Protection of Aluminum Overcas Constructions Against Fire

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Abstract

A test program was undertaken by the U. S. Mine Safety and Health Administration to evaluate various materials for protecting aluminum overcast constructions against fire. Selected coatings and one covering were tested under large-scale, simulated mine fire conditions to determine their effectiveness as a fire barrier for protection of aluminum.

Coatings consisting of expanded vermiculite, limestone, and portland cement; mineral wool fibers in hydraulic setting, inorganic binders; cellulose mixed with liquid sodium silicate; and a fiberglass-reinforced surface-bonding mortar were particularly effective in protecting the aluminum structures against the heat of the simulated mine fire. Three inches of a ceramic-fiber blanket and a four-inch coating of phenolic spray foam also proved to be relatively effective barriers for fire protection under the conditions of the test.

Introduction

Overcasts are enclosed airways in underground mines, which permit one air current to pass over another one without interruption or mixing. They are used in conjunction with other ventilation control structures, such as stoppings (walls) and regulators, to control the movement of ventilating air in the vast network of underground passageways.

Overcasts are generally constructed using incombustible materials, such as concrete, tile, stone, or brick. In the past few years, a number of underground mines have been incorporating overcasts constructed of aluminum into the ventilation control plan. There is some concern as to the ability of aluminum, used in these overcast constructions, to withstand high temperatures that may be encountered in the event of a

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nearby fire in an underground mine. Temperatures generated in underground coal mine fires can easily reach 1500°F. The disruption of ventilation due to failure of an overcast in an underground mine fire can adversely affect firefighting efforts and escape of miners working in the mine. Since most aluminum alloys melt in the vicinity of 1100-1200°F and, moreover, begin to display significant reduction in tensile and yield strengths at temperatures well below this, protection of structural aluminum in the event of a fire is an important concern.

The program attempted to focus on commercially available sealants used in underground mines and their application methods and thicknesses to aluminum overcasts for protection of these structures against a standard test fire for specified time periods. As a result of this effort, the agency has permitted appropriately coated ventilation controls to be used in some underground mines.

Testing

Test Facility

Fire tests were conducted in the U.S. Mine Safety and Health Administration Industrial Safety Division's fire gallery. The gallery consists of two perpendicular tunnels and is constructed of 4-ft high, concrete-filled, masonry block walls and an arch-shaped corrugated steel roof. The interior surfaces of the gallery have been lined with ceramic blanket material to protect them against the heat generated by the test fires. Junction boxes, located on the exterior walls of the gallery, house interfacing cable for recording temperatures, velocity, and other pertinent engineering data. A plan view of the gallery is shown in Figure 1.

The fire zone was constructed in the cross-cut of the gallery and designed to simulate, as nearly as possible, actual ventilation conditions through an overcast in an underground mine.

Conveyor belt covers constructed of Alclad 3004 16-gauge aluminum sections, 2 ft long and 7 ft in diameter, were used as transition sections between which the test overcast was placed. These covers were insulated with 2 inches of ceramic-fiber blanket to protect them against the heat of the test fire. Two transition sections, 4 ft in length, were utilized on each end of the 8-ft test overcast. A wall was constructed from concrete block and noncombustible board to seal the south end of the test section. The north end was sealed using a silicone-coated fiberglass curtain fitted around the perimeter of this transition section and pinned to the roof of the gallery. This configuration enabled two separate splits of air to be utilized in conjunction with the fire test. A portable fan, placed in the south section of the gallery, provided about 260 fpm of air (5000 cfm) through the underside of the overcast. A permanent gallery fan forced air at about 140 fpm (4500 cfm) over the top of the semicircular overcast construction. Ceramic blanket was also used to seal the

