Chemical Deicing of Aircraft Runways

W. P. CONRARDY
   Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio

•THE UNITED STATES AIR FORCE must operate under all weather conditions. The Air Defense Command, in particular, must be ready to scramble high-performance jet interceptors in any kind of weather and at a moment's notice. A dry, skid-free pavement is desirable for the safe take-off and landing of these aircraft.

Snow removal and ice control on airfields is a highly organized operation in many parts of the world. Standard practice is to remove the bulk of frozen precipitation by mechanical equipment such as plows, scrapers, and rotary brooms. Basically this solves the problem for launching aircraft, some of which would otherwise have difficulty reaching take-off speed in 2 or more inches of snow. However, landing aircraft and preventing skids during high-speed taxiing is a more critical problem. To stop a high-speed aircraft within the limits of runway available, braking conditions must be such that the aircraft can decelerate quickly without ground looping or running off the pavement. Safe, quick acting deicing chemicals are needed for control of thin layers of ice and snow not removed by mechanical means or for patch ice resulting from freeze and thaw cycles. Unfortunately, such chemicals meeting USAF requirements are simply not yet available. Consequently, the Air Force has tried a variety of unorthodox mechanical methods of ice removal without success. For example an attempt has been made to break up thin layers of ice with disc harrows followed by a sweeper for ice removal. However, ice adhesion on concrete is so tenacious that reasonable quantities of ice cannot be adequately removed by this or variations of the method in the time required. Considered also have been devices for melting the ice, such as road burners and jet engine exhausts, which are also much too slow to be practical. Coatings with very low adhesion to ice have been considered for use on both aircraft and runway surfaces. This presumably would facilitate breaking up and sweeping off the ice. Fluorinated hydrocarbons and some silicone materials have resulted in reduced adhesion (though not enough) on smooth aluminum surfaces but have had essentially no effect on concrete. The relatively rough surface of concrete pavement provides a strong mechanical bond to ice in addition to the very strong chemical bond normally encountered on most surfaces. To date no chemical method of ice control equivalent in effectiveness to chloride salt deicing has appeared. Therefore, the Air Force is forced to use sodium chloride and calcium chloride in those areas where ice is prevalent and active runways must be kept open.

Although suitable for highway use, loose abrasives are not used on jet runways because of the problem of ingestion into engines. The air intake suction of jet engines is such that loose objects can be sucked right through the engine. Large objects such as nuts and bolts can cause immediate disintegration of the engine; however, even small particulate matter such as sand and cinders cause severe erosion to compressor blades and turbine buckets. To avoid the use of corrosive chemicals and still provide braking action on runways, the RCAF in Canada sprays iced runways with water, and follows immediately with a sanding vehicle. The sand is held tightly by the ice formed and provides an abrasive surface which aids in braking aircraft. The amount of water and sand dispersed must be carefully controlled and such surfaces must be swept clean of loose material as it forms to keep the ingestion and erosion problem on turbine engine components under control.

Although civil engineers are concerned primarily with the effects of deicing chemicals on concrete pavements, the Air Force Materials people are much more interested in the effects of these materials on aircraft structural components. Concrete pavement deterioration is costly to repair; however, stress corrosion fractures of aircraft structures result in loss of life and loss of expensive first-line offensive and defensive weapons systems.

On low-strength materials such as the steels used in bridges and highway vehicles, corrosion is general, gradual and gives obvious evidence that maintenance is required, long before any failure occurs. In addition, quite effective preventive measures are employed in the form of protective coatings. It is common practice to undercoat vehicles, for example, and even when neglected, the corrosion problem is primarily one of annoyance and replacement cost. On the other hand, stress corrosion is extremely insidious. The USAF has experienced any number of failures from this cause, most of which showed little or no indication of corrosion on the surface before fracture of the part. Stress corrosion involves a complex interaction of sustained surface tension stresses and corrosive attack that results in rapid cracking and the premature brittle failure of a normally ductile material. The phenomenon has been observed in many metals and alloys, including both the low-alloy and stainless steels, high-strength aluminum alloys, titanium, and brass. There is apparently a direct relationship between the strength level of an alloy and its susceptibility to fracture by the stress corrosion mechanism.

The 7000 series aluminum alloys commonly used in modern aircraft are in the 65,000 psi yield strength range and above. Low-alloy steels commonly used in aircraft landing gear are all heat-treated to more than 200,000 psi and it is not uncommon to find them used in equipment at the 260,000 to 280,000 psi levels. Forgings made from materials at these high-strength levels are particularly susceptible to stress cracking because material in this form is often subjected to significant stress in the short transverse grain direction. Grain direction has a significant influence on stress cracking. An alloy is least susceptible in the longitudinal direction, more so in the transverse, and most susceptible in the short transverse. Therefore, stress cracking will occur at relatively low-stress levels if a given component is loaded in the short transverse direction and simultaneously exposed to a corrosive environment. In high-strength aluminum this stress level need be only 10 percent of its yield strength.

Components presenting the greatest difficulty are landing gear and heavy forgings such as in wing attachment fittings. Both are regularly exposed to the corrosive environment encountered on chemically treated runways during landing and take-off. Although protective coatings are often used, the erosion from particulate matter and other wear often leave these coatings chipped and damaged so that salts and other contamination can work on the base metal. Breakage of one of these components results in costly repairs, downtime and nonavailability of a weapons system, and perhaps loss of life or injury to the crew.

In view of the preceding, the following requirements for deicing compounds are desirable: (a) ability to melt ice quickly at temperatures to -40 F; (b) noncorrosive to aircraft materials; (c) no ingestion hazard to aircraft gas turbines; (d) nonlubricating on the runway; (e) minimum deteriorating effect on the pavements; (f) easy dispersal using conventional equipment; and (g) economical usage. These requirements eliminate the wholesale use of abrasives and the use of liquid deicing materials such as the glycols. Ideally, the material should be solid, free flowing, and granulated. The only material which presently meets most of these requirements is urea, but it is ineffective below 12 F.

Because the use of the ideal deicing material would be restricted to runways and taxiways, and then only for control of patch ice in most instances, it is not absolutely essential that this product compare in price with rock salt (NaCl). A higher cost material, within reason, could be justified on the basis of increased safety and reduced maintenance costs.

The Air Force Materials Laboratory has never pursued a development program for such a material; however, over the past several years a number of commercially

available materials have been evaluated, including sodium chloride (NaCl), calcium chloride ($CaCl_2$), ammonium sulfate, urea, and urea-formamide-acetamide mixtures. Various proprietary corrosion inhibitors were studied; however, all were variations of the first three materials and caused severe pitting, general corrosion and stress cracking of aluminum, magnesium and steel. As a general class, the inorganic chemicals examined are all similar in this regard, differing mainly in degree. The two organic materials are relatively noncorrosive but have limited utility. Urea has a relatively high slush point (about +12 F) and the mixture is more of a paste than a free-flowing solid.

