

MELTING PROPERTIES OF VOLCANIC ASH

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ABSTRACT

Volcanic ash from eastern Aleutian volcanoes (typical of circum-Pacific volcanoes) is composed of rhyolitic (silica-rich) glass, minerals (feldspars, pyroxene, hornblende and Fe-Ti oxides), and rock fragments. Melting temperatures of the glasses, estimated from liquidus phase relations in the system $\text{SiO}_2\text{-KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_8$, ranged from 1,000°C to 1,300°C, whereas minerals begin melting at about 1,100°C.

Volcanic ash that is ingested into operating turbofan engines will partially melt (i.e., all of the glass and some of the minerals). The molten ash is then deposited on high-temperature parts of the turbine—this can result in engine shutdown.

Reduction of engine operating conditions to idle settings lowers the engine temperatures below the melting point of volcanic glass (below 1,000°C), thus preventing the melting of ingested volcanic ash. However, at idle conditions, engines still operate at temperatures in excess of the glass transition temperature (700°–860°C), and annealing of glass particles to hot parts of the turbine may still be a problem.

INTRODUCTION

Volcanic ash is a widespread product of eruptions of volcanoes that are located around rim of the Pacific Ocean. Ash is formed by explosive fragmentation and quenching of magma (crystals + melt + gas) during an eruption. Melt in the magma is quenched to a glass when the temperature is rapidly lowered upon exposure to atmospheric conditions. The explosive character of these volcanoes is caused by the silica-rich melt, which often contains dissolved volatile components, such as H_2O or SO_2 . Crystallization of mineral phases (e.g., plagioclase, pyroxene, hornblende, Fe-Ti oxides, etc.) gradually enriches non-crystallizing components in the melt. In the case of components like silica or sodium, their concentrations in the crystallizing phases are low relative to their concentration in the melt, resulting in their overall enrichment. Bulk lava compositions from these volcanoes range from basalt to dacite (lavas generally contain from 48 to 70 weight percent SiO_2), and the melt fraction between mineral grains is andesitic to rhyolitic (53–78 weight percent SiO_2). The glassy fragments in

volcanic ash are the non-crystalline part of the magma and, hence, have the lowest crystallization temperature. Conversely, the glass also has the lowest melting temperature. When volcanic ash is ingested into operating jet aircraft engines, it is the glass particles that will melt first. As aircraft engine operating temperatures are lowered in an effort to reduce the ash fusion within the engine (Campbell, this volume; Casadevall and others, 1991; Przedpelski and Casadevall, this volume), it is the melting temperature of glass particles that will determine the operating temperatures below which the ash will not melt in the engine. The purpose of this paper is to review the compositions of glasses found in volcanic ashes from typical circum-Pacific volcanoes and to estimate their melting temperatures by comparison to published phase diagrams available in the geological and engineering literature. We report here on the melting properties of the more common silica-rich glasses. Mafic (andesitic) glass, similar to that erupted in the 1992 eruption of Mt. Spurr (Alaska), is currently under study and will be the subject of a future report. Alaskan volcanoes in the eastern Aleutian arc were selected for study because of their recent activity and potential hazard to aircraft safety (Steenblik, 1990; Przedpelski and Casadevall, this volume; Kienle, this volume). Several Alaskan volcanoes in the eastern Aleutian arc (fig. 1) have produced widespread volcanic-ash deposits that have covered south-central Alaska. Ash may be produced in short-lived, large eruptions (Novarupta in 1912, Spurr in 1953 and 1992) or in a series of intermittent, small eruptions (Redoubt Volcano, 1989–90). Jet aircraft encounters with ash have been recorded from eruptions of Augustine in 1976 and Redoubt in 1989 (Steenblik, 1990; Casadevall, 1991; Kienle, this volume).