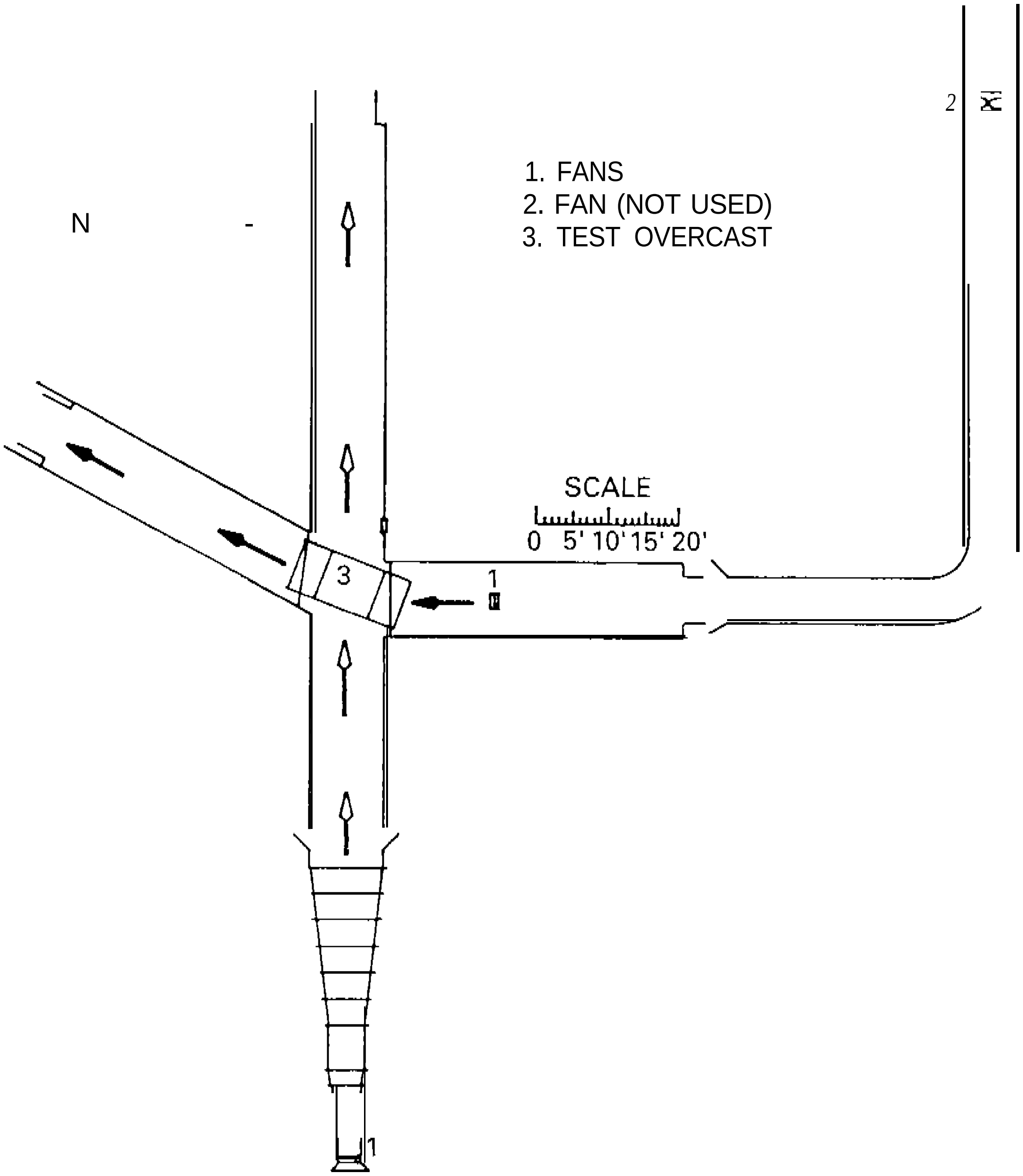

Figure 1. Plan view of Industrial Safety Division's fire gallery.

underside of the test overcast at the transition sections. Two inches of sand were placed on the floor in the fire area to protect it against the heat of the test fire.

Development of Standard Test Fire

A flammable liquid was used as a source of heat for the test fires conducted in this program. The flammable liquid was a commercially available solvent, consisting of a blend of about 80 percent hexanes and 20 percent cyclic paraffins. The heat of combustion of this solvent was determined to be 20,608 BTU/lb. This solvent is also used by the Division to assess other ventilation-control structures[1]

In order to provide a reservoir for the flammable liquid, a fire tray was constructed using 0.25-inch cold-rolled steel plates. The inside dimensions of the tray were 48 inches (length), 9 inches (width), and 12 inches (depth). An insulated 0.5-inch stainless-steel tubing line, attached to the fire tray near the bottom, delivered the solvent into the tray at prescribed rates during the test. A peristaltic pump, located outside of the gallery, pumped the solvent from two 5-gallon containers. The bottom 3 inches of the tray was filled with water to protect it against heat damage. Initially, one inch of solvent was placed over the water in the tray. This corresponds to about 1.7 gallons of fuel. The pump was activated after 3 minutes, which enabled remote control of fuel into the tray from that point on. The tray was placed on the floor of the gallery under the overcast to be tested. The location of the tray was determined by the type of test to be conducted and will be described later.