EVALUATION PROCEDURES AND DATA

As a quick and easy method of determining slush points, a saturated solution (room temperature) of each material in water is cooled in a dry-ice-in-solvent bath with constant stirring and the temperature of the solution is recorded at the point where slush forms.

A semiquantitative measurement of the ability of several materials ($CaCl_2$ as the dihydrate, NaCl, urea and the urea-formamide-acetamide mixture) to melt ice or to make it slush was also conducted.

The tests were made by measuring how far a penetrometer rod with a $3/4$-in. ball at the end would penetrate about 8 mm ($5/16$ in.) of ice. The rod was loaded to 1 lb. The materials, generally applied at a rate of $1/4$ psf but with some at $1/2$ psf, were tested until failure at 15, 0, -10, -30, and -50 F.

Summary

1. Only $CaCl_2$ was effective at all test temperatures, and was the only one of practical value below 0 F. At higher temperatures, it was more effective than the others because of quicker action.

2. NaCl is quite useful at 15 F, but heavy application is required to melt an appreciable amount of ice at 0 F. It is useless at -10 F.

3. The penetrometer sank $1/8$ in. into the ice at 15 F in 1 hr when the amide mixture was applied at $1/4$ psf, but only one-fourth as far at 0 F. Doubling the application rate produced a negligible increase at 0 F.

4. Urea was about as good as the mixed amides at 15 F, but had no effect at 0 F.

5. Under the test conditions, no slush was formed in any of the trials. The materials dissolved to whatever extent they would to form solutions, under which was hard ice.

Static Corrosion Tests

Conventional static corrosion testing on a number of metals and alloys was also conducted by immersing small coupons in a water solution of the deicing chemical, observing weight changes, discoloration, and pitting. The following results were obtained:

1. Uninhibited chlorides will etch and pit aluminum and magnesium alloys and cause general rusting of low-alloy steels.

2. Ammonium sulfate-type materials are very severe on magnesium, in some cases causing complete disintegration.

3. Some inhibited chloride solutions showed very little effect on aluminum, magnesium and steel on these unstressed specimens. This is not the case for metals under stress.

4. Urea has little or no effect on aluminum or steel. It is comparable to the blank water controls and, in fact, somewhat inhibits the general rusting of steel. Urea and other amides will cause some corrosion on copper alloys.

STRESS CORROSION EVALUATION PROCEDURES AND DATA

To establish the effect of these deicing chemicals on aircraft structural materials under stress, another series of corrosion tests were conducted. The first series of
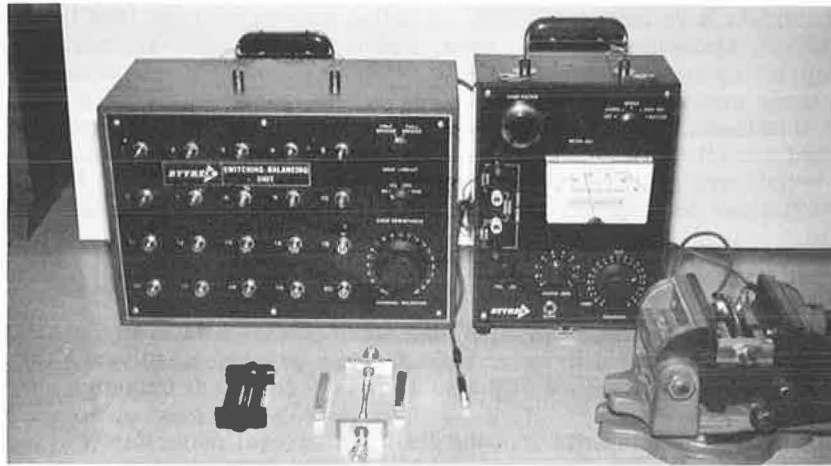
Figure 1. Test specimen, fixture and strain gage instruments used for loading specimen.

tests were conducted using metal specimens already available. The deicers used were NaCl, CaCl₂ and urea.

2014 Aluminum Alloy

Procedure. —2014-T6 aluminum alloy machined specimens cut from the longitudinal direction were used. The specimen, its fixture, a jig vise used for applying stress to the specimen fixture and strain gage instruments are shown in Figure 1. Each specimen was loaded to 80 percent of yield strength, determined by averaging data from three stress-strain curves for each specimen. After loading, each specimen and fixture was completely painted with stop-off lacquer except for the gage length of the specimen. Salt solution concentrations were arbitrarily selected at saturation for 32 F.

The stress corrosion test was conducted at room temperature, which varied between 68 and 78 F. The specimens were alternately immersed in nitrogen gas-agitated solutions for 10 min, then air-dried for 20 min. The specimens were removed, washed with distilled water, and dried at the end of each day because observations were made on the day shift only. After 230 cycles, or 115 hr of testing, some of the specimens were removed from their fixtures and pulled in the tensile testing machine.

Results. —Specimens exposed to saturated NaCl solutions showed pitting after only 20 hr of testing (Table 1). Specimens in the saturated urea solution did not show any general corrosion before 100 hr of testing. Whereas general corrosion was well advanced on the NaCl specimens, there was no visible evidence of stress corrosion cracking at the time they were checked for physical properties by tensile testing. The ductility of all exposed specimens was reduced by about the same

TABLE 1

RESULTS OF STRESS CORROSION TESTS ON 2014 ALUMINUM ALLOYS

Specimen Number	Salt Sol.	Temperature (°C)	Ultimate Strength (psi)	Yield Strength (psi)	Elongation (%)	Pitting Initiated After (hr)
2014T-02	-	-	82,500	62,400	16.0	-[a]
2014T-04	-	-	84,100	65,200	-	-[a]
2014T-13	-	-	82,100	62,400	16.0	-[a]
2014T-14	-	-	85,600	64,700	16.0	-[a]
2014T-03	NaCl	21-26.5	82,200	64,600	9.3	20
2014T-05	NaCl	21.5-26	81,000	63,200	9.3	20
2014T-06	NaCl	21.5-26.5	80,900	64,300	9.3	20
2014T-07	CaCl₂	21-26.5	-	-	-	25
2014T-08	CaCl₂	22-27.5	82,900	64,900	9.3	25
2014T-09	CaCl₂	19-24.5	-	-	-	25
2014T-10	Urea	21.5-26.5	-	-	-	100
2014T-11	Urea	21.5-26.5	81,900	62,800	11.0	100
2014T-12	Urea	19.5-26	-	-	-	100

[a]Unexposed control specimen.

Figure 2. Specimen corroded by exposure to NaCl solution and pulled.

