by the former, but which were below the detection limit of the NMR spectroscopy, and also that the present glass is outside the phase-separation region."

On the addition of \( \text{Fe}_2\text{O}_3 \), the base glass borosilicate network expands to accommodate the \( \text{Fe}^{3+}/\text{Fe}^{2+} \) cations. This expansion is greater than that for the soda–lime–silica glass of Ref. 5, due to the conversion of negatively charged \( \text{BO}_4^- \) tetrahedra into trigonal borate structural units incorporating nonbridging oxygen atoms. The most likely scenario for the inclusion of the \( \text{Fe}_2\text{O}_3 \) into the base glass structure is that the tetrahedrally co-ordinated \( \text{Fe}^{3+} \) cations form \( \text{FeO}_4^- \) structural units that are incorporated into the network of silicate chemical groupings, whereas more easily leached \( \text{Fe}^{3+} \) cations in octahedral co-ordination are present as \( \text{FeBO}_4 \) chemical groupings, consisting of \( \text{Fe}^{3+} \) cations plus \( \text{BO}_3^3- \) orthoborate anions, which may become non-stoichiometric due to the presence of \( \text{Fe}^{2+} \) cations. The fact that network-modifying \( \text{Fe}^{3+}/\text{Fe}^{2+} \) cations are located within borate chemical groupings has implications for the long-term leachability of vitrified nuclear and other toxic wastes.

Finally, it is interesting to note that the relative ease with which foreign cations can be incorporated into the sodium borate component of a sodium borosilicate glass is reminiscent of the well-known borax bead test used in qualitative chemical analysis. The compound containing an unknown cation is melted together with borax (\( \text{Na}_2\text{B}_4\text{O}_7\cdot10\text{H}_2\text{O} \)) and cooled to form a glass bead in a platinum wire loop, the colour of this bead being characteristic of the unknown cation.

**Acknowledgements**

This work was supported financially by BNFL, who also funded purchase of the isotopically-enriched \( ^{57}\text{Fe}_2\text{O}_3 \), and the UK EPSRC, and JLS and RH would like to thank BNFL and the EPSRC, respectively, for PhD studentships. The authors are also grateful to the Institut Laue-Langevin for neutron beam time and experimental assistance. The NMR facilities employed in this study were part funded by Birmingham Science City Advanced Materials Projects 1 and 2, supported by Advantage West Midlands (AWM) and the European Regional Development Fund (ERDF).

**References**

Table 1. Neutron scattering lengths\textsuperscript{(11)} and sample compositions

<table>
<thead>
<tr>
<th>Element</th>
<th>$b$ $(10^{-14}$ m)</th>
<th>Base glass</th>
<th>Fe-containing glasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>0.363±0.002</td>
<td>0.1246</td>
<td>0.1039</td>
</tr>
<tr>
<td>Fe\textsuperscript{57}Fe</td>
<td>0.945±0.002 (0.284±0.010)</td>
<td>-</td>
<td>0.0675</td>
</tr>
<tr>
<td>11B</td>
<td>0.659±0.004</td>
<td>0.1098</td>
<td>0.0915</td>
</tr>
<tr>
<td>Si</td>
<td>0.4149±0.00010</td>
<td>0.1795</td>
<td>0.1497</td>
</tr>
<tr>
<td>O</td>
<td>0.5803±0.0004</td>
<td>0.5861</td>
<td>0.5874</td>
</tr>
</tbody>
</table>

Table 2. Chemical structure of the base glass from thermodynamic modelling

<table>
<thead>
<tr>
<th>Chemical grouping</th>
<th>Fraction (± 0.03)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na\textsubscript{2}O.3B\textsubscript{2}O\textsubscript{3}</td>
<td>0.01</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.2B\textsubscript{2}O\textsubscript{3}</td>
<td>0.08</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.B\textsubscript{2}O\textsubscript{3}</td>
<td>0.01</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.B\textsubscript{2}O\textsubscript{3}.2SiO\textsubscript{2}</td>
<td>0.18</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.B\textsubscript{2}O\textsubscript{3}.6SiO\textsubscript{2}</td>
<td>0.06</td>
</tr>
<tr>
<td>3Na\textsubscript{2}O.8SiO\textsubscript{2}</td>
<td>0.01</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.2SiO\textsubscript{2}</td>
<td>0.15</td>
</tr>
<tr>
<td>Na\textsubscript{2}O.SiO\textsubscript{2}</td>
<td>0.01</td>
</tr>
<tr>
<td>SiO\textsubscript{2}</td>
<td>0.49</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 3. Structural unit fractions from thermodynamic modelling (±0.03) and NMR spectroscopy (±0.015)