METHODS OF STUDY

All of the glass samples used in this study were obtained from volcanic ash deposits from south-central Alaska. The White River ash and the ash from Hayes Volcano are voluminous prehistoric ashes that covered south-central Alaska (Riehle, 1985; Westgate, 1990; Beget and others, 1991). Novarupta, which erupted in 1912, is the largest historic Alaskan eruption and spread ash throughout southern Alaska (Griggs, 1922; Hildreth, 1987). Ash from Augustine Volcano, the most active volcano in the eastern

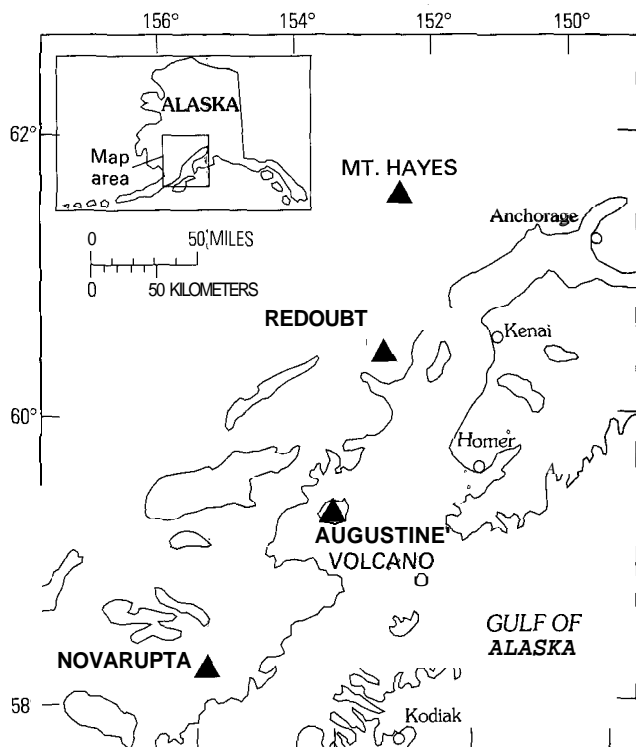


Figure 1. Volcanoes (solid triangles) in the eastern Aleutian volcanic arc, Alaska.

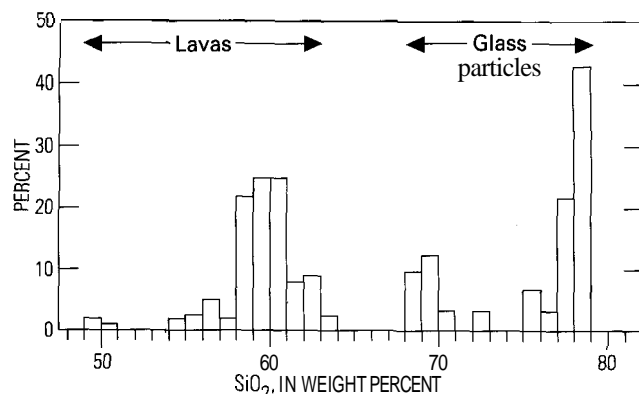
Aleutian arc, was collected from prehistoric deposits on Augustine Island that span approximately 2,700 years of eruptive history (Swanson and Kienle, 1986; Beget and Kienle, 1992). Ash from Redoubt Volcano is represented by samples from the 1989–90 eruption. Together, this suite of samples provides a representative collection of the ashes that is to be expected from eruptions of these Alaskan volcanoes.