Figure 3. Specimen corroded by exposure to CaCl₂ and pulled.
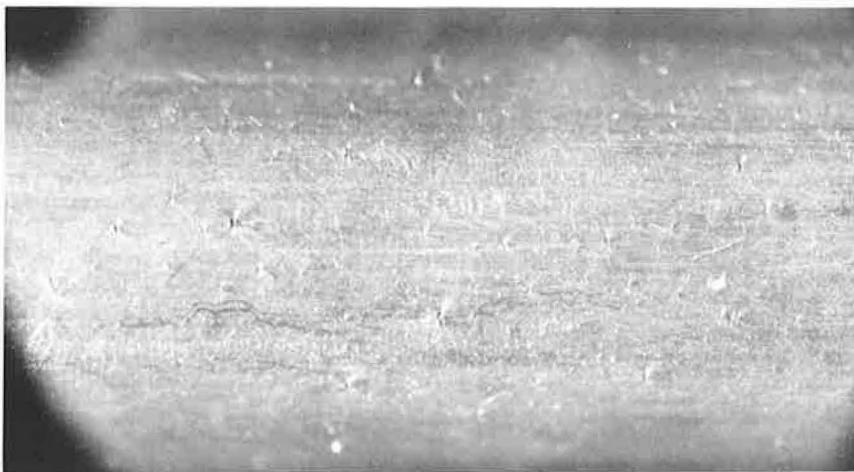

Figure 4. Specimen corroded by exposure to urea solution and pulled.

amount as indicated by the elongation data. A distinctive corrosion pattern was produced by each type of salt solution. A comparison of these surfaces shows that the specimen exposed to NaCl (Fig. 2) was appreciably more corroded than the specimens exposed to either $CaCl_2$ (Fig. 3) or urea (Fig. 4) solutions.

General corrosion was most severe with NaCl and least severe with urea. Whereas there was no visible evidence of stress corrosion cracking, all corrosion tested specimens tested for tensile strength showed increased brittleness over the unexposed specimens pulled for determining the yield strength. The lack of stress corrosion cracking was attributed to the use of specimens cut from the longitudinal direction, which is the least susceptible to this type of cracking. Because aircraft structural components are also stressed in the transverse direction, all subsequent test specimens were prepared with that in mind.

7079-T6 High Strength Aluminum Alloy

A second series of tests was conducted using specimens cut from the long transverse direction (Fig. 5) of a forged billet of 7079 aluminum in the T-6 condition (i.e., solution heat-treated and artificially aged). As in the initial test series, the aluminum test specimens were preloaded to 80 percent of their yield strength and exposed at room temperature under alternate immersion in solutions (saturated at 32 F) of NaCl, $CaCl_2$, urea and an amide mixture. The tests were conducted on a 24-hr day, 5-day week basis.
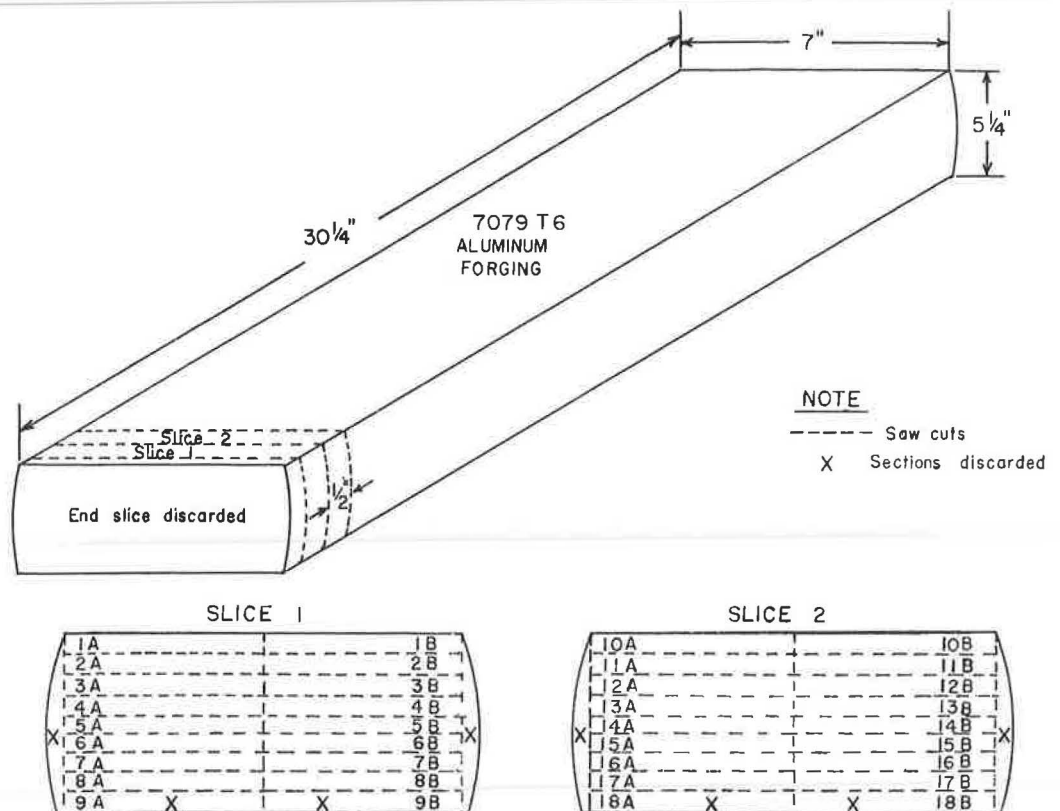

Figure 5. Location of tensile blanks cut in long transverse direction from 7079-T6 aluminum forging.

Procedure. —A 5¼- by 7- by 30¼-in. forged billet of 7079-T6 aluminum alloy was procured. The physical properties of this forging surpassed minimum requirements of AMS 4138, which specified a minimum tensile strength of 70,000 psi and a yield strength of 60,000 psi with a 6 percent elongation in the long transverse direction.

Tensile specimen blanks were cut from the long transverse direction of this forging, as shown in Figure 5. A ¾-in. slice was cut from the end of the forging and discarded. Because specimens cut from end slices often exhibit erratic effects due to unusual end grains produced during forging, the next two ½-in. slices were sawed into specimen blanks located as shown. Blanks 9 and 18 proved undersized and were discarded. All remaining specimen blanks were then machined to ASTM Standard (E8-57T) small-size specimen dimensions. The gage length sections of each specimen were carefully polished with No. 600 metallographic paper.

The machined specimens were then cleaned with acetone and two strain gages were cemented, using Armstrong Cement A-2, 180° apart on the gage lengths of each specimen. The specimens were then mounted in jigs and loaded to the proper stress level. Once the loaded specimens were stabilized, the strain gages were removed. The jig and everything except the test gage section of the specimens were coated with stop-off lacquer. Following this, the jigs were mounted in the apparatus (Fig. 6) which provided alternate immersion in the test solutions and air-drying of the specimens.

