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Effect of $\text{Fe}_2\text{O}_3/\text{ZnO}$ on Two Glass Compositions
for Solidification on Swedish Nuclear Wastes

by

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INTRODUCTION:

Low melting alkaliborosilicate glasses have been considered for use in the immobilization of high level radioactive wastes for years (1-2). A recent study comparing the surface behavior of two nuclear waste glasses concluded that "Addition of Fe_2O_3 to a soda borosilicate nuclear waste glass significantly reduces damage by water attack because of a Fe-rich film that forms on the glass surface". (3) However, in the previous study there were significant differences in the concentration of SiO_2 , B_2O_3 , CaO and simulated fission products in the glasses which made it impossible to ascribe the improved leach resistance solely to Fe_2O_3 content. Thus, the objective of the present investigation is to compare the leaching and surface behavior of two nuclear waste glasses which differ only by the substitution of Fe_2O_3 for some of the ZnO in the glass. By this comparison we hope to establish whether Fe_2O_3 provides a unique contribution to improvements in the leach resistance of these complex glasses.

Both glass compositions studied are compatible with the low melting temperature, $< 1150^\circ\text{C}$, required for the French AVM Process. The quantity of simulated waste products is 9%, characteristic of the Swedish nuclear waste program.

MATERIALS PREPARATION:

The materials studied (Table 1) are two zinc borosilicate glasses. The only difference between the two compositions is= ABS 29 contains ten times more ZnO than Fe_2O_3 and ABS 41 contains the same quantity of each oxide. Table 1 also includes the composition of the 9% (by wt) of simulated waste products added to the glass compositions.

The glasses were prepared by T. Lakatos of the Swedish Glass Research Institute by melting at 1200°C in platinum crucibles for 2-3 hours followed by casting into rods 1 x 1 cm in steel molds. After annealing at 550°C for 15 minutes, followed by slow cooling, the blocks were sliced into approximately 2 mm thick samples using a diamond bladed wafering saw operating

saw operating at moderate speed with water as a coolant and lubricant.

The as-cut samples were dry polished with 320 and 600 grit SiC paper. After polishing, the samples were cleaned twice in an ethanol ultra-sonic bath for three minutes.

EXPERIMENTAL PROCEDURE:

Leachings were conducted by suspending the samples on Teflon(R) thread inside Teflon or polypropylene containers filled with distilled and deionized water of initial pH= 5.5. (Figure 1). Two different ratios of glass surface area (SA) to solution volume (V) were used in the study, $SA/V=1\text{cm}^{-1}$ and $SA/V=0.1\text{cm}^{-1}$ to determine the influence of this parameter on the chemical durability. Other studies have indicated that the dependence of leaching behavior of glasses on SA/V can be related to the mechanisms of leaching and the long term performance of glasses (4).

All procedures followed were as far as possible equivalent to that described in the MCC-1 Standard Test for Static Leaching (5). Leaching times were 1, 3, 7, 14 and 28 days for each glass. An oven was used to maintain the temperature of $90\pm 0.25^\circ\text{C}$.

After leaching, the glass samples were removed from the leaching cells, dried at room temperature and stored in a desiccator. Infrared reflection spectroscopy (IRRS) was used for surface analysis on all leached samples using the techniques previously described. (6-8). The pH of the leachant solutions was measured using a pH microelectrode.* The concentrations of Si^{4+} , B^{3+} , Al^{3+} and Mo^{6+} in the leachant solutions were determined with ICP spectroscopy.** The concentrations of Na^+ were determined with Atomic Emission spectroscopy and the concentrations of Fe^{3+} with Atomic Absorption spectroscopy.**

Average leach rates are calculated from the leachant data and with the different parameters as:

$$L_i(0,t) = \frac{\Delta m_i(0,t)}{m_{i,0}} \cdot \frac{m_{i,0}}{s.t} \quad (1)$$

- $\Delta m_i(0,t)$ = mass of element i in the solution water t days of leaching (g).

- m_0 = initial total mass of the sample (g).

(R) Trademark EI Dupont de Nemours, Inc.

* Micro combination pH probe MI-410. Microelectrodes, Inc. Model 201 digital pH meter. ORION RESEARCH

** ICP Plasmatherm (1.5KW). AA/AE spectrometer IL 451 Videos Instrumentation Laboratory.

- $m_{i,0}$ = initial mass of element i in the sample (g).
- s = surface area exposed to the leaching (cm^2).
- t = leaching time (day).

This formula of average leach rate is the formula used in the Marcoule Research Program (Commissariat à l'Energie Atomique, FRANCE) and proposed in the MCC-1 Static Leach Test of the Materials Characterization Center (5).

To permit the comparison of this work with the researches of other laboratories (Swedish Nuclear Waste Program KBS), a second formula was used as well:

$$\text{Loss rate} = \frac{\text{ppm of element}}{10^6} \cdot \frac{1}{\text{day}} \cdot \frac{1}{\text{SA/V}} \quad (2)$$

- loss rate in $\text{g.cm}^{-2} \cdot \text{d}^{-1}$
- SA= surface area exposed to the leaching (cm^2).
- V = volume of leachant (cm^3).
- day= leaching time (day).

The weight losses were too little to give good results and therefore are not reported.

RESULTS:

Solution_data

Table 2 presents the pH of the leaching solutions for the two ratios of SA/V. Figure 2 shows the curves of $\text{pH}=f(t)$ for each glass and each SA/V. All curves have the same behavior, the pH increasing continuously with time. The values of the pH for $\text{SA/V}=1 \text{ cm}^{-1}$ are higher (9.45 after 28 days) than the pH for $\text{SA/V}=0.1 \text{ cm}^{-1}$ (8.8 and 9.2 after 28 days). The shape of the pH curves indicates that the pH attains a limiting value under static leaching conditions of > 8.5 after 28 days.

After 28 days the solution pH for both ABS 29 and ABS 41 are the same (9.45) at $\text{SA/V}=1 \text{ cm}^{-1}$, but at $\text{SA/V}=0.1 \text{ cm}^{-1}$ the pH of the leachant for ABS 41 is higher (9.20) than the pH of the leachant for ABS 29 (8.80).

Leaching results for the different experiments are given in parts per million (ppm) of ions in the leachant (table 3). Tables 4 and 5 present the average leach rates and the loss rates calculated from the concentration data with formulas (1) and (2). The solution analysis were made only for $\text{SA/V}=0.1 \text{ cm}^{-1}$; for $\text{SA/V}=1 \text{ cm}^{-1}$ the quantity of the leachant was too little for accurate measurements. Figures 3 a, 3 b and 4 a, 4 b show the time dependence of the average leach

rates and the loss rates for the two glasses.

The values of the solution concentrations (ppm), the average leach rates, the loss rates and the solution pH are all higher for the mixed ZnO-Fe₂O₃ composition (ABS 41) than for the high ZnO composition glass (ABS 29). The differences between the two compositions become important and increase after 7 days of leaching showing that ABS 29 is more resistant to attack of 90°C water than glass ABS 41.

For ABS 29, the average leach rates for all the elements decrease with duration of exposure. For example,

$$L_{\text{Si}}(0,1) = 5.3 \cdot 10^{-5} > L_{\text{Si}}(0,28) = 1.9 \cdot 10^{-5} \text{ g. cm}^{-2} \cdot \text{d}^{-1}$$

$$L_{\text{B}}(0,1) = 1.6 \cdot 10^{-4} > L_{\text{B}}(0,28) = 5.8 \cdot 10^{-5} \text{ g. cm}^{-2} \cdot \text{d}^{-1}$$

$$L_{\text{Na}}(0,1) = 7.0 \cdot 10^{-5} > L_{\text{Na}}(0,28) = 2.4 \cdot 10^{-5} \text{ g. cm}^{-2} \cdot \text{d}^{-1}$$

Thus the quantity of element passing each day into solution decreases with duration of the leaching. This result suggests a continuing change in the surface character of the glass ABS 29 and that equilibrium has not been reached.

For contrast, for ABS 41 the average leach rates are relatively constant with duration of exposure. For example,

$$L_{\text{Si}}(0,1) = 5.1 \cdot 10^{-5} \approx L_{\text{Si}}(0,28) = 5.3 \cdot 10^{-5} \text{ g. cm}^{-2} \cdot \text{d}^{-1}$$

$$L_{\text{B}}(0,1) = 2.1 \cdot 10^{-4} \approx L_{\text{B}}(0,28) = 1.4 \cdot 10^{-4} \text{ g. cm}^{-2} \cdot \text{d}^{-1}$$

For the other elements Al, Na, Fe, Mo, Zn the average leach rates decrease a little with the number of days. However, for this glass equilibrium is almost attained and the quantities of Si⁴⁺ and B³⁺ passing each day into solution are nearly the same. Thus ABS 41 seems to attain an equilibrium behavior in 90°C water more rapidly than ABS 29.