ANALYTICAL TECHNIQUES

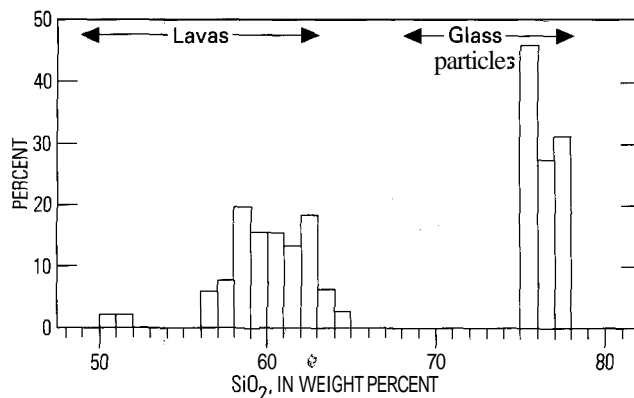
Glass from these ash samples was analyzed with a Cameca MBX electron microprobe at Washington State University using a 15-kV electron beam and a sample current of 13.5 nA. A beam spot diameter of 8 μm was used, and the counting time was 10 seconds. The glass analyses are reported as oxides and are normalized to 100 percent. Actual totals ranged from 98 to 100 percent, depending on the degree of hydration (water in the glass.) Well-characterized natural glasses were used as standards (KCl was used for Cl measurements).

RESULTS

When compared with lavas, glass particles (shards of quenched melt) in the volcanic ash from Alaskan volcanoes are much richer in silica as a consequence of crystallization



A



B

Figure 2. Silica contents of lavas (bulk samples) and glass particles (shards) in volcanic ashes from A, Redoubt and B, Augustine Volcanoes. The numbers of analyses of lavas and glasses from each volcano are in excess of 50 and have been normalized to 100 percent for comparison. Volcanic glass is consistently higher in silica than the whole-rock lavas. Glass analyses are from unpublished data in the authors' files (representative analyses given in table 1). Lava compositions for Augustine Volcano are from Kienle and others (1983) and Daley (1986); compositions for Redoubt Volcano are from Nye and others (in press) and Swanson and others (in press).

to form phenocryst minerals before eruption. For example, lavas from Redoubt Volcano have basaltic and andesitic bulk compositions (50–64 weight percent SiO_2 , fig. 2), whereas the glass in the volcanic ash from the 1989–90 eruption of Redoubt ranges from 69 to 78 weight percent SiO_2 (fig. 2). Similar relations are shown for Augustine Volcano (fig. 2), but the Augustine glasses show a more restricted range of compositions (75–78 weight percent SiO_2).

Representative glass compositions are shown in table 1 both as weight percent oxide and as normative minerals. The normative composition is the rock analysis recalculated to a set of standard anhydrous normative minerals. For silica-rich volcanic rocks or glasses, the abundant normative minerals are quartz (Q), albite (Ab), and orthoclase (Or), with lesser amounts of anorthite (An), corundum (C), hypersthene (Hy),

Table 1. Representative electron microprobe analyses of volcanic glass from ash from Alaskan volcanoes.

[Analyses are presented as weight percent of oxides and as normative minerals (see text for explanation of normative minerals). Numbers in parentheses represent units of standard deviation]