The heat production rate of the test fire was varied in three stages:

1. 20 minutes at 0.175 gal/min. = 20,200 Btu/min.;
2. 20 minutes at 0.243 gal/min. = 27,988 Btu/min.; and
3. 20 minutes at 0.272 gal/min. = 31,328 BWmin.

The average heat production rate for a 60-minute test fire was determined to be about 26,500 Btu/min. (0.47 MW).

The fuel-feed rates were selected based on some preliminary tests and were limited essentially to quantities which would burn fairly clean, permitting observations of the test zone by a video camera. The fuel used in these tests exhibited erratic burning characteristics at higher fuel-feed rates, characterized by rapid development into a fuel-rich condition, production of heavy smoke, and back-up of heat into the south section of the gallery.

Test Procedures

Aluminum overcast test sections consisted of corrugated, semicircular, 8 ft long pieces of aluminum alloy Alclad 3004, 16 gauge, 7 ft in diameter. This alloy is used in the construction of conveyor belt covers for industrial use. Mine overcasts are generally constructed using aluminum 5052-H141 in a thickness of approximately 100 mils. Alloy Alclad 3004 was used in the test program due to size limitations of our gallery. The smallest commercially available overcast section incorporates a span of nearly 15 feet. Since the Division's fire gallery's inside tunnel width is 9 ft, 6 in., it was necessary to utilize a smaller, commercially available section of wrought aluminum as a substrate. Since the tensile, yield, and thermal expansion properties of the two alloys (3004 and 5052) are comparable,[2] the test results on the Alclad 3004 test sections should apply aIso to 5052 alloys.

Fire testing of nine coatings and one covering was undertaken utilizing two different test regimes. Regime I investigated coatings which covered the entire inside area of the test overcast section. Regime II testing examined two coatings on one aluminum test section. Regime II tests were conducted to maximize the amount of test information that could be gained with the limited test sections of overcast available. The position of the fire tray was adjusted according to the testing regime. The leading edge of the fire tray was located 18 in. south of the test section centerline in Regime I and 36 in. south of the centerline in Regime II. An overview of the fire zone is shown in Figure 2.

Twenty-gauge, chromel-alumel (Type K) thermocouples were utilized to make temperature measurements. Thermocouple measurements were taken in the fire zone (l/8 inch from the coatings), at the coating/ aluminum interface, and on the outside surface of the overcast.

Table 1 describes the pertinent information for the materials tested in this program. Some of the coatings were applied to aluminum test sections, which had been fitted with wire screen and/or coated with latex primer to enhance their bonding characteristics. These surface preparation techniques are also listed in the table.

Coatings 2 and 3, the expanded vermiculite, portland cement, limestone, glass-fiber coating, and the fiberglass-reinforced mortar coating, respectively, were wet-sprayed and displayed a wide variation in thickness over the test area. Coating 2 was discovered to vary in thickness from 1.25 in. to 2.5 in. and Coating 3 displayed thicknesses varying from 1 in. to 2.25 in., as verified by a post-test destructive depth profile conducted on I-ft. centers along the surface of both test sections. Coating 10, the phenolic spray foam, also varied widely in thickness from 3.5 in. to 8.0 in. The other coatings tested were applied with satisfactory results and indicated thicknesses did not vary by more than l/8 in.