Room-temperature solutions of NaCl, $CaCl_2$, urea and the amide mixture were used as the corrosive media. Solutions were prepared by dissolving the following quantities of each ice melting material in 2 liters of distilled water: NaCl (technical grade) 700 gm; $CaCl_2$ (technical grade), 1,180 gm; urea (technical grade), 1,560 gm; and mixed
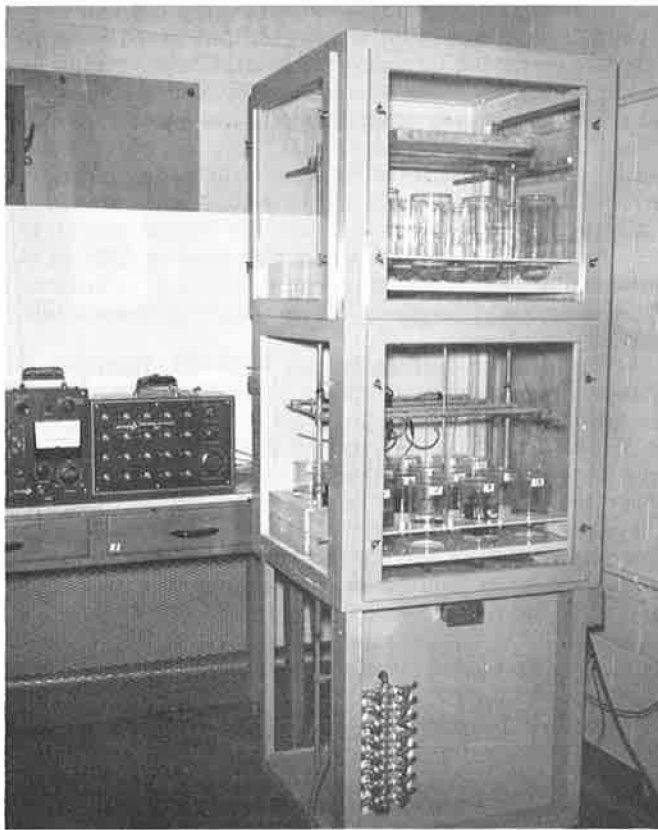

Figure 6. Apparatus for alternate immersion of specimen in ice melting solutions and suspending in air.

TABLE 2

RESULTS OF TENSILE TESTS ON
7079-T6 ALUMINUM

Specimen	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)
1A	74,700	64,400	7
4A	74,100	63,700	9.4
8B	73,700	63,900	7
11B	74,900	63,700	8
14B	73,400	63,500	7
Avg.	74,200	63,800	8

TABLE 3

TIMES-TO-FAILURE OF 7079-T6 ALUMINUM
ALLOY SPECIMENS SUBJECTED TO CYCLIC
STRESS CORROSION[a]

Salt Sol.	Specimen	Time-to-Failure (hr)
CaCl$_2$	13B	82
	15A	220
	5B	318
	2B	493
	Average	333
NaCl	5A	138
	13A	238
	2A	588
	Average	321
Mixed Amides	17B	536
	6A	543
	4B	938[b]
	Average (pseudo)	672[b]
Urea	14A	355
	3A	938[b]
	11A	938[b]
	12A	938[b]
	Average (pseudo)	792

[a] In saturated solutions at 32 F of ice melting salts.
[b] Test halted before specimen failure to start new series of stress corrosion tests.

amides, 1,180 gm. The quantities of ice melting material used for each 2 liters of water were based on the approximate solubility of each material at 32 F, an approximation of the condition encountered on runways. Distilled water was used for the preparation of each solution because it was felt that distilled, rather than tap, water would more closely simulate melted snow or ice found on runways. To minimize stratification of the test salt solutions, each beaker contained a fritted glass plate bottom, and a small amount of nitrogen was bubbled continuously through the solution during the test period.

The stress corrosion tests consisted of intermittent immersion (10 min) in the salt solution followed by an air-drying period of 20 min. These cycles were repeated until the specimen failed by breaking. The specimen was then washed in distilled water and subjected to visual and microscopic examination of the fractured and exposed lateral surfaces.

Results. —Table 2 gives the results of tensile tests on five specimens run for the purpose of determining the average yield strength (0.2 percent offset) of specimens cut from the two slices shown in Figure 5. Both the tensile and yield strengths of the test specimens were greater than the minimum required by AMS 4138 specification. On the basis of the average yield strength given in Table 2, a preload stress of 51,000 psi (80 percent of the average yield strength) was applied to each test specimen exposed to the ice melting solutions.

Table 3 compares the time-to-failure for the 7079-T6 aluminum alloy specimens tested in the four ice melting solutions. These results show that CaCl$_2$ and NaCl have equally deleterious effects on the life of 7079-T6 aluminum alloy. For example, the average time-to-failure for specimens exposed to CaCl$_2$ and NaCl solution was 333 and 321 hr, respectively. This is less than one-half the pseudo average life (672+ hr) of specimens exposed to solutions of the mixed amide ice melting material, and even less than the pseudo average life (792+ hr) of specimens exposed to solutions of urea. The term "pseudo average life" is used here since the life of several specimens included in the averages given in Table 3 were undetermined (no failure). Several of the specimens exposed to the latter two solutions had not failed in 938 hr, the time at which the test was halted to permit starting a new test series. The actual average time-to-failure for a specimen exposed to the urea and mixed amide ice melting materials has not yet been determined.

Figures 7 and 8 are photomicrographs (60X) representative of the 7079-T6 forging from which all specimens were cut. Figure 7 shows a view of the gross grain structure of the billet parallel to the long axis of forging. The grains, while not well defined, appear to be generally greater than 0.075 in. long. Even at this low magnification their length is greater than the field shown. Such grain size is considered typical for the alloy in a T-6 condition. Figure 8, taken perpendicular to the long axis of the 7079 forging, shows the distribution and size of the grains in Figure 7 from an end

Figure 7. Photomicrograph of typical structure(parallel to long axis)of forged 7079-T6 billet (60X)—Keller's etch.
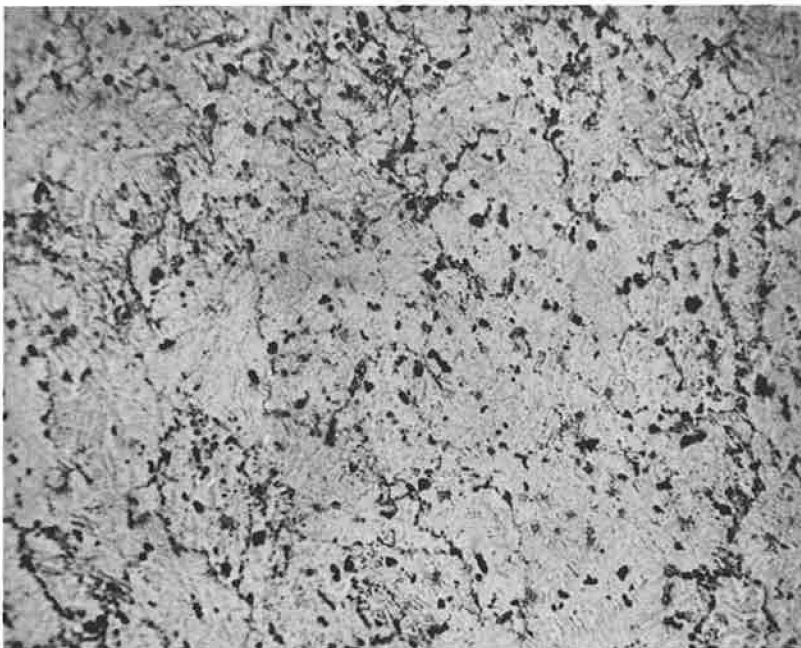