Quantity analyzed	Redoubt Volcano (12/15/89)			Augustine Volcano		Hayes Volcano	White River ash	Novarupta		
Analyses expressed as weight percent of oxides										
SiO ₂	69.35 (0.45)	71.91 (0.31)	75.94 (0.36)	77.81 (0.35)	75.38 (0.36)	76.36 (0.31)	73.65 (0.36)	73.77 (0.43)	78.20 (0.37)	76.94 (0.17)
TiO ₂	0.51 (0.11)	0.45 (0.03)	0.31 (0.07)	0.22 (0.01)	0.39 (0.04)	0.37 (0.06)	0.23 (0.03)	0.21 (0.02)	0.18 (0.06)	0.35 (0.07)
Al ₂ O ₃	15.59 (0.54)	14.75 (0.16)	13.32 (0.21)	12.40 (0.18)	12.98 (0.10)	12.58 (0.17)	14.50 (0.14)	14.54 (0.26)	12.00 (0.15)	12.29 (0.12)
Fe ₂ O ₃ total	3.26 (0.31)	2.58 (0.14)	1.46 (0.22)	1.22 (0.09)	2.30 (0.15)	2.06 (0.12)	1.94 (0.21)	1.71 (0.14)	1.34 (0.15)	1.87 (0.13)
MgO	0.87 (0.17)	0.67 (0.02)	0.30 (0.11)	0.23 (0.03)	0.49 (0.05)	0.43 (0.05)	0.54 (0.03)	0.36 (0.03)	0.14 (0.05)	0.26 (0.04)
CaO	3.25 (0.29)	2.48 (0.10)	1.57 (0.25)	1.16 (0.10)	2.28 (0.27)	2.04 (0.16)	2.23 (0.10)	1.85 (0.11)	0.85 (0.19)	1.27 (0.09)
Na ₂ O	4.37 (0.18)	4.21 (0.08)	3.92 (0.21)	3.71 (0.12)	3.95 (0.13)	3.89 (0.09)	3.93 (0.08)	4.16 (0.13)	4.07 (0.13)	3.98 (0.13)
K ₂ O	2.54 (0.12)	2.79 (0.11)	3.04 (0.14)	3.14 (0.17)	2.00 (0.27)	1.98 (0.08)	2.62 (0.11)	3.07 (0.10)	3.03 (0.10)	2.85 (0.08)
Cl	0.17 (0.08)	0.16 (0.02)	0.15 (0.04)	0.13 (0.06)	0.24 (0.11)	0.29 (0.07)	0.36 (0.03)	0.33 (0.03)	0.19 (0.03)	0.19 (0.03)
n ¹	11	7	5	7	18	16	15	15	18	10
Analyses recast as normative minerals										
Q	26.04	30.43	37.69	41.38	39.13	41.14	35.18	33.32	40.90	39.77
Or	15.01	16.49	17.97	18.56	11.82	11.70	15.48	18.14	17.91	16.84
Ab	36.98	35.62	33.17	31.39	33.42	32.92	33.25	35.20	34.44	33.68
An	15.70	12.30	7.7	5.75	11.31	10.12	11.06	9.18	4.22	6.30
C	0.00	0.30	0.73	0.79	0.17	0.33	1.14	1.01	0.48	0.35
Hy	2.17	1.67	0.75	0.57	1.22	1.07	1.34	0.90	0.35	0.65
Hm	3.26	2.58	1.46	1.22	2.30	2.06	1.94	1.71	1.34	1.87
Tn	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ru	0.39	0.45	0.31	0.22	0.39	0.37	0.23	0.21	0.18	0.35

¹ Number of points per analysis, n.

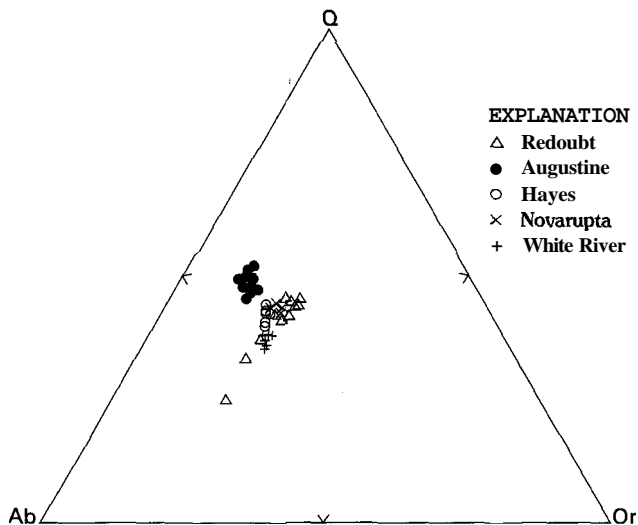


Figure 3. Normative compositions (in terms of albite, Ab; orthoclase, Or; and quartz, Q—see text for explanation) of glasses from the White River ash, the 1912 eruption of Novarupta, and eruptions of Mt. Hayes and Augustine and Redoubt Volcanoes. The Redoubt data are for glasses from the 1989–90 eruption. White River, Augustine, and Hayes data are from prehistoric ashes. Mt. Hayes data are from Beget and others (1991); other data are from the authors' unpublished files.

hematite (Hm), sphene (Tn), and rutile (Ru). The recalculation of the oxide components into normative minerals facilitates comparison of glass compositions to experimental laboratory results on melting temperatures of rocks.