The average leach rates for Al³⁺ are rather important and are comparable with the average leach rates for B³⁺ and Na⁺ for these conditions. Leaching results for Zn are somewhat lower but the leaching rates for Fe³⁺ are nearly 30 times less than the other elements, even for ABS 41 which contains significant quantities of Fe₂O₃ in the glass.

Surface Analysis

IRRS spectra were obtained to compare changes in the sample surface due to leaching. The interpretation techniques of the IRRS spectra were previously described (6-8). The spectrometer is calibrated with a vitreous silica sample. The primary peak of vitreous silica is located at 1120 cm^{-1} and corresponds to silicon - bridging oxygen - silicon stretching vibrations (8). A second major peak of vitreous silica is located around 475 cm^{-1} and is due to the silicon - bridging oxygen - silicon bending vibrations. The little peak around 800 cm^{-1} is not used for the interpretation. Most interpretations of surface corrosion of glasses is based upon changes in the stretching vibration peak (6,9). The spectrometer is calibrated to have 80% of reflectance for the primary peak (1120 cm^{-1}) and 50% of reflectance for the second major peak (475 cm^{-1}) of pure vitreous silica.

Figure 5 shows the vitreous silica spectrum with its two characteristic peaks and the spectra of glasses ABS 29 and ABS 41 before corrosion. The spectral intensity in the region between 800 and 900 cm^{-1} for the nuclear waste glasses is due to the presence of stretching vibrations of the silicon - non bridging oxygen - alkali and alkaline earth ions in the glass surfaces.

When corrosion of the surface occurs, the exchange of alkali and alkaline earth cations with hydrogen ions from the solution reduces the intensity of that portion of the spectral region. The same reactions cause the maximum of the peak around 1000 cm^{-1} to increase and move to 1120 cm^{-1} . These changes in spectra are characteristic of formation of a silica-rich film on the surface of the sample. This phenomenon can be seen by comparing the spectra before corrosion (Figure 5) and the spectra after 1 day of corrosion (figure 6).

For the 7 first days, the evolution of the spectra (Figures 6, 7 and 8) shows only the formation of a silica-rich film on the glass surface and no difference between the two glasses. After 14 and 28 days (Figures 9 and 10) the reflectance intensity of the spectra is reduced by a gradual destruction of the surface film that had formed on the glass. This produces a roughening of the surface and scattering of the infrared beam incident on the sample. The attack of the surface film is due to the high solution pH obtained after 14 days which results in an attack of the Si-O-Si bonds on the silica-rich film and a breakdown of the film structural network.

Thus the IRRS analysis confirms the solution results; i e ABS 29 is a more leach resistant composition than ABS 41 for $SA/V = 0.1\text{ cm}^{-1}$. However, when solution conditions correspond to $SA/V = 1\text{ cm}^{-1}$ the two glasses give nearly identical results.

* Spectrometer model 577 PERKIN-ELMER

Discussion of Results:

The substitution of Fe_2O_3 for ZnO in this pair of glasses results in important differences in leaching and surface characteristics. ABS 41 (3.0% Fe_2O_3 , 3.0% ZnO) yields average leach rates and elemental loss rates that are nearly 3 times higher for Si^{4+} , B^{3+} , Na^+ and Mo^{6+} than ABS 29 (0.6% Fe_2O_3 , 6.0% ZnO).

Although the leach rates and loss rates for Al^{3+} are the same for the two compositions, the rates for Fe^{3+} release are three times higher for the low Fe_2O_3 glass (ABS 29) than for high Fe_2O_3 glass (ABS 41). However, the values of leaching and elemental loss rates of Fe^{3+} are more than 30 times lower for both glasses than observed for the other elements.

The difference in behavior of the two glasses cannot be attributed to variations in solution pH since little difference was observed between the glasses. Higher solution pH values were observed for $\text{SA/V} = 1 \text{ cm}^{-1}$ than for $\text{SA/V} = 0.1 \text{ cm}^{-1}$ (Figure 2). However, there was only little evidence of a difference in rate of attack of the glass surface as shown by IRRS analysis (Figures 8-10). Glass ABS 29 which shows the lowest solution pH value after 14 and 28 days (Figure 2) at $\text{SA/V} = 0.1 \text{ cm}^{-1}$ also shows the least change in the IRRS spectra for this condition (Figures 9b, 10b). However, at the higher value, $\text{SA/V} = 1.0^{-1}$, the solution pH for both glasses is the same, and higher, and the IRRS spectra for both glasses shows little difference between them (Figures 9a, 10a).

The decrease in intensity of the IRRS spectra of ABS 41 after 14 and 28 days at $\text{SA/V} = 0.1^{-1}$ shows that the surface is undergoing network breakdown and destruction of protective films on the surface. In contrast, the IRRS spectra of glass ABS 29 shows little change under the same conditions. This difference in extent of surface damage is consistent with the leach behavior which shows glass ABS 29 having the lower leach rates for most species.

Thus, a mixture of ZnO and Fe_2O_3 in the glass is less effective in controlling release of ions into 90°C water than ZnO by itself. The previous study that reported enhanced leach resistance due to Fe_2O_3 ⁽³⁾ was comparing a glass containing 6.4 weight percent Fe_2O_3 . In the present study, ABS 29 contains 6 weight percent ZnO and exhibits good leach resistance. This suggests that a critical concentration of multivalence ions may be necessary for the surface to develop a protective second film on top of the SiO_2 -rich layer that results from rapid dealkalization. This type of dual protective film is termed a Type III glass surface (10), and was characteristic of the previously reported nuclear waste glass containing 6.4 per cent Fe_2O_3 ⁽³⁾. Apparently if a mixture of multivalent ions

are present, the concentration required to stabilize the protective secondary film is higher than if one species is concentrated in the surface film.

At the higher SA/V = 1.0 cm⁻¹ value the concentration of the mixed Fe + Zn film is able to be reached and the surface is protected more effectively than in the more dilute solution of SA/V = 0.1 cm⁻¹. These results show the importance of understanding both the effects of glass composition and solution concentrations on the behavior of nuclear waste glasses.

Conclusions:

Replacement of half of the ZnO in an alkali-zinc-borosilicate nuclear waste glass with Fe₂O₃ degrades leach resistance by approximately a factor of 3. Leach rates for the higher ZnO containing glass after 28 days are generally in the range of 5.10⁻⁵ g.cm⁻² . d⁻¹ for B³⁺, Al³⁺, Mo⁶⁺; 2.10⁻⁵ g.cm⁻² .d⁻¹ for Na⁺, Si⁴⁺; and 2 to 7.10⁻⁶ g.cm⁻² .d⁻¹ for Fe³⁺ and Zn²⁺. The surface of both types of glass appears to be protected by dual protective layers, one rich in SiO₂ and a second very thin film rich in multivalent species. The second film that contains a mixture of Zn and Fe is less effective as a diffusion barrier and is less resistant to network breakdown than the film without the Fe³⁺. This apparently is because a critical concentration of multivalence species is necessary to stabilize the second protective film. Differences in SA/V ratios affect the formation of the protective films and the rates of surface damage of the glass.

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TABLE 1

NUCLEAR WASTE GLASS COMPOSITIONS (WEIGHT %)

OXIDE \ GLASS	ABS 29	ABS 41
SiO ₂	52.0	52.0
B ₂ O ₃	15.9	15.9
Al ₂ O ₃	2.5	2.5
Na ₂ O	9.4	9.4
Fe ₂ O ₃	0.6	3.0
ZnO	6.0	3.0
Li ₂ O	3.0	3.0
UO ₂	1.66	1.66
S.W.P*	9	9

* Simulated waste products

COMPOSITION OF SIMULATED NUCLEAR WASTE (WEIGHT %)

OXIDE	Cs ₂ O	SrO	BaO	Y ₂ O ₃	ZrO ₂	MoO ₃	MnO ₂	Ag ₂ O
WEIGHT %	9.78	2.89	5.11	1.67	14.22	18.11	8.56	0.12

OXIDE	SnO	Sb ₂ O ₃	La ₂ O ₃	Nd ₂ O ₃	Pr ₂ O ₃	Ce ₂ O ₃	NiO	CdO
WEIGHT %	0.19	0.04	7.89	13.44	4.22	8.33	4.11	0.29

TABLE 2

LEACHANT pH

$$-\frac{SA}{V} = 1 \text{ cm}^{-1}$$

GLASS \ DAYS	1	3	7	14	28
ABS 29	6.35	7.95	7.85	9.2	9.45
ABS 41	6.30	7.55	8.55	9.05	9.45

$$-\frac{SA}{V} = 0.1 \text{ cm}^{-1}$$

GLASS \ DAYS	1	3	7	14	28
ABS 29	6.40	7.10	8.25	7.75	8.80
ABS 41	6.35	7.25	8.35	8.70	9.20

TABLE 3
 CONCENTRATION (ppm) OF ELEMENTS
 LEACHED INTO SOLUTION

$$\frac{SA}{V} = 0,1 \text{ cm}^{-1}$$

- ABS 29 =

Days	pH	Si	B	Al	Na	Fe	Mo	Zn
1	6.40	1.3	0.79	0.25	0.49	< 0.01	0.16	0.22
3	7.10	3.48	1.98	0.72	1.19	0.01	0.43	0.52
7	8.25	5.58	3.36	1.09	1.92	0.01	0.62	0.80
14	7.75	13.56	8.61	2.01	4.75	0.02	1.52	0.78
28	8.80	13.10	8.02	2.30	4.61	0.03	1.44	0.96