Figure 8. Photomicrograph of typical structure (perpendicular to long axis) of forged 7079-T6 billet (60X)—Keller's etch.

on view. More importantly, it shows the distribution, size and number of intermetallic constituents and inclusions found in the test specimens.

CaCl$_2$ Solution. —The surface of all specimens exposed to this solution appeared dull or matte after the first 50 hr of cyclic exposure. Extensive surface pitting was noted on the specimen that failed at 82 hr. As the life of the specimen exposed to this solution increased, surface pitting was deeper and somewhat more extensive. Pitting seemed to take place intergranularly and also at the site of the larger inclusions. The test specimens showed no evidence of cone-cup or ductile failures. Failure was judged to result from an increase in stress resulting from a decrease in the area of the specimen as pitting depth and area of pitting attack increased. The presence of numerous inclusions in an alloy of this type offers sites for initiation of pitting-type corrosion.

Figure 9 is a photomicrograph of specimen 5B which failed after 318-hr exposure to the test solution. The large pit shown here is 0.014 in. deep by 0.008 in. wide and is located about $\frac{1}{4}$ in. from the fracture zone. There appear to be numerous such pits scattered over the test gage length. Several smaller pits may be seen in the surface of the specimen in both directions from the large pit.

NaCl Solution. —The surface of test specimens exposed to this solution also appeared dull or matte within the first 50 hr of testing. Extensive pitting over the gage length surface occurred in all cases. Such pitting appeared to increase in severity or depth of penetration with lengthening time of exposure to the solution. As with the specimens tested in CaCl$_2$ solution, all exhibited brittle-type failures.

Figure 10 is a photomicrograph at 60X of specimen 13A, which failed after cyclic exposure of 238 hr in NaCl solution. This specimen appears different from that of Figure 9, as it was etched with Keller's solution. The pit shown is about 0.005 in. deep by 0.002 in. wide and was the only one found on the particular cross-section. In general, substantially fewer pits were found in the general area of the pit shown. In this series, surface pitting was less frequent and extensive on specimens exposed to NaCl solutions than ones exposed to CaCl$_2$ solutions.
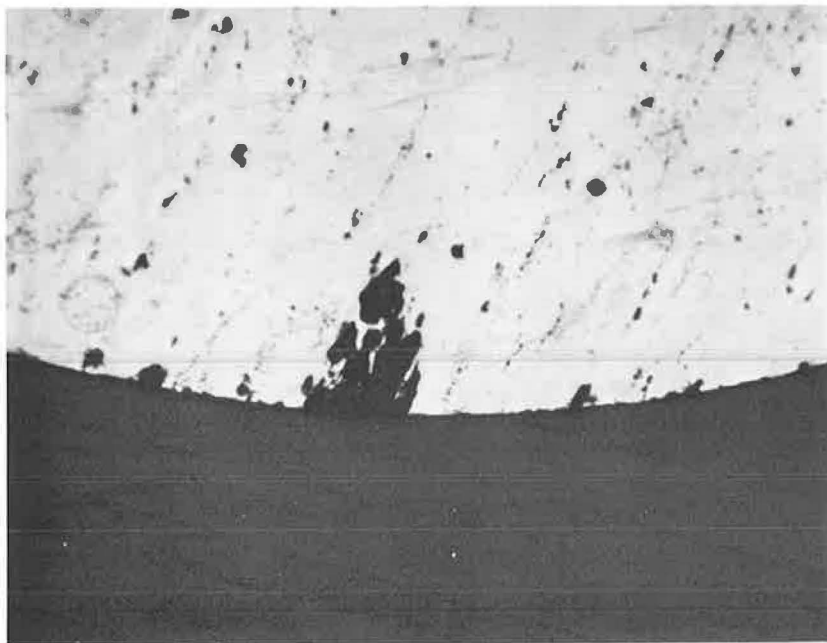

Figure 9. Photomicrograph of unetched cross-section of specimen 5B after cyclic exposure under stress to CaCl$_2$ solution for 318 hr (60X).

Figure 10. Photomicrograph of cross-section of specimen 13A after cyclic exposure under stress to NaCl solution for 238 hr (60X)—HF etch.
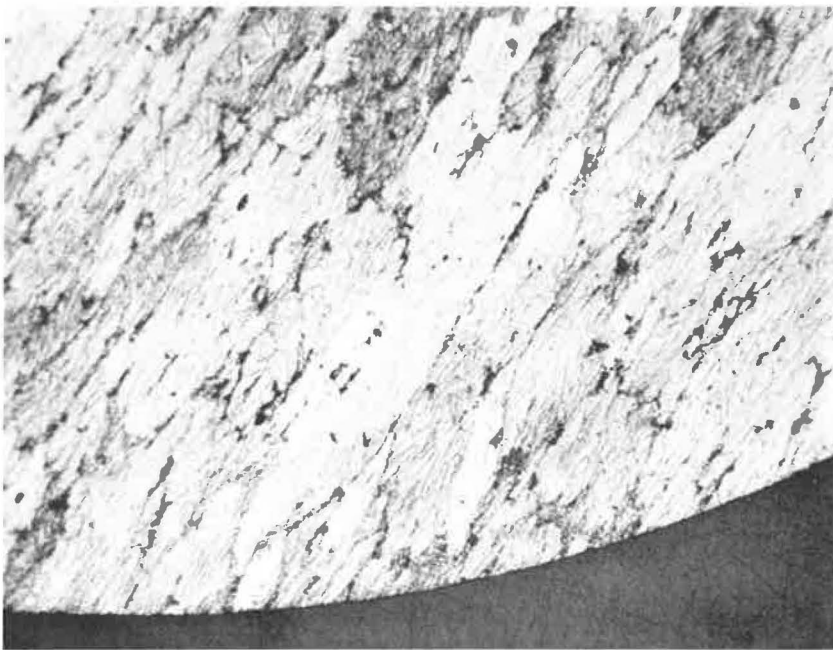

Figure 11. Photomicrograph of specimen exposed for 536-hr cyclic tests in solution of sample D ice melting product (60X)—Keller's etch.