Glass compositions displayed on triangular variation diagrams, with normative components as the variables, cluster into fields for each suite of glasses (fig. 3). Glasses from single, short-lived eruptions (e.g., White River ash and Novarupta) cluster in small fields, whereas glasses from multiple eruptions (Augustine and Hayes) define slightly larger fields. The 1989–90 Redoubt glasses form a range of compositions related to the mixing of two different magmas (with different compositions of melt quenched to glass) in the early (December 1989) stages of the eruption (Swanson and others, in press).

MELTING RELATIONS OF GLASSES

Liquidus phase relations (temperatures required to completely melt a solid) at a pressure of 1 bar in the system SiO_2 (quartz, Q)— KAlSi_3O_8 (orthoclase, Or)— $\text{NaAlSi}_3\text{O}_8$ (albite, Ab) are shown in figure 4. This system is well known to geologists as the "granite system" because of its use in describing the melting and crystallization behavior of granitic rocks. The triangular composition diagram is divided into primary phase fields by boundary curves. Isotherms (lighter solid lines that represent constant

temperature) describe the melting temperatures for any solid that contains the normative minerals quartz, orthoclase, and albite (fig. 4). The boundary curve between the primary phase fields of the SiO_2 polymorphs cristobalite (Cr) and tridymite (Tr), and alkali feldspar (Af) has a temperature minimum (m, fig. 4) at 960°C . For any combination of these three normative minerals (quartz-orthoclase-albite), melting at 1 bar will initially start at 960°C , and the composition of the first melt will correspond to m (fig. 4). The incongruent melting of K-feldspar (Or) at low pressure is represented by the boundary curve between alkali feldspar (Af) and leucite (Lc) phase fields (fig. 4). The small (10–20 bar) pressure increase within operating turbofan engines does little to change the 1 bar melting relations of figure 4.

In addition to the albite (Ab), orthoclase (Or), and quartz (Q) components, the volcanic glasses contain appreciable normative anorthite (An) (table 1). Addition of the anorthite component raises the melting temperatures relative to the anorthite-free albite-orthoclase-quartz compositions; however, the magnitude of this effect is difficult to predict, especially for this system without water. Experiments done on ingestion of dust containing appreciable anorthite component along with albite, orthoclase, and quartz into operating jet engines find that ash begins to melt at temperatures of about $1,000^\circ\text{C}$ (Kim and others, 1992). These results are in good agreement with the predictions from figure 4, where

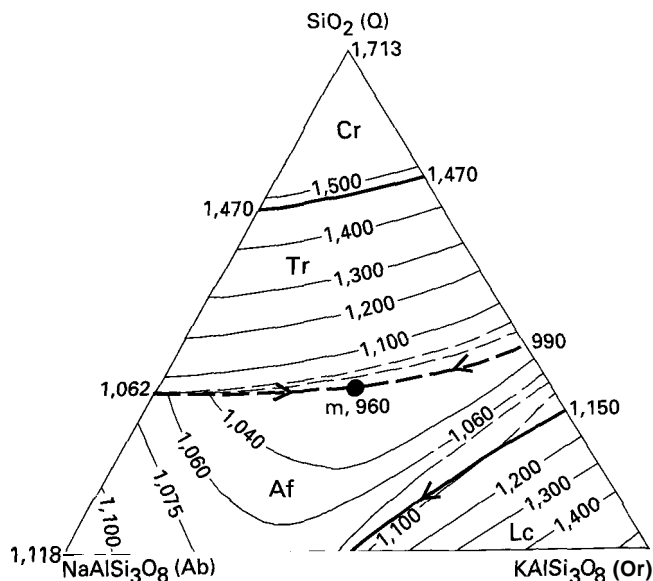


Figure 4. Liquidus phase diagram for the system Ab-Or-Q at one bar pressure, modified from Schairer (1950). Heavy lines are boundary curves with arrows indicating the direction to lower temperature. Primary phase fields are shown for cristobalite (Cr), tridymite (Tr), alkali feldspar (Af), and leucite (Lc). Symbol, m, indicates temperature minimum on boundary curve between cristobalite/tridymite and alkali feldspar. See text for further explanation.