- ABS 41 =

Days	pH	Si	B	Al	Na	Fe	Mo	Zn
1	6.35	1.25	0.78	0.19	0.65	0.01	0.26	0.12
3	7.25	4.82	3.12	0.59	1.80	< 0.01	0.59	0.17
7	8.35	7.36	4.67	0.83	2.69	0.03	0.73	0.19
14	8.70	21.88	14.52	1.97	7.50	0.04	2.65	0.23
28	9.20	36.31	24.90	2.91	10.80	0.05	4.55	0.24

TABLE 4

AVERAGE LEACH RATES IN 90° C WATER

AT SA/V = 0.1 cm⁻¹- ABS 29 = (g.cm⁻².d⁻¹)

DAYS	pH	Si	B	Al	Na	Fe	Mo	Zn
1	6.40	5.3 10 ⁻⁵	1.6 10 ⁻⁴	1.9 10 ⁻⁴	7.0 10 ⁻⁵	2.4 10 ⁻⁵	1.5 10 ⁻⁴	4.6 10 ⁻⁵
3	7.10	4.8 10 ⁻⁵	1.3 10 ⁻⁴	1.8 10 ⁻⁴	5.7 10 ⁻⁵	7.9 10 ⁻⁶	1.3 10 ⁻⁴	3.6 10 ⁻⁵
7	8.25	3.3 10 ⁻⁵	9.7 10 ⁻⁵	1.2 10 ⁻⁴	3.9 10 ⁻⁵	3.4 10 ⁻⁶	8.2 10 ⁻⁵	2.4 10 ⁻⁵
14	7.75	4.0 10 ⁻⁵	1.2 10 ⁻⁴	1.1 10 ⁻⁴	4.9 10 ⁻⁵	3.4 10 ⁻⁶	1.0 10 ⁻⁴	1.2 10 ⁻⁵
28	8.80	1.9 10 ⁻⁵	5.8 10 ⁻⁵	6.2 10 ⁻⁵	2.4 10 ⁻⁵	2.6 10 ⁻⁶	4.7 10 ⁻⁵	7.1 10 ⁻⁶

- ABS 41 (g.cm⁻².d⁻¹)

DAYS	PH	Si	B	Al	Na	Fe	Mo	Zn
1	6.35	5.1 10 ⁻⁵	1.6 10 ⁻⁴	1.4 10 ⁻⁴	9.3 10 ⁻⁵	4.8 10 ⁻⁶	2.4 10 ⁻⁴	5.0 10 ⁻⁵
3	7.25	6.6 10 ⁻⁵	2.1 10 ⁻⁴	1.5 10 ⁻⁴	8.6 10 ⁻⁵	1.6 10 ⁻⁶	1.8 10 ⁻⁴	2.4 10 ⁻⁵
7	8.35	4.3 10 ⁻⁵	1.4 10 ⁻⁴	9.0 10 ⁻⁵	5.5 10 ⁻⁵	2.0 10 ⁻⁶	9.6 10 ⁻⁵	1.1 10 ⁻⁵
14	8.70	6.4 10 ⁻⁵	2.1 10 ⁻⁴	1.1 10 ⁻⁴	7.7 10 ⁻⁵	1.4 10 ⁻⁶	1.7 10 ⁻⁴	6.8 10 ⁻⁶
28	9.20	5.3 10 ⁻⁵	1.8 10 ⁻⁴	7.9 10 ⁻⁵	5.5 10 ⁻⁵	8.5 10 ⁻⁷	1.5 10 ⁻⁴	3.6 10 ⁻⁶

TABLE 5
LOSS RATES IN 90° C WATER
AT SA/V = 0.1 cm⁻¹

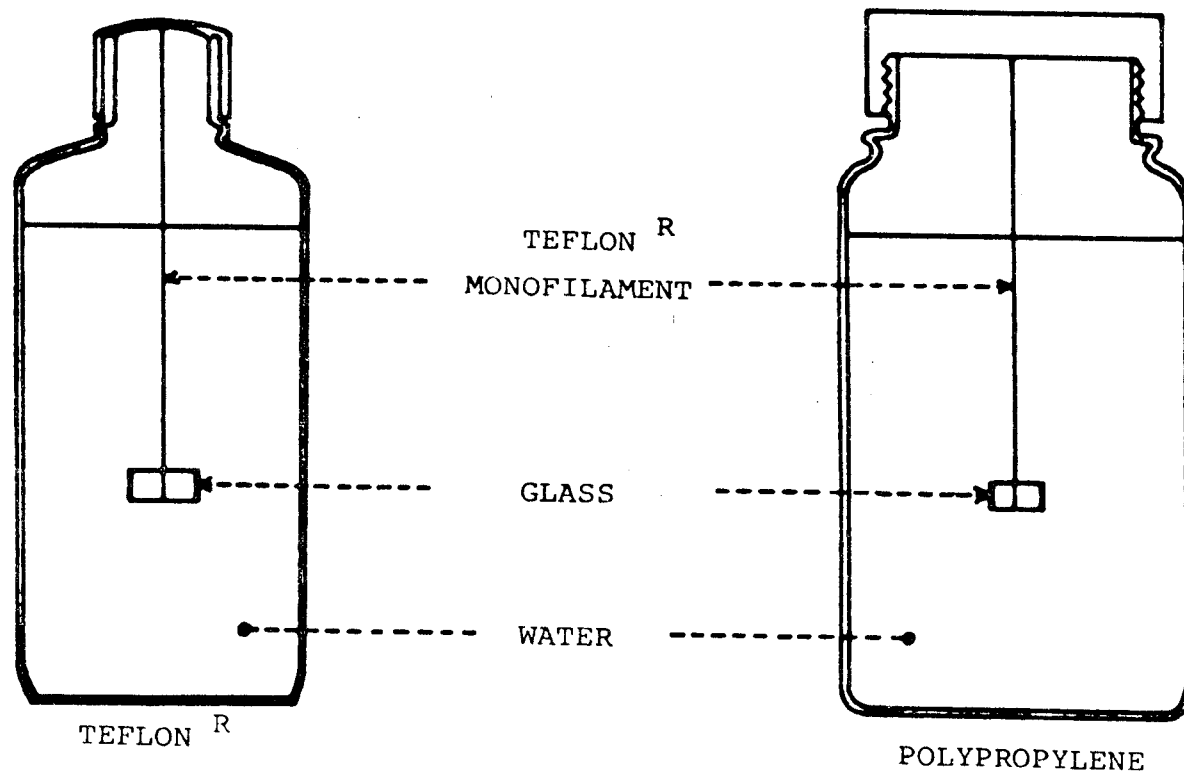
- ABS 29 = (g.cm⁻².d⁻¹)

DAYS	pH	Si	B	Al	Na	Fe	Mo	Zn
1	6.40	1.3 10 ⁻⁵	7.9 10 ⁻⁶	2.5 10 ⁻⁶	4.9 10 ⁻⁶	<1.0 10 ⁻⁷	1.6 10 ⁻⁶	2.2 10 ⁻⁶
3	7.10	1.2 10 ⁻⁵	6.6 10 ⁻⁶	2.4 10 ⁻⁶	4.0 10 ⁻⁶	3.3 10 ⁻⁸	1.4 10 ⁻⁶	1.7 10 ⁻⁶
7	8.25	8.0 10 ⁻⁶	4.8 10 ⁻⁶	1.6 10 ⁻⁶	2.7 10 ⁻⁶	1.4 10 ⁻⁸	8.9 10 ⁻⁷	1.1 10 ⁻⁶
14	7.75	9.7 10 ⁻⁶	6.2 10 ⁻⁶	1.4 10 ⁻⁶	3.4 10 ⁻⁶	1.4 10 ⁻⁸	1.1 10 ⁻⁶	5.6 10 ⁻⁷
28	8.80	4.7 10 ⁻⁶	2.9 10 ⁻⁶	8.2 10 ⁻⁷	1.6 10 ⁻⁶	1.1 10 ⁻⁸	5.1 10 ⁻⁷	3.4 10 ⁻⁷

- ABS 41 = (g.cm⁻².d⁻¹)