Mixed Amide Material. —This solution showed less outward evidence of surface or corrosion attack than any of the four solutions evaluated. The surface of each test specimen exposed to this solution appeared as shiny and metallic at the end of more than 900 hr of testing as it was at the start of the test. No sign of surface pitting was found on any of the test specimens.

Figure 11, a photomicrograph of specimen 17B which failed only after 536 hr of testing, shows a complete absence of any surface pitting in the area illustrated. A complete examination of several cross-sections of this and other specimens did not reveal a single area of attack by pitting. However, the specimen did fail in a brittle manner, typical of all specimens tested in this program. The method of attack or mode of failure is not understood as of this date.

Urea Solution. —There was considerable metallic lustre on the surface of specimens exposed to urea solutions, even after 500-hr cyclic exposure to the test solution, but the surfaces of these specimens were not as metallic in lustre as those exposed to the mixed amide solution. As indicated in Figure 12, severe pitting of the specimen surface occurred with the urea solution. Whereas the pitting attack was quite widespread and rather homogenous with solutions of $CaCl_2$ and NaCl, the urea solution seemed to cause patches of more severe pitting. Deep pits in the surface were found. Despite this, three out of four of the test specimens did not fail in 938 hr of exposure. Failure of specimen 14A may have resulted when several surface pits became sufficiently aligned to reduce the specimen cross-sectional area to a point where its ultimate tensile strength was exceeded.

Discussion. —Notwithstanding the limited number of specimens exposed under stress conditions in solutions of various ice melting materials, there is little doubt that both NaCl and $CaCl_2$ are significantly more corrosive to 7079-T6 alloy than mixed amide and urea ice melting materials. The severe general (surface dulling) and localized (pitting) attack by solutions of the alkali halide ice melting salts was quite evident and appreciably greater than experienced with either the mixed amide or the urea-type ice melting materials.
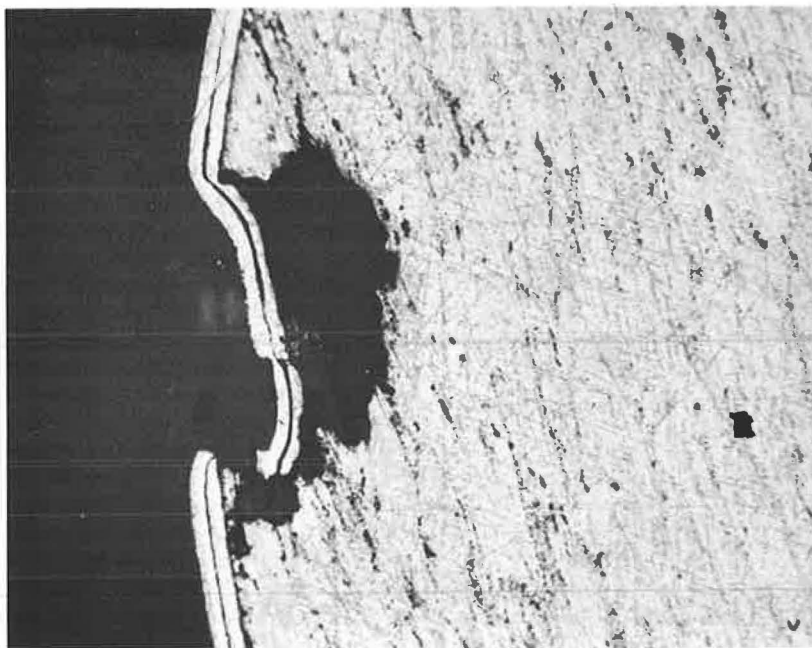

Figure 12. Photomicrograph of specimen exposed for 938+ hr cyclic tests in solution of urea ice melting compound (60X)—Keller's etch.
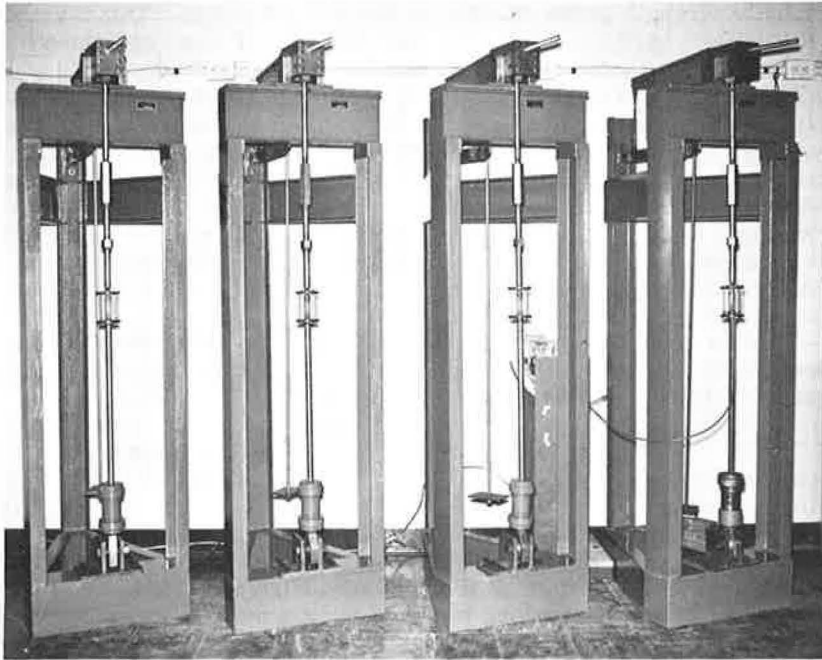
Figure 13. Stress corrosion stands for testing steel specimens.

On the basis of test results, the average stress corrosion life of 7079-T6 exposed to NaCl and $CaCl_2$ solutions was less than one-half the pseudo average life of specimens exposed to the solution of the urea ice melting material.

AISI 4340 High-Strength Steel

The next set of corrosion tests was to determine the effects of NaCl, $CaCl_2$ and urea on stressed high-strength steel parts. A program was set up to determine stress corrosion susceptibility or failure vs time-to-failure by stressing the specimens to 80 percent of yield strength.

Apparatus. —Special stands (Fig. 13) were fabricated to provide the loadings to stress specimens to the required level. Small glass containers with rubber ends contained the salt solutions around the specimen. These containers were fed from a reservoir system which alternately raised and lowered the solution according to a predetermined cycle. This cycle, repeated until the specimen failed, consisted of exposing the specimen to the salt solution for 10 min, draining the solution from around the specimen and allowing it to air-dry for 20 min. Each test specimen was under constant load for the duration of the test.