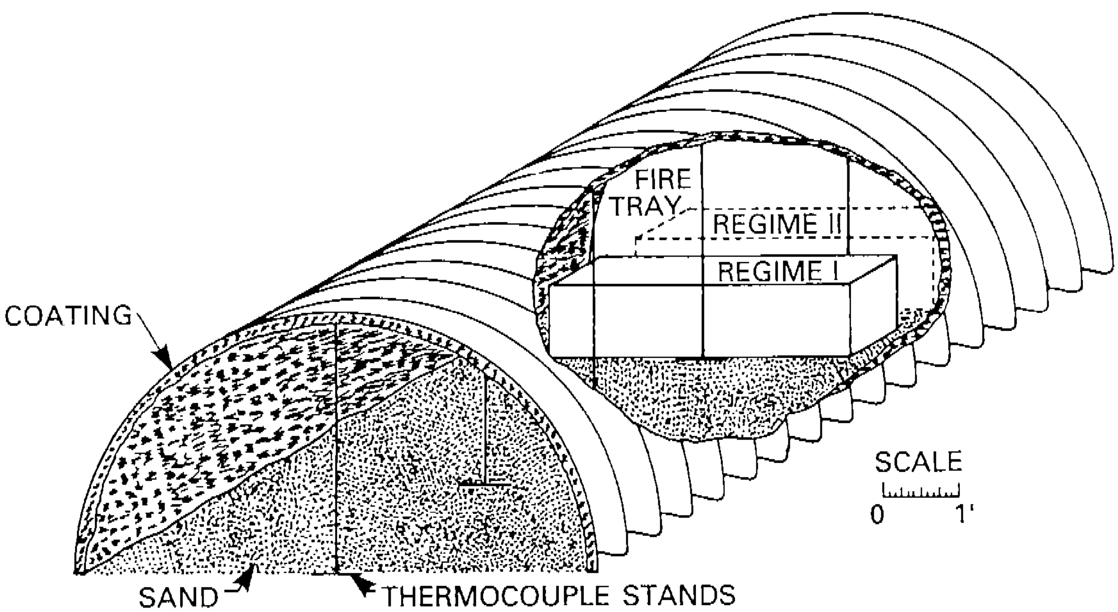

Figure 2. Aluminum overcast fire in test zone. Fire tray position in Regimes I and II.

Table 1. Coatings /coverings used in aluminum overcast fire tests.

Test	Coating Number	Description	Wet Density (lb/ft^3)	Reinforced	Thickness (inches)	Regime	Application Technique
1	1	Ceramic-fiber blanket	6*	Yes	3.0	I	Impaled over S.S. studs
2	2	Expanded vermiculite, portland cement, and limestone and glass fibers	60	Yes	1.2-2.5	I	Wet spray (P)
3	3	Fiberglass reinforced surface bonding mortar	96	Yes	1.0-2.25	I	Wet spray (PM)
4	4	Ablative coating of proprietary formulation	–	No	0.2	I	Spray
5	5	Mixture of inorganic mineral wool fibers and	50	Yes	1.0	II	Dry spray
5	5	hydraulic setting inorganic binders	50	No	1.0	II	Dry spray (P)
6	6	Expanded vermiculite, portland cement,	60	Yes	2.0	II	Wet spray
6	6	and limestone	60	Yes	1.0	II	Wet spray
7	7	Cement-based insulating plaster with polystyrene beads	23	Yes	1.0	II	Trowel (P)
7	8	Fiberglass-reinforced surface bonding mortar	90	Yes	1.0	II	Trowel (P)
8	9	Cellulose/liquid sodium silicate	50	No	1.0	II	Spray
8	9		50	No	1.5	II	Spray
9	10	Polymeric foam consisting of phenol and formaldehyde	5.9	Yes	3.5-8.0	II	Spray

*dry blanket density
(P) - surface of overcast coated with a latex primer.
(PM) - primer mixed with coating prior to application.

The test began by remotely igniting the fuel in the tray. The fire was allowed to burn for a period of 60 minutes, or until **a** failure of the aluminum overcast had occurred, whichever occurred first,

The locations of the thermocouples used in Regimes I and II are shown in Figures 3 and 4. Plots of typical exposed surface temperatures generated are depicted in Figures 5 and 6. Preliminary tests that were conducted utilizing arrays of thermocouples in the fire zone, indicated that the difference between east, center, and west exposed surface temperatures at a particular cross-section of coating was minimal and rarely exceeded 100°F.

Coating Reinforcing Strategies

Coating 1

The ceramic blanket coating is fastened to the overcast by using 0.25 in. by 5 in. stainless-steel-notched studs and retaining clips, The studs were attached to the aluminum overcast by spot-welding a retention washer onto each stud and then placing these assemblies into the overcast through predrilled l/4-in. holes and fastening with No. 8, l-in. self-drilling, self-tapping screws driven through the clip and into the overcast. The studs were placed at l-ft centers with each sequential row being offset from the prior by 6 inches, giving a staggered configuration. The blanket is impaled over the studs and the 1 in. by 1.5 in. retaining clips were placed in the appropriate notches, in accordance to blanket thickness, and held the coating against the overcast surface (Figure 7).