DAYS	pH	Si	B	Al	Na	Fe	Mo	Zn
1	6.35	1.3 10 ⁻⁵	7.8 10 ⁻⁶	1.9 10 ⁻⁶	6.5 10 ⁻⁶	1.0 10 ⁻⁷	2.6 10 ⁻⁶	1.2 10 ⁻⁶
3	7.25	1.6 10 ⁻⁵	1.0 10 ⁻⁵	2.0 10 ⁻⁶	6.0 10 ⁻⁶	<3.3 10 ⁻⁸	2.0 10 ⁻⁶	5.7 10 ⁻⁷
7	8.35	1.1 10 ⁻⁵	6.7 10 ⁻⁶	1.2 10 ⁻⁶	3.8 10 ⁻⁶	4.3 10 ⁻⁸	1.0 10 ⁻⁶	2.7 10 ⁻⁷
14	8.70	1.6 10 ⁻⁵	1.0 10 ⁻⁵	1.4 10 ⁻⁶	5.4 10 ⁻⁶	2.9 10 ⁻⁸	1.9 10 ⁻⁶	1.6 10 ⁻⁷
28	9.20	1.3 10 ⁻⁵	8.9 10 ⁻⁶	1.0 10 ⁻⁶	3.9 10 ⁻⁶	1.8 10 ⁻⁸	1.6 10 ⁻⁶	8.6 10 ⁻⁸