<table>
<thead>
<tr>
<th>Structural unit</th>
<th>Borate</th>
<th>Silicate</th>
<th>Overall</th>
<th>NMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO\textsubscript{4}  \textsuperscript{-}</td>
<td>0.72</td>
<td>-</td>
<td>0.27</td>
<td>0.285</td>
</tr>
<tr>
<td>BO\textsubscript{3}</td>
<td>0.25</td>
<td>-</td>
<td>0.10</td>
<td>0.094</td>
</tr>
<tr>
<td>BO\textsubscript{2}  \textsuperscript{-}</td>
<td>0.03</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>SiO\textsubscript{4}</td>
<td>-</td>
<td>0.77</td>
<td>0.48</td>
<td>0.475</td>
</tr>
<tr>
<td>SiO\textsubscript{3}  \textsuperscript{-}</td>
<td>-</td>
<td>0.22</td>
<td>0.13</td>
<td>0.146</td>
</tr>
<tr>
<td>SiO\textsubscript{2}  \textsuperscript{2-}</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Table 4. Parameters obtained from fitting the $^{29}$Si spectrum of the base glass. The intensities include the contributions from the spinning sidebands. During the fitting procedure, the half-widths of the spinning sidebands were constrained to be similar to the centreband peaks.

<table>
<thead>
<tr>
<th>Species</th>
<th>Isotropic shift (ppm ±1)</th>
<th>FWHM (ppm ±1)</th>
<th>Intensity (% ±2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si$^{[4]}$(nB)$^*$</td>
<td>−100</td>
<td>18</td>
<td>75</td>
</tr>
<tr>
<td>Si$^{[3]}$</td>
<td>−88</td>
<td>14</td>
<td>25</td>
</tr>
</tbody>
</table>

$^*$ n ∼ 1·3, see text.

Table 5. Fit to the $^{11}$B MAS NMR spectrum

<table>
<thead>
<tr>
<th>Species</th>
<th>Isotropic shift (ppm)</th>
<th>$C_Q$ (MHz)</th>
<th>$\eta_Q$ (fixed)</th>
<th>Relative intensity$^*$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$^{[3]}_{\text{ring}}$</td>
<td>17·6</td>
<td>2·58</td>
<td>0·2</td>
<td>13</td>
</tr>
<tr>
<td>B$^{[3]}_{\text{non-ring}}$</td>
<td>15·1</td>
<td>2·44</td>
<td>0·2</td>
<td>11</td>
</tr>
<tr>
<td>B$^{[4]}$(B,3Si)</td>
<td>−1·5</td>
<td>-</td>
<td>-</td>
<td>56</td>
</tr>
<tr>
<td>B$^{[4]}$(4Si)</td>
<td>−2·2</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
</tbody>
</table>

$^*$ As fitted, and uncorrected for the B$^{[3]}$ intensity loss into sidebands.

Table 6. Average bond lengths in independent borate and silicate structural units, calculated from the data in Table 2 of Ref. 10

<table>
<thead>
<tr>
<th>Borate units</th>
<th>B–O (Å)</th>
<th>B–O$^-$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$O_4^-$</td>
<td>1·468</td>
<td>-</td>
</tr>
<tr>
<td>B$O_3$</td>
<td>1·368</td>
<td>-</td>
</tr>
<tr>
<td>BO$O_2^-$</td>
<td>1·400</td>
<td>1·324</td>
</tr>
<tr>
<td>BO$O_2^-$</td>
<td>1·438</td>
<td>1·358</td>
</tr>
<tr>
<td>BO$O_3^-$</td>
<td>-</td>
<td>1·383</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Silicate units</th>
<th>Si–O (Å)</th>
<th>Si–O$^-$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si$O_4^-$</td>
<td>1·607</td>
<td>-</td>
</tr>
<tr>
<td>Si$O_3$</td>
<td>1·639</td>
<td>1·570</td>
</tr>
<tr>
<td>Si$O_2$</td>
<td>1·675</td>
<td>1·592</td>
</tr>
<tr>
<td>Si$O_3$</td>
<td>1·682</td>
<td>1·622</td>
</tr>
<tr>
<td>Si$O_4$</td>
<td>-</td>
<td>1·640</td>
</tr>
</tbody>
</table>
Table 7. Base glass and $\Delta T_X(r)$ peak fit parameters

<table>
<thead>
<tr>
<th>Fit</th>
<th>$r_{B-O}$ (Å)</th>
<th>$&lt;u_{B-O}^2&gt;^{1/2}$ (Å)</th>
<th>$n_{B(O)}$</th>
<th>$r_{Si-O}$ (Å)</th>
<th>$&lt;u_{Si-O}^2&gt;^{1/2}$ (Å)</th>
<th>$n_{Si(O)}$</th>
<th>$R_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(r)$</td>
<td>1.477</td>
<td>0.103</td>
<td>3.89</td>
<td>1.617</td>
<td>0.071</td>
<td>3.96</td>
<td>0.021</td>
</tr>
<tr>
<td>$\Delta T_X(r)$</td>
<td>1.427</td>
<td>0.094</td>
<td>3.43</td>
<td>1.627</td>
<td>0.053</td>
<td>3.97</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 8. Peak fit parameters for the first (Fe–O) peak in $\Delta T_{Fe}(r)$

<table>
<thead>
<tr>
<th>$r_{Fe-O}$ (Å)</th>
<th>$&lt;u_{Fe-O}^2&gt;^{1/2}$ (Å)</th>
<th>$n_{Fe(O)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.895±0.002</td>
<td>0.079±0.010</td>
<td>4.30±0.20</td>
</tr>
<tr>
<td>2.182±0.030</td>
<td>0.041±0.010</td>
<td>0.58±0.20</td>
</tr>
</tbody>
</table>