Procedure. —AISI 4340 alloy steel was selected because of its susceptibility to stress corrosion cracking when heat-treated to high-strength levels. The specimen blanks were cut from a steel forging in a direction transverse to the length of the forging. Location of the specimen within the forging was recorded and each specimen was given a number so that at any future time its location within the forging could be determined. The blanks were then rough machined into $\frac{1}{4}$-in. diam tensile test (Fig. 14) bars and heat-

Figure 14. Modification of ASTM (E8-57T) miniature test bar.

treated to a tensile strength in the 260,000 to 280,000 psi range. This strength corresponds to a Rockwell hardness of Rc 54. The hardness of each specimen was recorded before grinding the gage length. So that the stress corrosion tests could be conducted at stress levels of approximately 80 percent of yield strength, it was necessary to determine the actual tensile and yield strength of a number of specimens. As all specimens were approximately of the same hardness, it was considered valid to take the average value of the tested specimens as the approximate yield strength for the specimens used in the stress corrosion test. Each stand was calibrated with a strain gage load cell (Fig. 15) and the weights required to obtain the necessary load for each test specimen were put in place. The load cell was then replaced by the test specimen. A record was maintained for each stand to show room-temperature fluctuation with time and the total time-to-failure.

Results.—Table 4 gives the stress corrosion data on the highly heat-treated 4340 alloy steel tested. Solutions of the following ice melting compounds were evaluated: (a) NaCl, 700 gm in 2 liters of distilled water; (b) CaCl₂, 1,180 gm in 2 liters of distilled water; (c) urea, 1,560 gm in 2 liters of distilled water; and (d) tap water from Dayton city water. Twelve $\frac{1}{4}$-in. diam test specimens were failed in these tests. The average time-to-failure per specimen exposed to the CaCl₂ solution was 4.5 hr. This compares with an average time-to-failure per specimen of 53.5 hr for test bars exposed to the NaCl solution, 237 hr for urea and 130 hr for tap water.

On the basis of visual examinations of the failed specimens, some ductility was exhibited, evidenced by "shear lips" at the fractured surfaces (Figs. 16, 17, 18).

Discussion.—As regards corrosion, test data show a definite superiority for urea ice melting compounds over NaCl and CaCl₂. Further, CaCl₂ appears to have a more severe effect on failure rate than does NaCl. It is felt that the relative severity of attack of CaCl₂ vs NaCl is not in itself as valid as the significant differences in failures under stress corrosion conditions between chloride compounds and urea. Both CaCl₂ and NaCl have a more pronounced and detrimental effect on the life of high-strength AISI 4340 alloy tested than does urea. The apparent readiness of this highly heat-treated alloy to fail when loaded above 190,000 psi and exposed to corrosive ice melting materials should be recognized. It should be noted that all of the data collected thus far have been obtained using transverse grain specimens. Specimens cut from the longitudinal forging direction would most likely exhibit greater resistance to stress corrosion cracking.
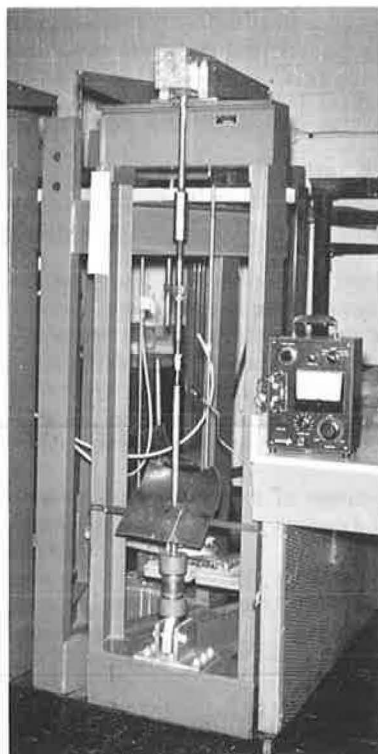

Figure 15. Strain gage load cell.

TABLE 4

STRESS CORROSION OF AISI 4340 STEEL

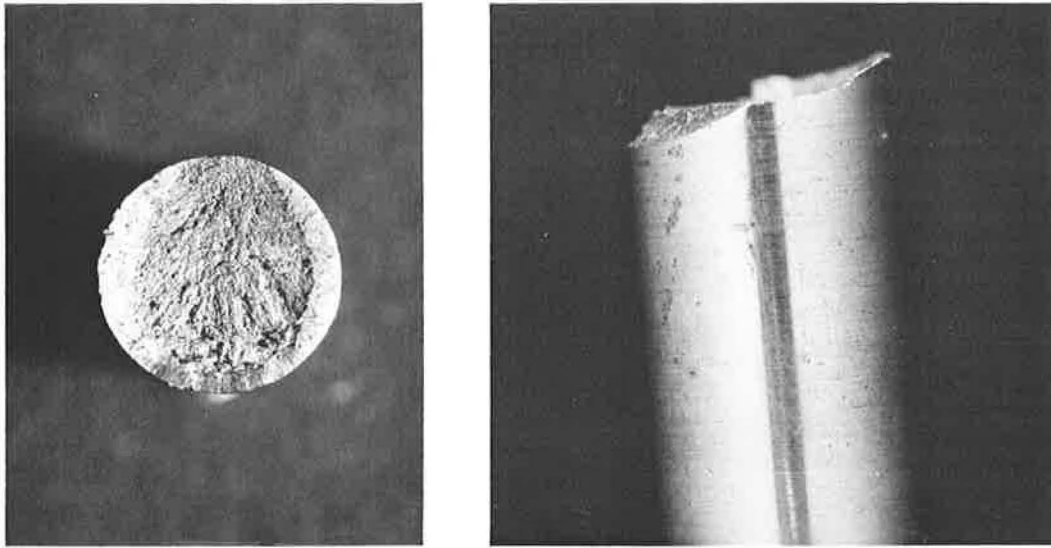| Corrosive Media	Specimen	Time-to-Failure (hr)
CaCl₂ sol.	41	6.25
	93	3.50
	11	3.75
NaCl sol.	27	67.50
	120	40.50
	89	53.50
Urea sol.	121	92.00
	101	277.5
	92	342.0
Tap water	17	102.00
	28	148.00
	126	140.00