the beginning of melting for anorthite-free compositions occurs at 960°C. Thus, the effect of anorthite on melting relations seems small and is probably on the order of less than 50°C. Melting of any volcanic glass that contains normative quartz, orthoclase, and albite can be modeled in the system albite-orthoclase-quartz, as illustrated for the glasses in this study on figure 5. Augustine glasses plot between the 1,200°C and 1,300°C isotherms; the glasses from the Hayes Volcano and Novarupta plot between the 1,100°C and 1,200°C isotherms; and White River glasses plot near the 1,100°C isotherm (fig. 5).

The large field of Redoubt glass compositions (fig. 5) is caused by variation in composition of glass shards erupted during December 1989 (table 1) and gives a melting range of 1,000°–1,200°C. These glasses (with the higher silica contents—77 to 78 weight percent SiO₂) were erupted from December 1989 to April 1990; they melt at temperatures of 1,100°C to 1,200°C. Lower silica glasses (68 to 73 weight percent SiO₂) were only erupted during December 1989 and melt at lower temperatures: 1,000°C to 1,100°C.

Maximum-cruise operating temperatures of high performance turbofan engines currently used on long-range commercial aircraft (747-400, DC-10, etc.) are on the order of 1,400°C (E.E. Campbell, Boeing Co., oral commun., 1991; Kim and others, 1992). Most of the compositions in the system albite-orthoclase-quartz are above liquidus temperatures at 1,400°C (fig. 4) and includes all the volcanic glasses modeled in this study (fig. 5). Indeed, some of the minerals found in the volcanic ash (e.g., sodic plagioclase) will also melt at 1,400°C. Ingestion of volcanic ash by turbofan engines effectively grinds the ash to fine particles ($\cong 7 \mu\text{m}$;

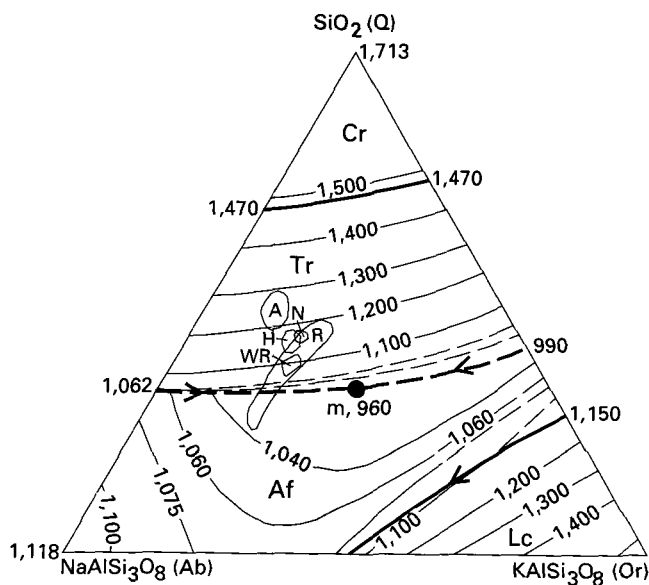


Figure 5. Composition fields of volcanic glasses (fig. 3) on liquidus Ab-Or-Q phase diagram at 1 bar pressure showing isotherms that define melting temperatures for various glasses. A, Augustine; N, Novarupta; H, Hayes; WR, White River; R, Redoubt.