STATIC LEACHING CELLS



R Trademark, EI Dupont De Nemours, Inc

Figure 1

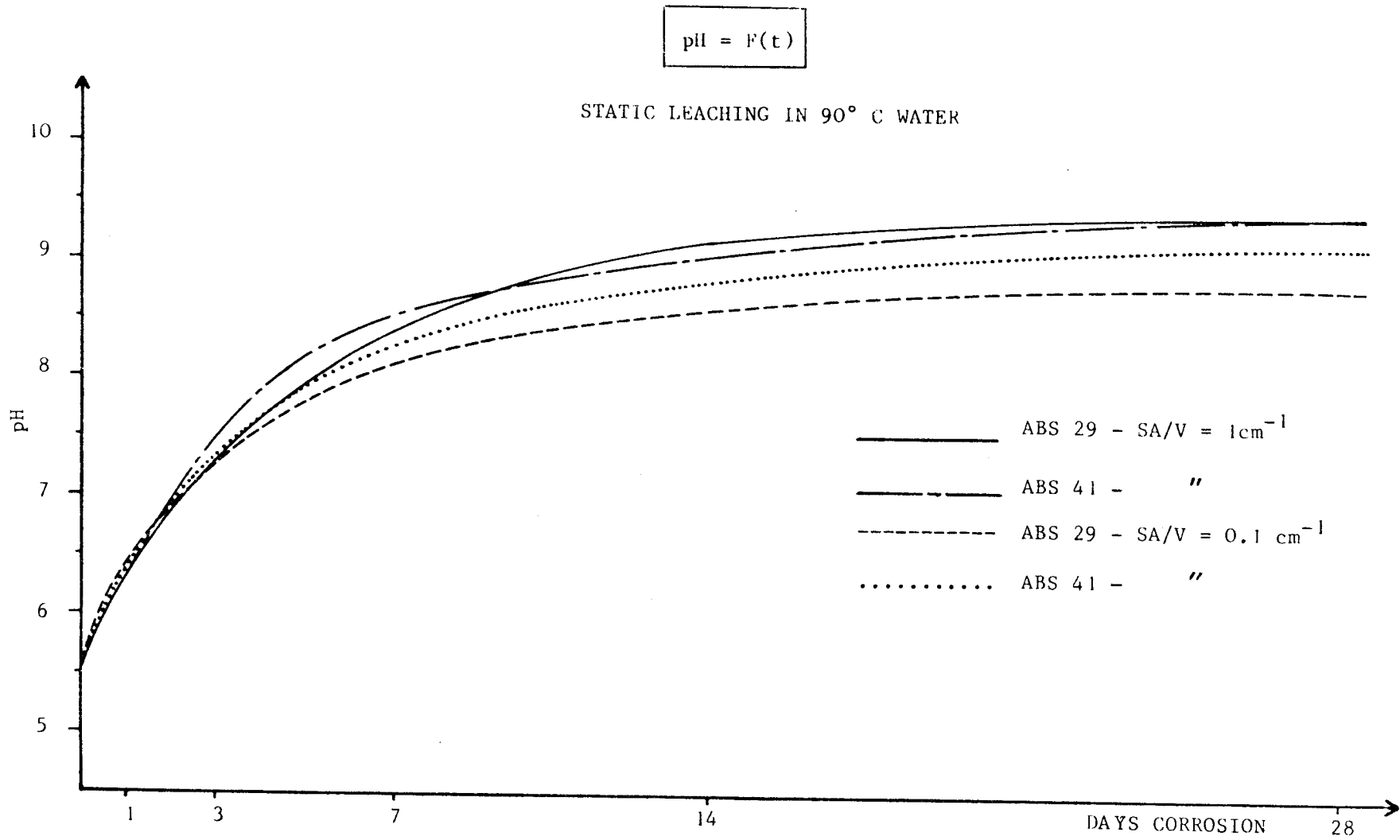


FIGURE 2

ABS 29

AVERAGE LEACH RATES
STATIC LEACHING IN 90° C WATER
AT SA/V = 0.1 cm⁻¹

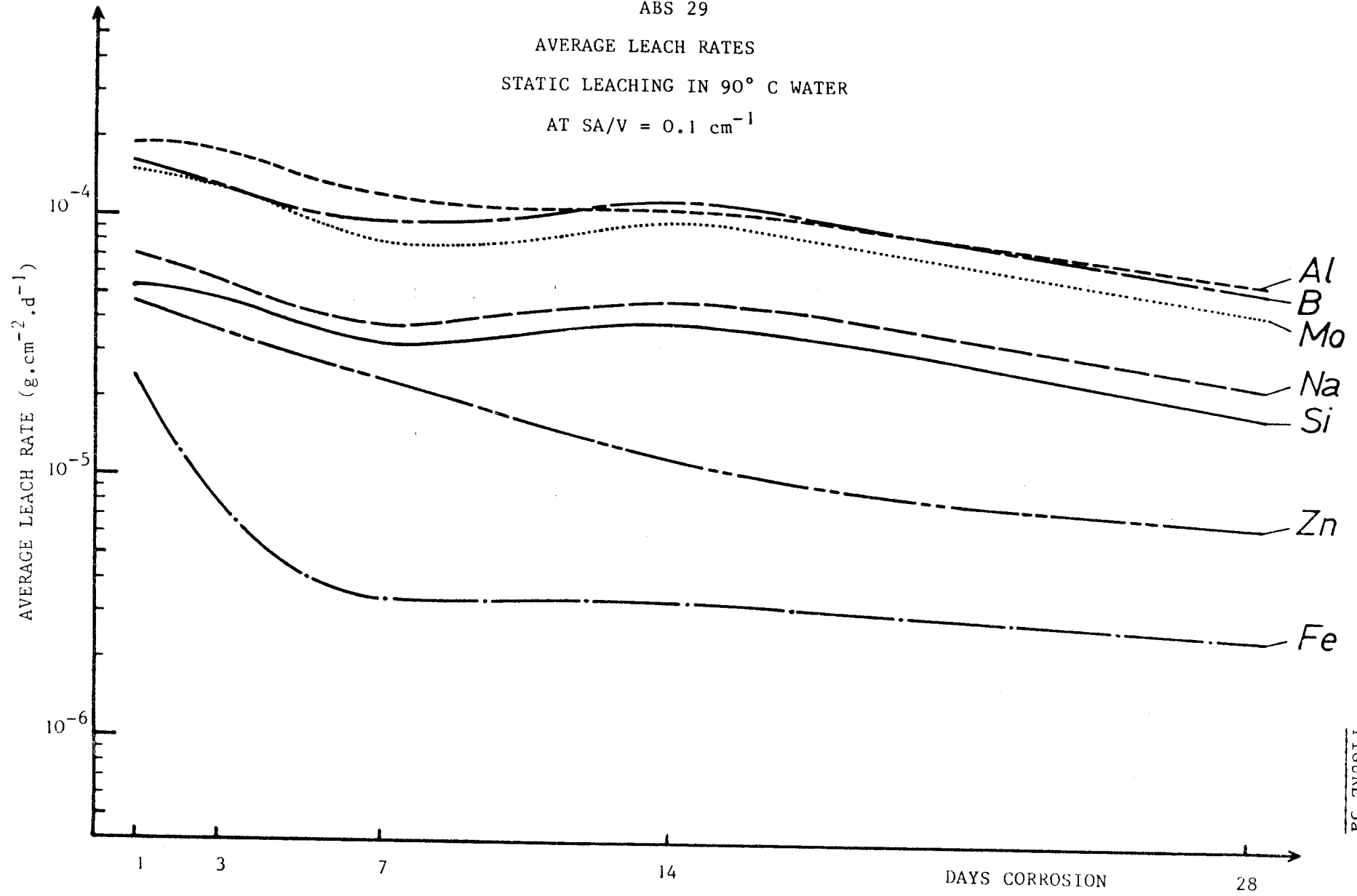


FIGURE 3a

ABS 29