Figure 16. End-on and lateral view of fractured test bars subjected to stress in CaCl$_2$ solution, for less than 5 hr.
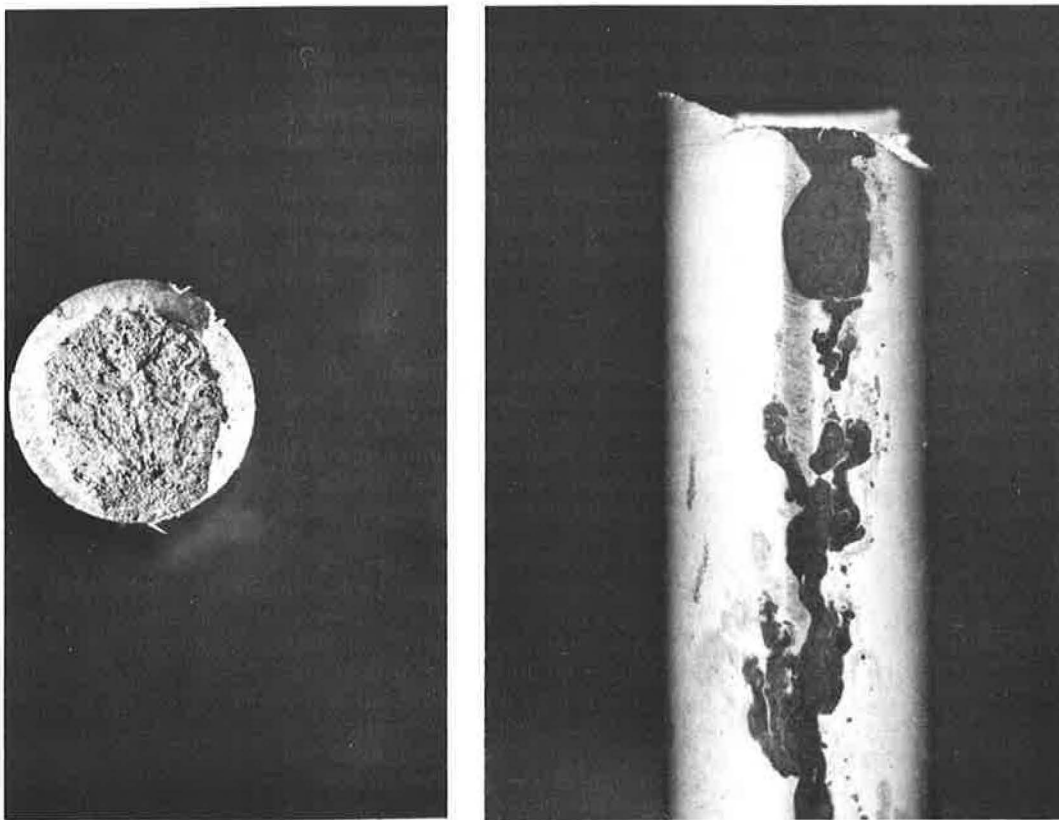

Figure 17. End-on and lateral view of fractured test bars subjected to stress in solution of Dayton tap water, exposed for over 100 hr.
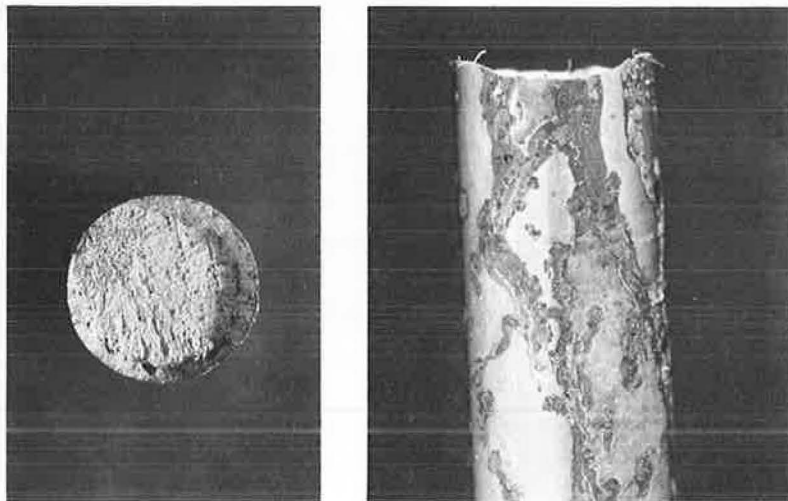
Figure 18. End-on and lateral view of fractured test bars subjected to stress in solution of urea, exposed for over 250 hr.

Since the completion of the particular work reported here, the Federal Aviation Authority has sponsored a program for the development of an effective noncorrosive deicing material for aircraft runways. The contract for this work was awarded to the Monsanto Chemical Corp. and they are presently conducting a systematic screening of candidate deicing materials based on requirements similar to those listed previously in this paper. It is still too early in the program to predict what success might be achieved; however, both the FAA and the USAF are hoping to test the promising new materials in service next winter.

REFERENCES

1. Conrardy, W. P., "A Review of USAF Service Problems Related to Materials-Processes-Environments." Inst. Environ. Sci. Proc. (1963).
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3. "Runway Ice Control Using Crystal Urea." RCAF Central Exp. and Proving Estab. Interim Rept. 1475 (May 1960).
4. "Deicing Materials for Military Runways." U. S. Naval Civil Eng. Res. and Eval. Lab., Port Hueneme, Calif. Tech. Memo. M-124.
5. "Effects of De-Icing Chemicals on Structures: A Symposium." HRB Bull. 323 (1962).

Discussion

COMMITTEE ON SNOW AND ICE CONTROL, Highway Research Board. —The Committee and the Department of Maintenance sponsored this paper because the test procedures and findings it describes warranted presentation and publication. There is no disagreement with the author's findings, but there is some concern that the report might be misinterpreted. This discussion is presented to clarify the meaning of some of the report's findings to highway organizations.

The study was limited to the behavior of highly stressed aluminum alloys and high-tensile steels. Among other things, it discusses the susceptibility of aircraft metals to stress corrosion caused by chloride compounds.

Automobile steels, of course, are not subject to the high-stress conditions found in airframe components. As a result, special corrosion problems encountered in clearing runways have no pertinence to snow and ice removal on streets and highways. The committee feels obliged to point out that highway officials should not use the report's information on airframe corrosion as the basis for modifying their use of chlorides for removing snow and ice from vehicular pavements. Those responsible for purchasing deicing compounds should also note that costs quoted for urea and other compounds are several times those given for either NaCl or $CaCl_2$.

W. P. CONRARDY, <u>Closure</u>.—No issue is taken with the preceding remarks. Application must be the governing factor in the selection of deicing materials. In the case of highway pavements, maximum effectiveness at lowest cost is the important criterion. The paper attempted to point out that the low-strength materials used in vehicles, bridges, etc., rarely if ever fail by catastrophic stress corrosion cracking. In addition, because weight is not a factor, protective coatings may be extensively used. Moreover, the enormous amount of deicing materials purchased for ice control on United States highways is such that even fractional increases in deicing materials costs represent an increase in operating cost that is difficult to justify.

On the other hand, aircraft are weight critical. Materials are at their maximum strength level in many cases. This makes them prone to failure by stress corrosion. This, of course, can and does result in lost lives and equipment. In addition, relatively much smaller amounts of the more expensive materials would be used, thus limiting the over-all increase in cost. This combination of factors does justify the use of the more expensive material for airport runways.