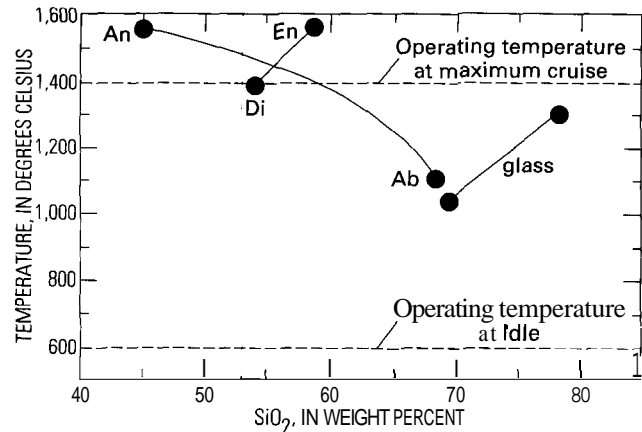


Figure 6. Melting relations of plagioclase (An-Ab), pyroxene (Di-En), and volcanic glasses (from fig. 5) at 1 bar pressure. Dashed lines represent the approximate operating temperatures of typical high-performance turbofan engines at idle and maximum-cruise conditions.

Casadevall and others, 1991) and, in the process, erodes the tips of the compressor airfoils (Przedpelski and Casadevall, this volume). This combination of small ash particle size and the high operating temperatures of the engine ensures that much of the volcanic ash will melt upon ingestion into an operating engine and be deposited on the turbine (specifically on the high-pressure nozzle guide vanes).

A reduction of engine thrust to idle has been recommended if a jet aircraft encounters volcanic ash in the air (Campbell, this volume; Przedpelski and Casadevall, this volume). Turbofan engines operating at idle run at about 600°C, considerably below the melting temperatures of all volcanic glass (fig. 6). Cooling of turbofan engines from normal operating temperatures (1,400°C) to idle temperatures is almost instantaneous. Volcanic ash will not melt when ingested into the engines at idle conditions (600°C). In addition, the rapid cooling from operating conditions to idle thrust setting induces a thermal shock related to the differential thermal expansion of the molten glass and the engine-metal substrate that can remove much of the previously melted glass that was deposited in the engine.

CONCLUSIONS

Ingestion of volcanic ash by high performance turbofan engines at operating conditions melts glass shards and some of the minerals that make up the ash (fig. 6). Volcanic glass compositions can show wide variations and still be melted upon ingestion into the engine because of high engine operating temperatures. Operating temperatures must be lowered below the lowest melting temperature ($\cong 1,000^\circ\text{C}$ for glass, fig. 6) to prevent melting of ingested volcanic ash. Reduction of engine operating conditions to idle settings ($\cong 600^\circ\text{C}$) will prevent melting of ingested volcanic ash.

RECOMMENDATIONS

Industry recommendations involving aircraft encounters with airborne volcanic ash (Lloyd, 1990; Campbell, this volume; Przedpelski and Casadevall, this volume; AIA, 1991) emphasize the need to exit the ash as quickly as possible and to reduce engine thrust to idle. Reduction of engine operating temperatures will prevent the melting of volcanic ash (including glass) ingested into the engines. Dynamic experiments done on ingestion of dust into operating engines (e.g., Kim and others, 1992; Dunn and Wade, this volume) should be done with volcanic ash (including an abundance of glass) at engine-idle temperatures. The question to be answered is whether glass particles can anneal and flow as a supercooled liquid above the glass transformation temperature (T_g), the temperature between lower temperature glass and higher temperature supercooled liquid (Carmichael and others, 1974). For most silicate glasses, T_g is about 0.66 of the melting temperature (Carmichael and others, 1974). Volcanic glasses in this study thus have glass transformation temperatures of about 700'–860°C. Will these volcanic glasses anneal at engine-idle conditions and adhere to the hotter parts of the engine? Probably not. The glass transformation temperatures are close to the idle operating temperatures (= 600°C), and the transit time of the ash through the engine is short. M.G. Dunn does not believe that glass annealing will occur (CALSPAN, oral commun., 1991) and does not find an adhesion of ash below 1,000°C in his experiments (Kim and others, 1992; Dunn and Wade, this volume). However, such ash-ingestion experiments should be tried at engine-idle conditions with a volcanic ash rich in volcanic glass.

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