Coating 2

The vermiculite, portland cement, limestone, and glass fibers coating was reinforced with 2 in. by *60* in. (hole size by wire width), 20-gauge chicken wire to support the coating against the smooth aluminum overcast surface (Figure 8). Copper tubing spacers were used to maintain a 0.5-in. space between wire and overcast to allow for the proper application of the coating. The wire was placed between two 1.25-in. O.D. washers and fastened to the spacers and the overcast with l-in. self-tapping screws. The 108 screws, used to attach the wire, were placed 1 ft apart from center to center. During the application of the coating, the wire began sagging between the screws and additional screws were required to hold the wire in position. To remedy this problem, 46 additional screws were placed randomly in the sagging areas.

Copper tubing spacers were used because they were readily available. Use of copper is not recommended in-mine for long-term applications since its use may result in enhanced corrosion of aluminum. Use of plastic or aluminum spacers would be more suited for this application.

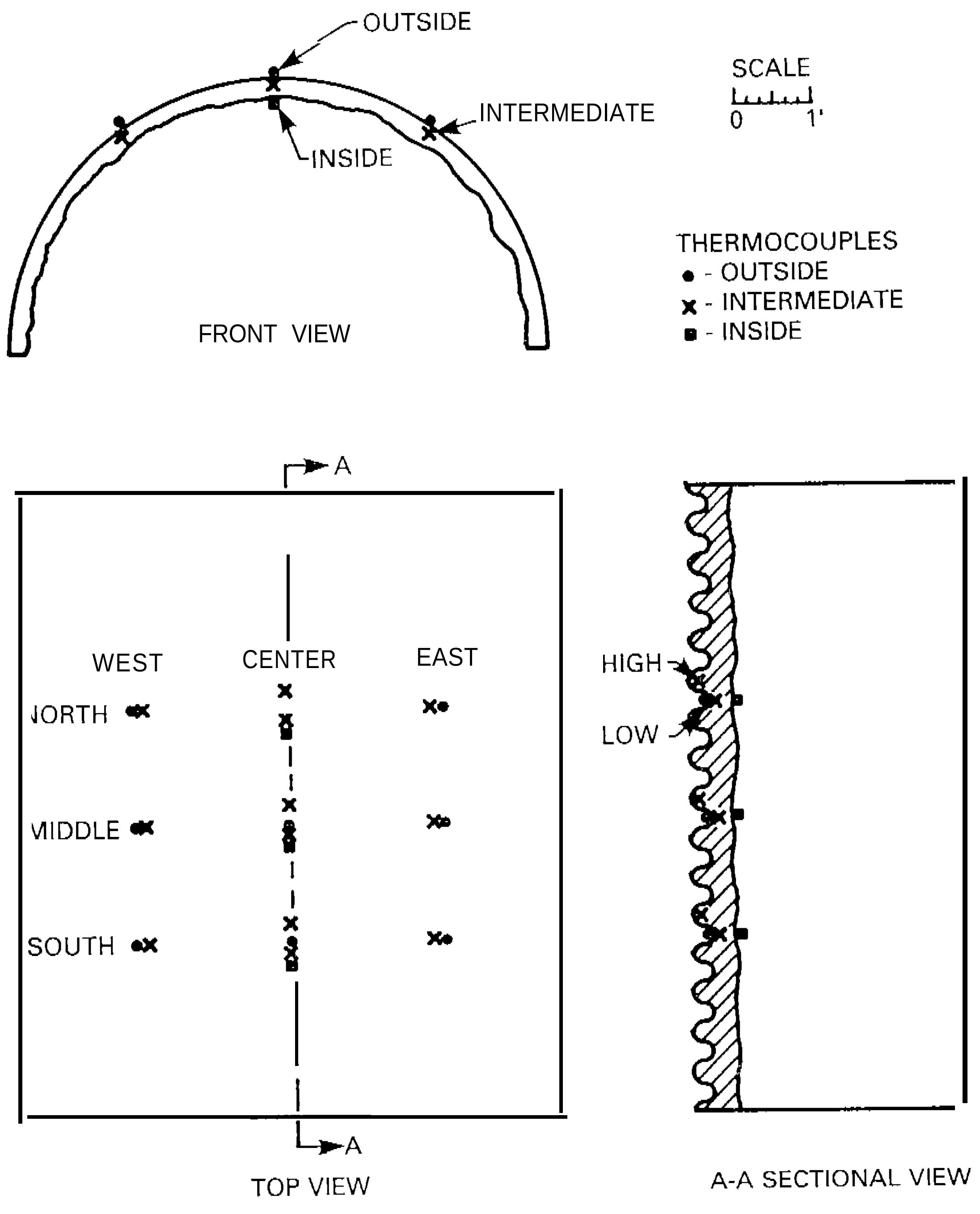

Figure 3. Thermocouple locations-Regime I.