Table 9. Calculation of the average Si(B) co-ordination number, $n_{SiB}$, using the thermodynamic prediction for the chemical groupings in the base glass

<table>
<thead>
<tr>
<th>Chemical groupings</th>
<th>$n_{SiB}$</th>
<th>Overall fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$O.B$_2$O$_3$.2SiO$_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na$_2$O.B$_2$O$_3$.6SiO$_2$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3Na$_2$O.8SiO$_2$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Na$_2$O.2SiO$_2$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Na$_2$O.SiO$_2$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Na$_2$O.B$_2$O$_3$.2SiO$_2$</td>
<td>2×0.18</td>
<td>6×0.06</td>
</tr>
<tr>
<td>Na$_2$O.B$_2$O$_3$.6SiO$_2$</td>
<td>-</td>
<td>2×0.01</td>
</tr>
<tr>
<td>3Na$_2$O.8SiO$_2$</td>
<td>-</td>
<td>6×0.01</td>
</tr>
<tr>
<td>Na$_2$O.2SiO$_2$</td>
<td>-</td>
<td>2×0.15</td>
</tr>
<tr>
<td>Na$_2$O.SiO$_2$</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>-</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Si$^{[4]}$ 2×0.18 6×0.06 2×0.01 - 0.49 0.769 1.27
Si$^{[3]}$ - - 6×0.01 2×0.15 - 0.225 0
Si$^{[2]}$ - - - - 0.01 0.006 0
Figure Captions

Figure 1. Neutron diffraction data reduction for the \( ^{\text{NAT}} \text{Fe}_2\text{O}_3 \)-containing glass. Top, raw diffraction pattern (points) with cubic-spline fit (solid line); centre, corrected, normalised diffraction pattern, \( I(Q) \) (solid line), and the paramagnetic plus self-scattering (dashed line) and bottom, the interference function, \( Q_i(Q) \).

Figure 2. (A) Lorentzian and (B) Extended Voigt-based (xVBF) fits to the Mössbauer spectrum for the \( ^{\text{NAT}} \text{Fe}_2\text{O}_3 \)-containing glass.

Figure 3. Corrected, normalised diffraction patterns, \( I(Q) \), for the \( ^{\text{NAT}} \text{Fe}_2\text{O}_3 \)- and \( ^{57} \text{Fe}_2\text{O}_3 \)-containing samples, together with that for the base glass.

Figure 4. Real-space total correlation functions, \( T(r) \), for the \( ^{\text{NAT}} \text{Fe}_2\text{O}_3 \)- and \( ^{57} \text{Fe}_2\text{O}_3 \)-containing samples, with their difference, \( \Delta T(r) \).

Figure 5. The \( \text{Fe}–\text{Fe}^+\text{X}–\text{X} \) and base glass real-space total correlation functions plus their difference, \( \Delta T(r) \). Note that \( \Delta T_X(t) \) is divided by the base glass fraction (0.88) to allow subtraction of the base glass correlation function to give \( \Delta T(r) \).

Figure 6. Gaussian fits to the \( ^{29} \text{Si} \) MAS NMR spectrum for the base glass (Larmor frequency 59.6 MHz; MAS frequency 4.5 kHz. Points, data; solid blue lines, peak fits and solid red line, summed fit).

Figure 7. Simulation of the \( ^{11} \text{B} \) MAS NMR spectrum for the base glass (points, data; solid and dashed blue lines, peak fits and solid red line, summed fit).

Figure 8. Two-peak fit (Table 7) to the first (\( \text{B}–\text{O}^+\text{Si}–\text{O} \)) peak in (A) the experimental real-space correlation function, \( T(r) \), for the base glass, and (B) the \( \text{Fe}–\text{Fe}^+\text{X}–\text{X} \) difference correlation function, \( \Delta T_X(t) \), (—, experiment; ——, fit; ······, individual peaks and −·····, residual).

Figure 9. Two-peak fit (Table 8) to the first (\( \text{Fe}–\text{O} \)) peak in the \( \text{Fe}–\text{Fe}^+\text{Fe}–\text{X} \) difference correlation function, \( \Delta T_{Fe}(t) \). (Key as Figure 8)

Figure 10. Running \( \text{Fe}(O) \) co-ordination number between 1.5 Å and \( r \), obtained from the area under \( r \Delta T_{Fe}(r) \).

Figure 11. The \( \Delta T_X(t) \) – base glass difference correlation functions, \( \Delta T(r) \), for the present glasses (solid line), together with that for the soda–lime–silica system from Ref. 5 (dashed line).

Figure 12. A comparison of the \( \text{Fe}–\text{Fe}^+\text{Fe}–\text{X} \) difference correlation functions, \( \Delta T_{Fe}(t) \), for the present glass (solid line) with that for vitreous \( \text{Na}_2\text{O}–\text{CaO}–\text{Fe}_2\text{O}_3–\text{SiO}_2 \) (dashed line).
Figure 1.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8(A).
Figure 8(B).
Figure 9.
Figure 10.