LOSS RATES IN 90° C WATER AT SA/V = 0.1 cm⁻¹

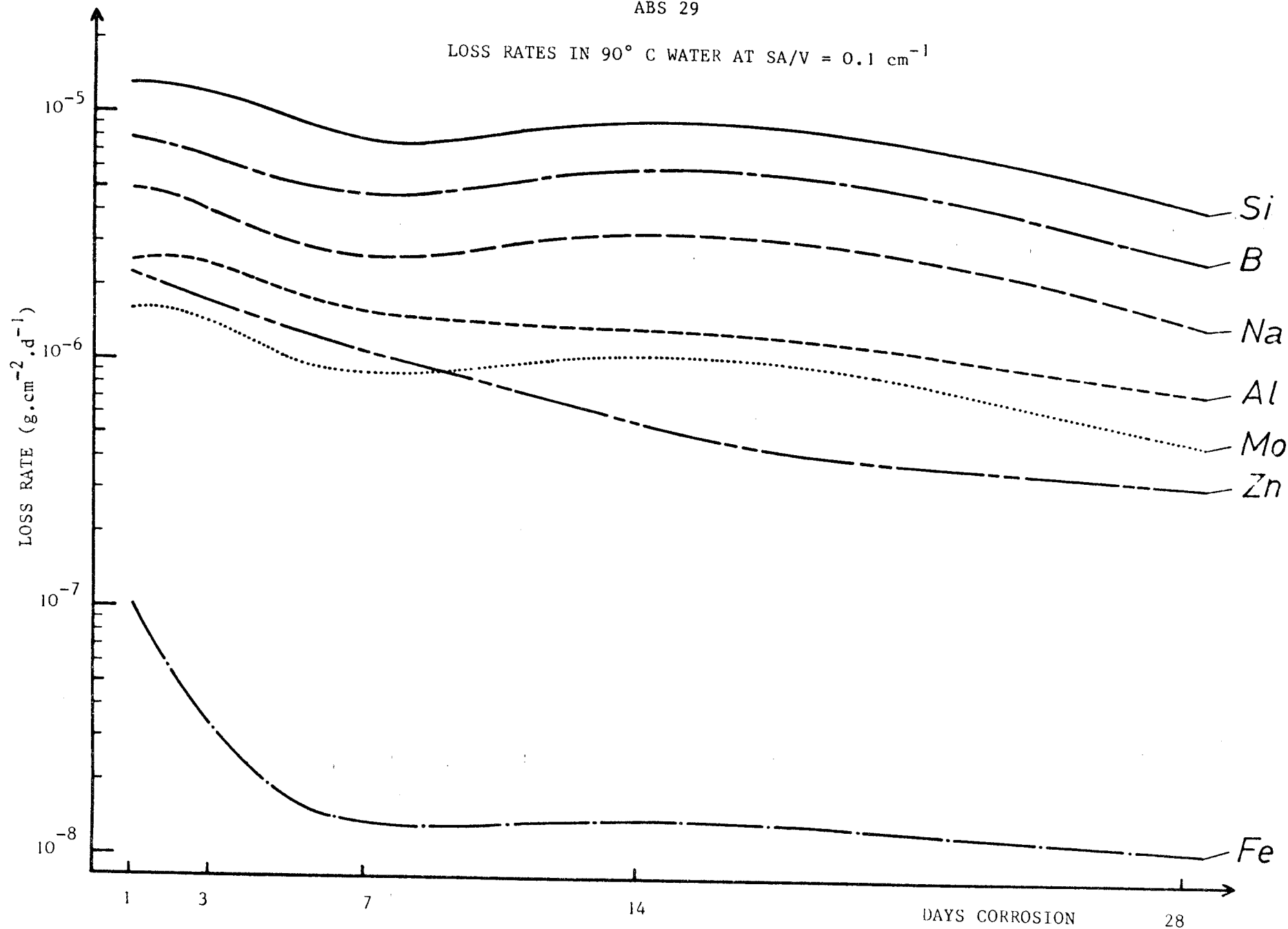


FIGURE 3b

ABS 41

AVERAGE LEACH RATES
STATIC LEACHING IN 90° C WATER
AT SA/V = 0.1 cm⁻¹

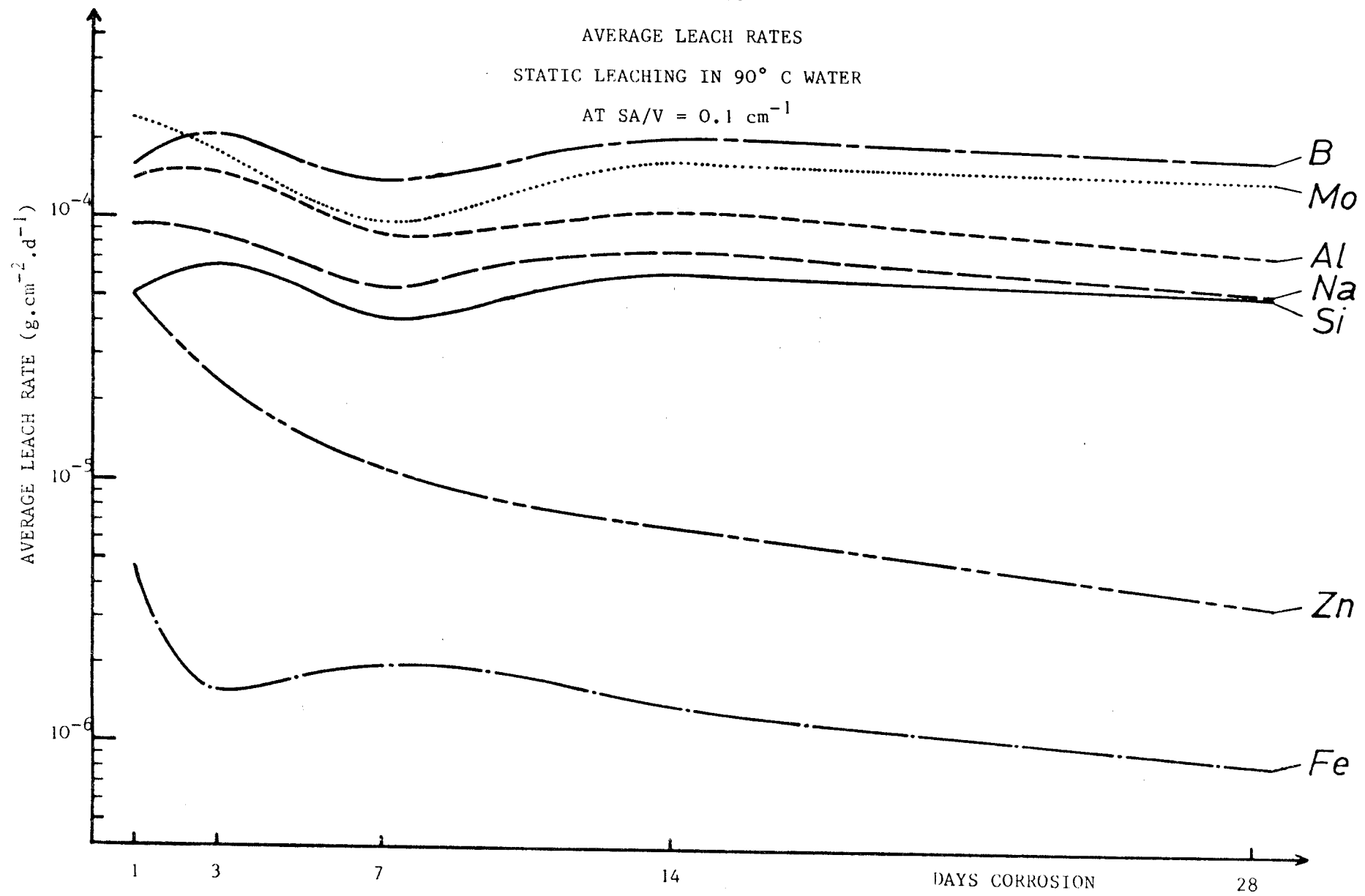


FIGURE 4a

ABS 41

LOSS RATES IN 90° C WATER AT SA/V = 0.1 cm⁻¹