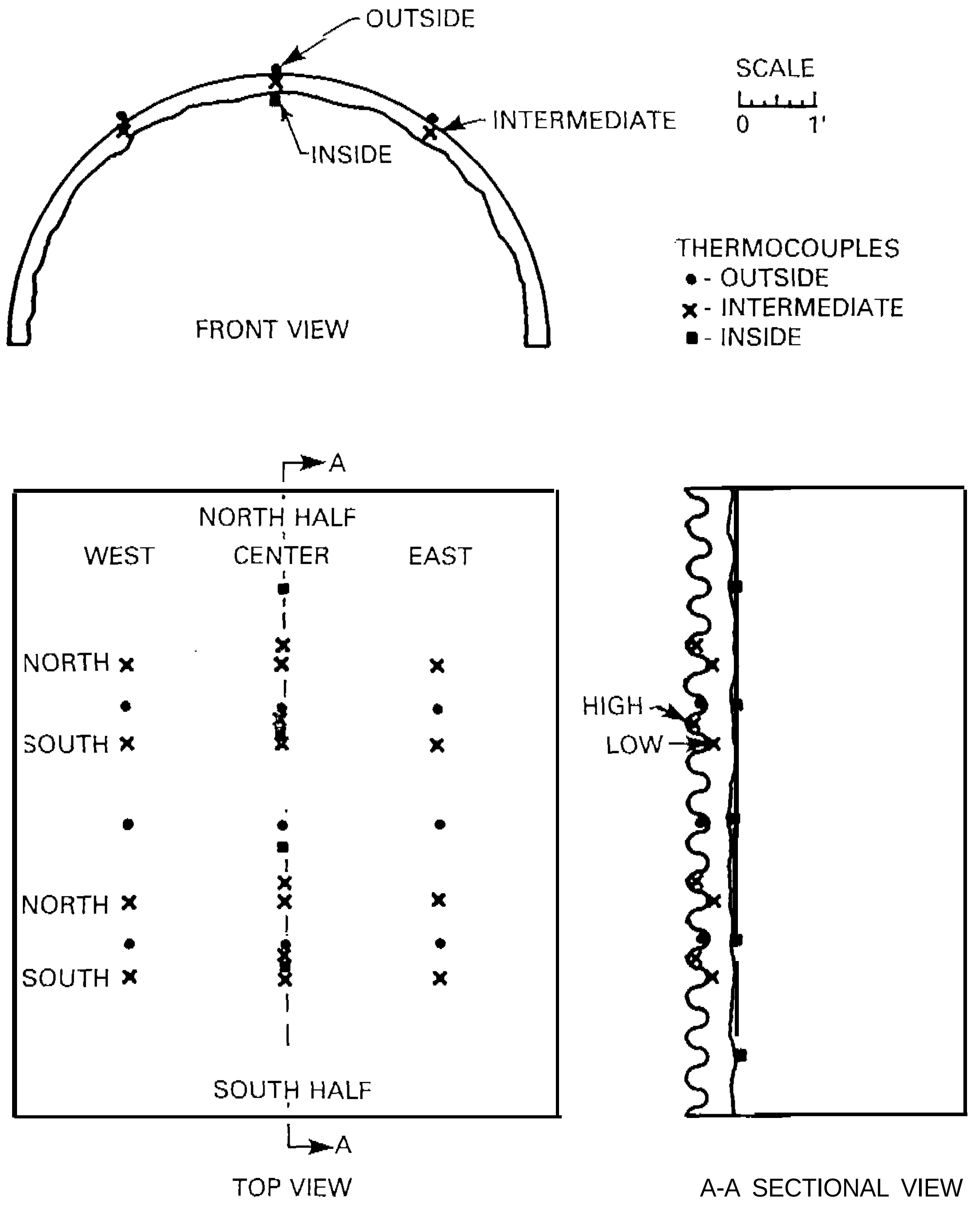

Figure 4. Thermocouple locations-Regime II.

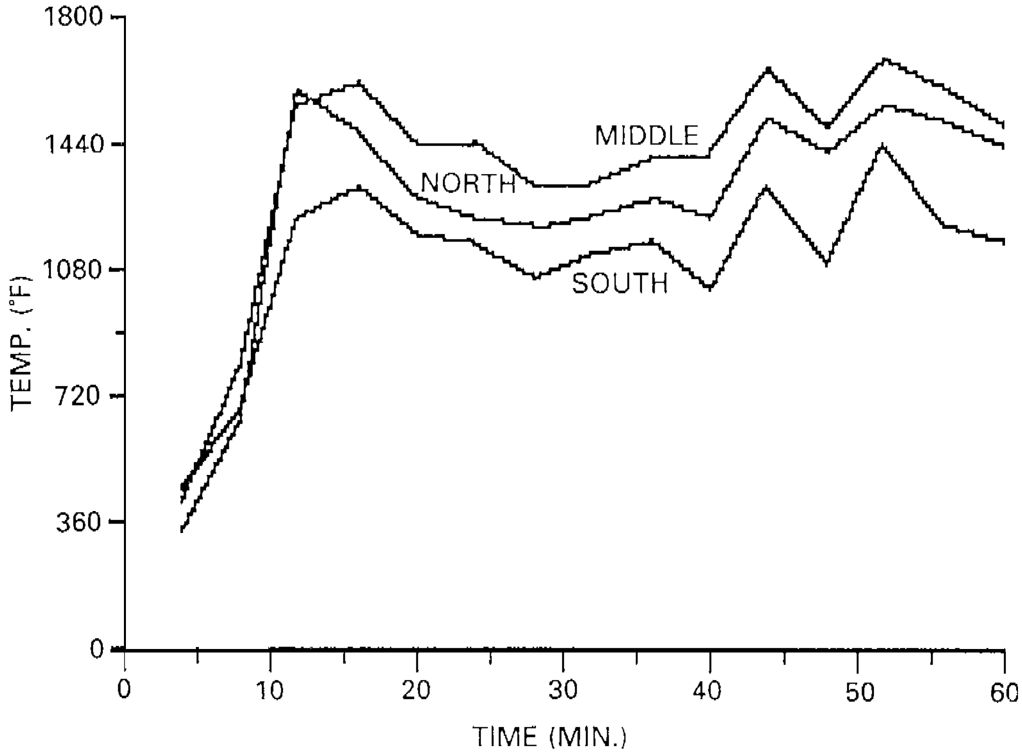

Figure 5. Fire zone temperatures-Test l-Regime I.

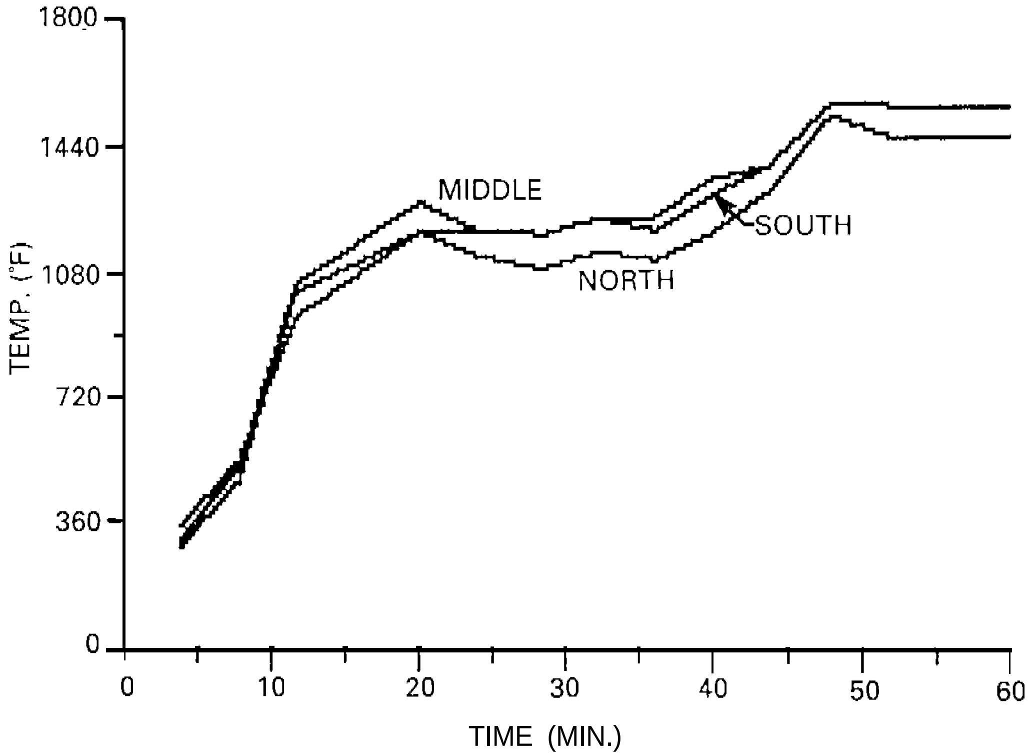

Figure 6. Fire zone temperatures-Test 7-Regime II.