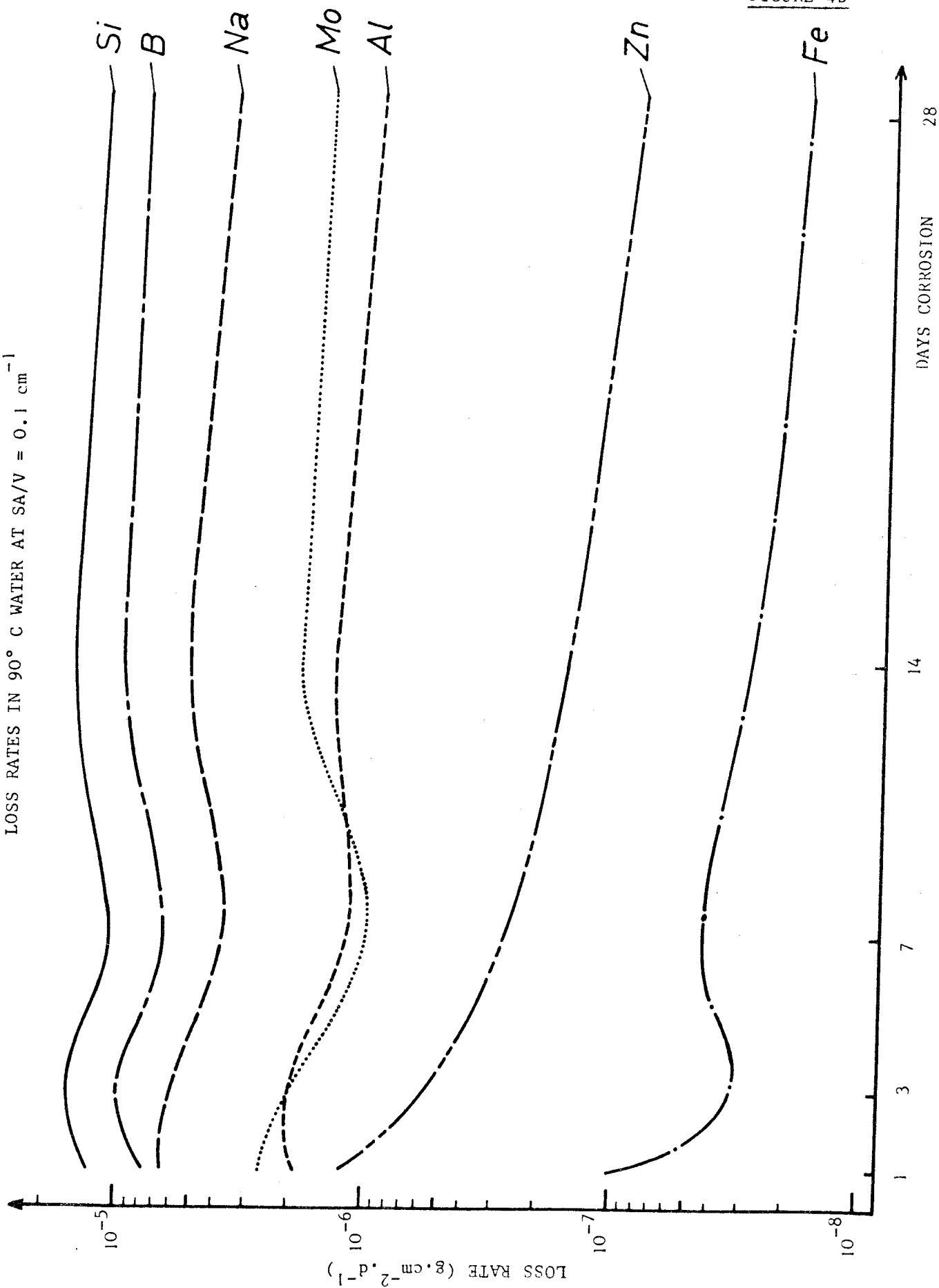


FIGURE 4b

DAYS CORROSION

28

14

7

3

1

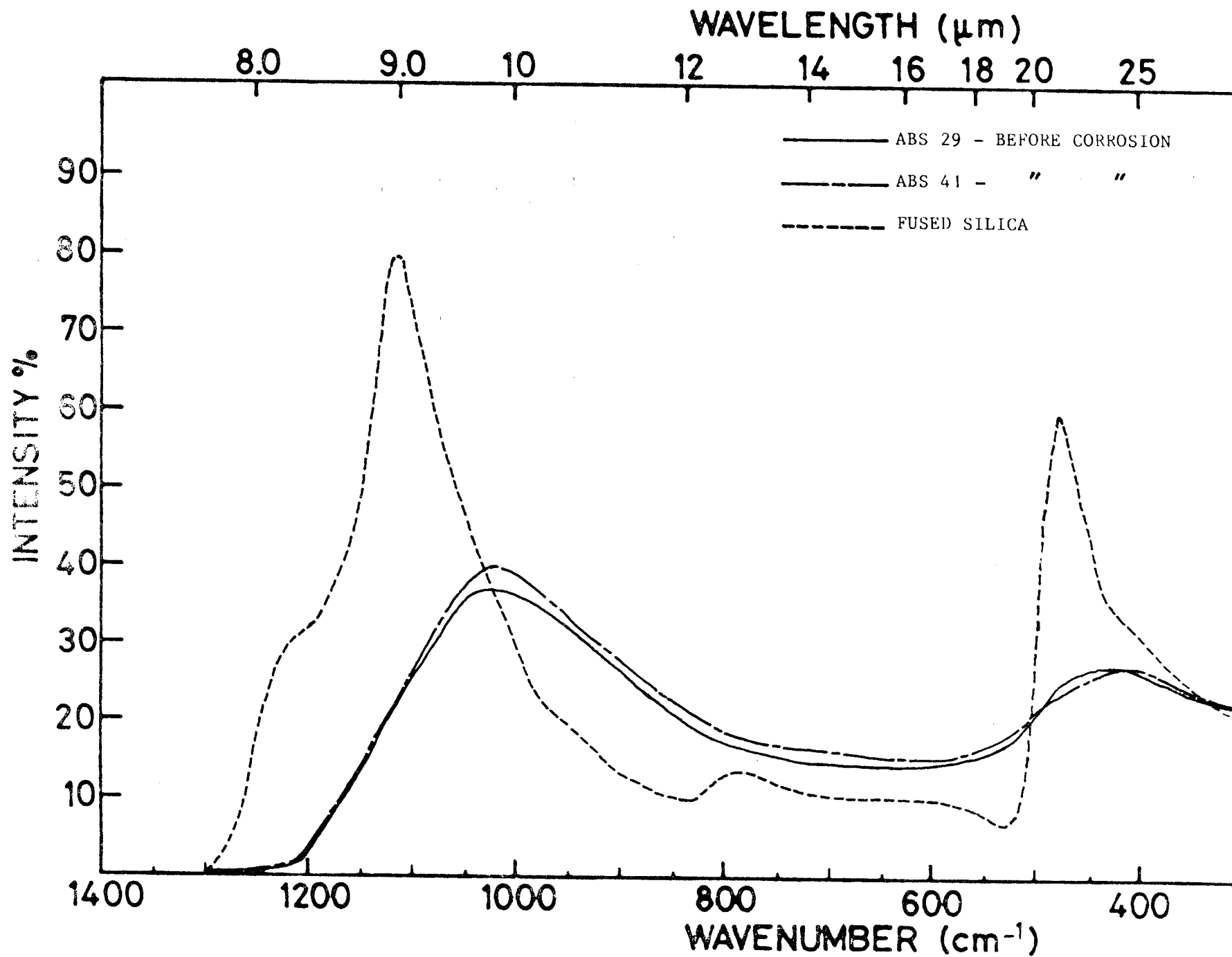


FIGURE 5

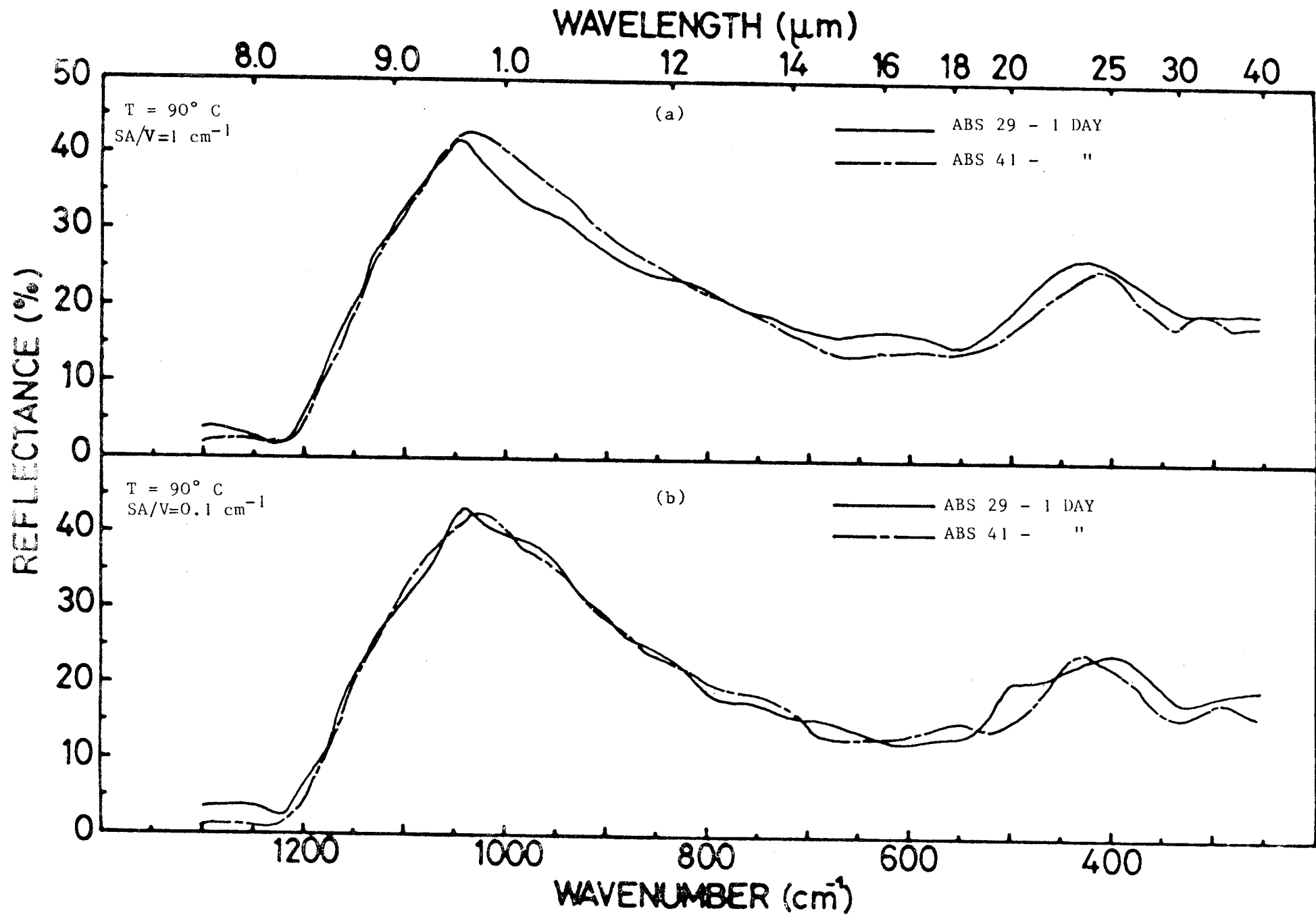


FIGURE 6

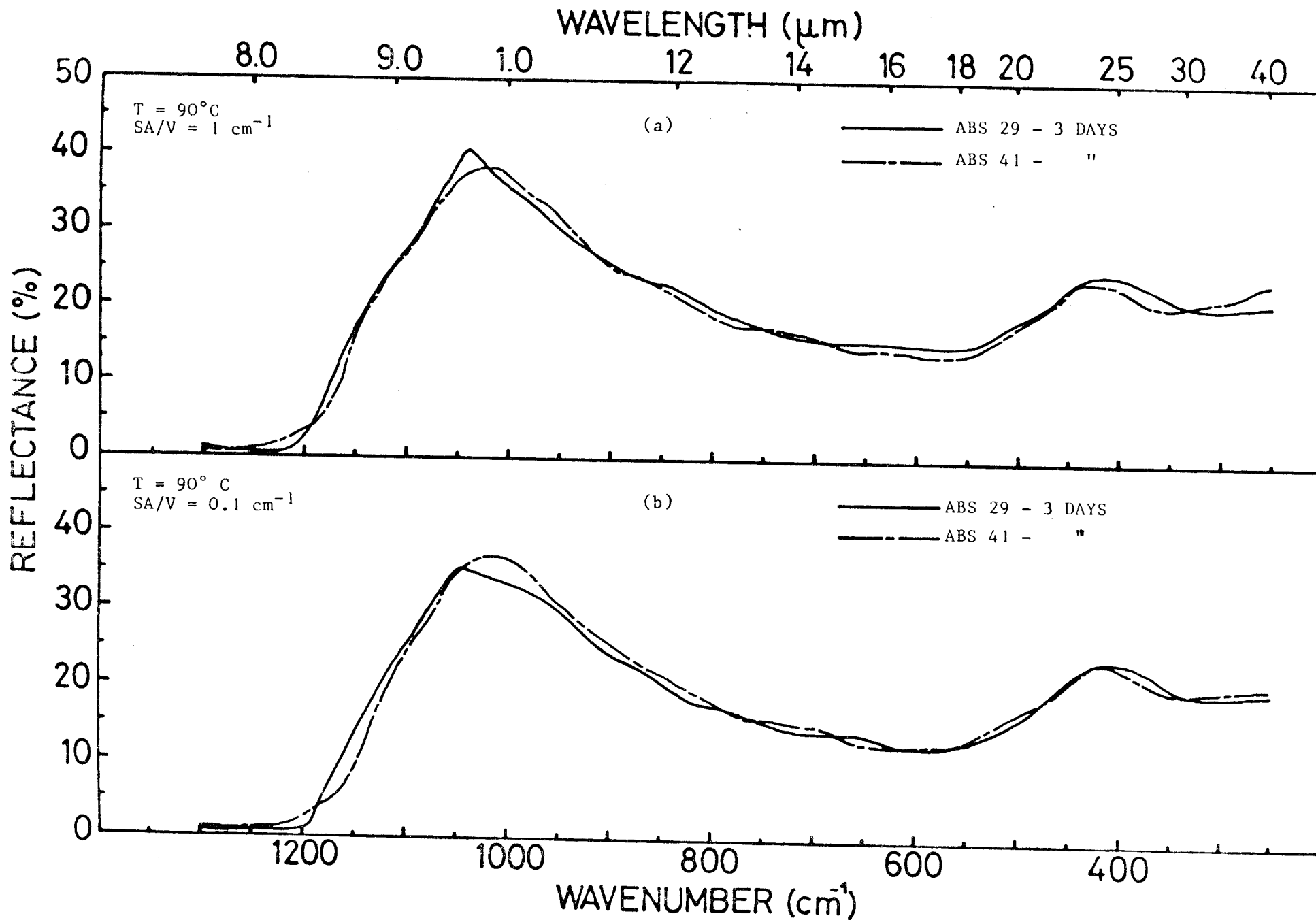


FIGURE 7

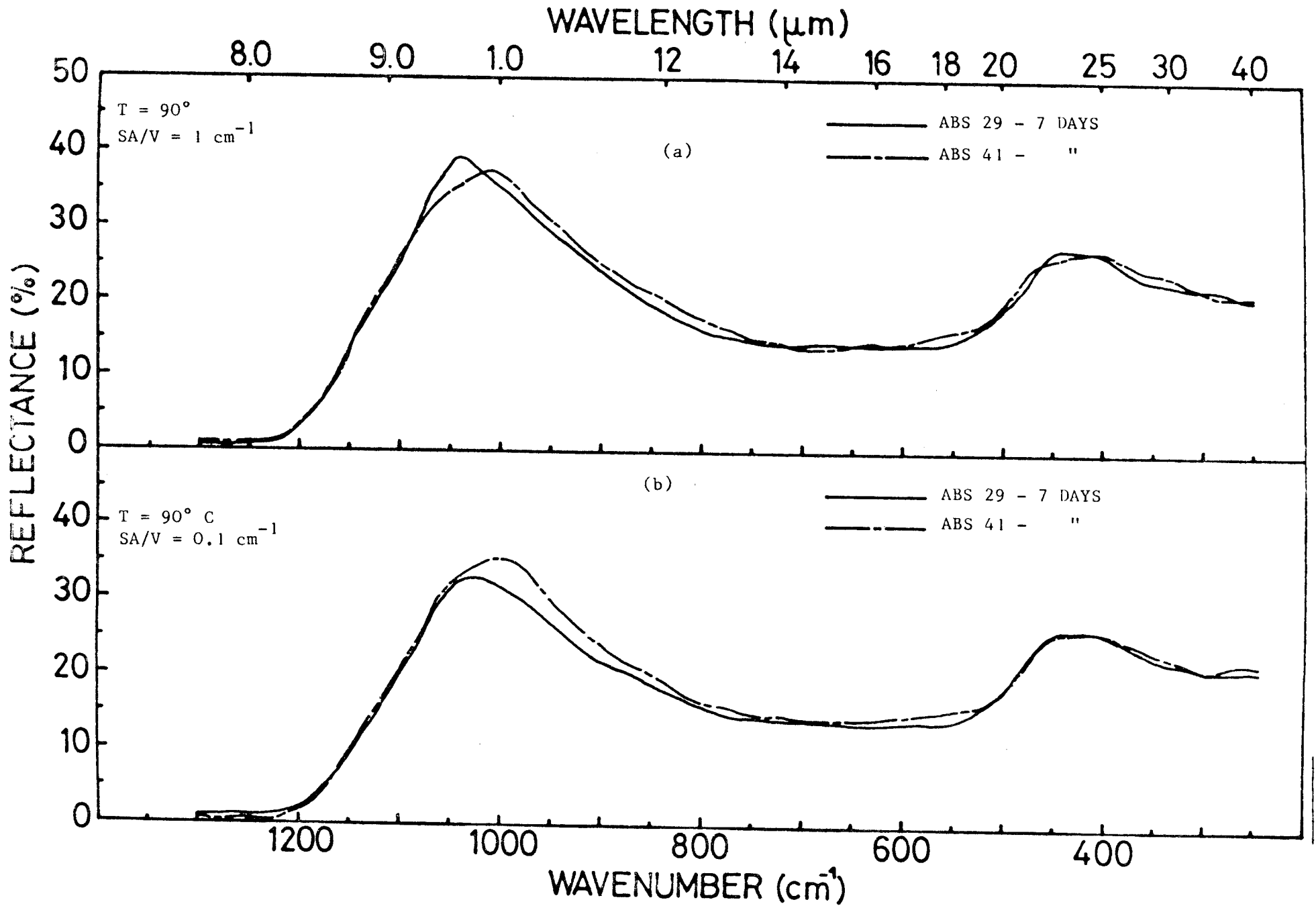


FIGURE 8

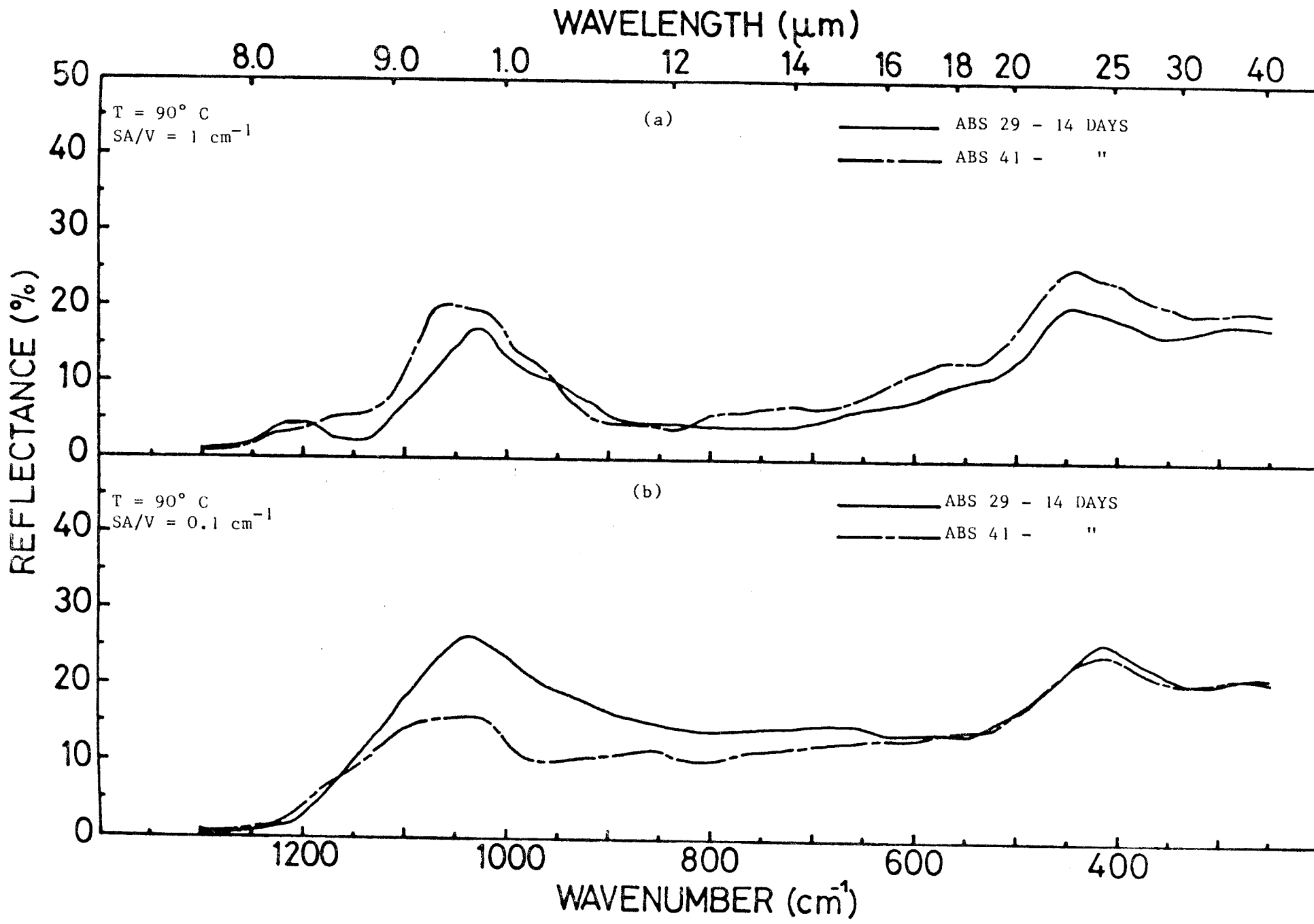


FIGURE 9

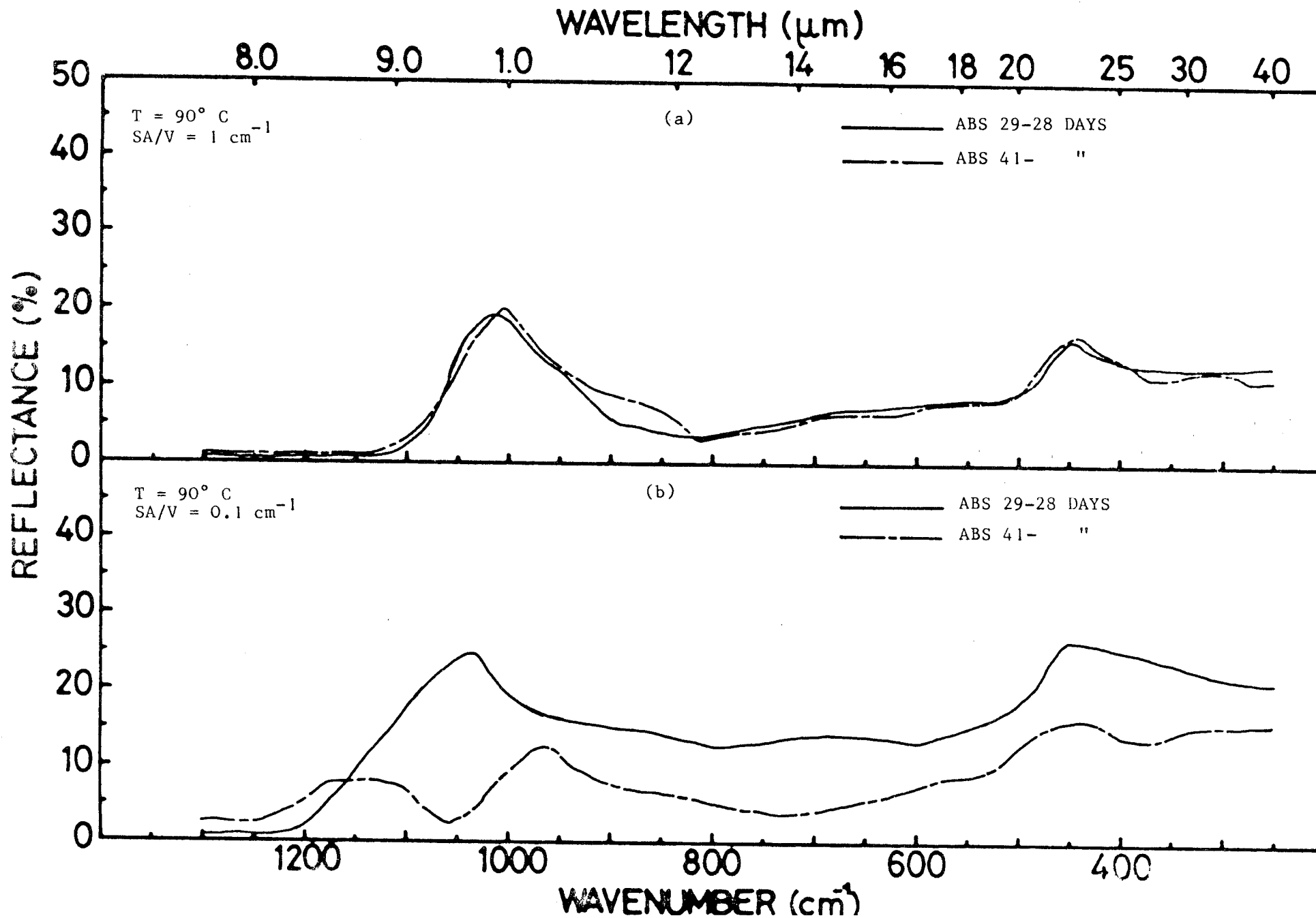


FIGURE 10

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- TR 81-12 Ion diffusion in compacted sodium and calcium bentonites
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