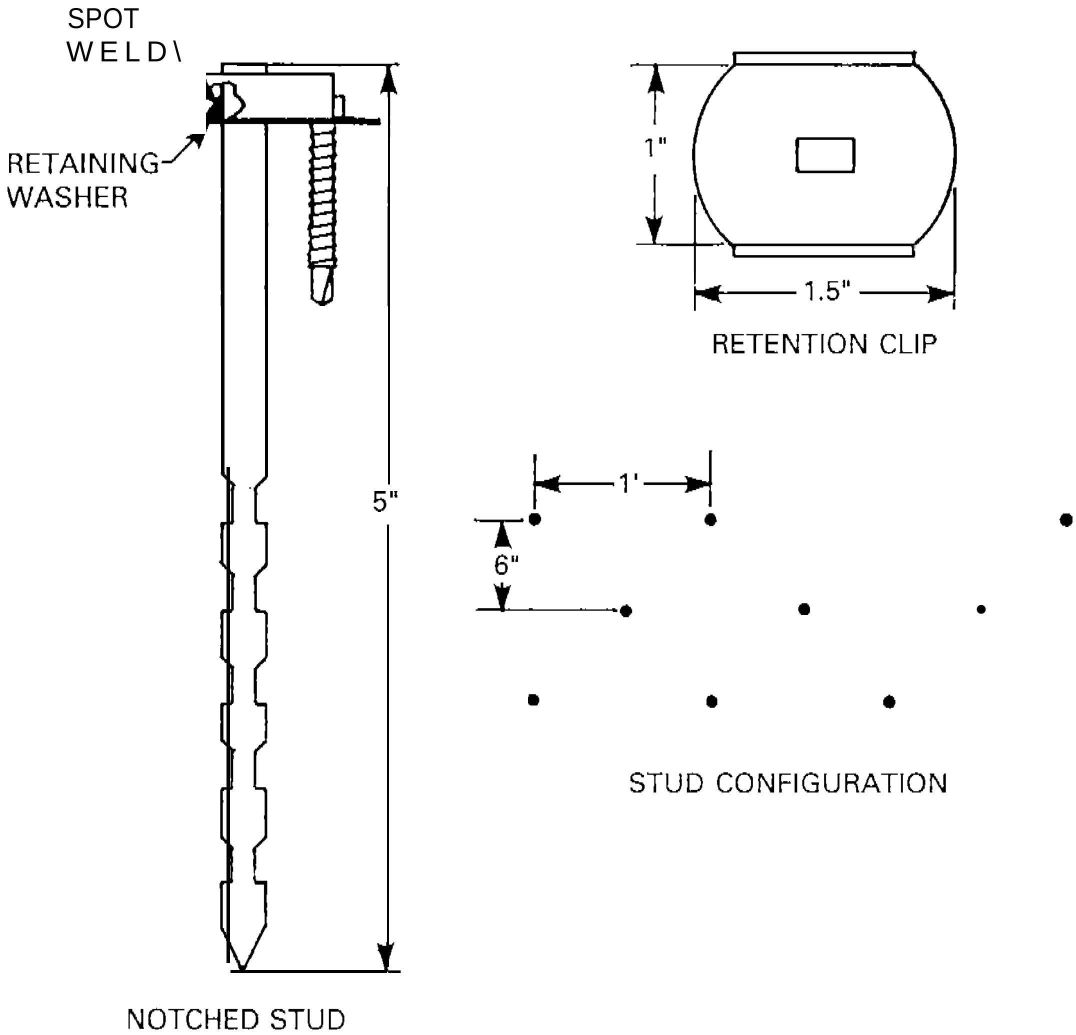

Figure 7. Ceramic blanket fastening system.

Coating 3

The same coating technique that was used for Coating 2 was also used here. However, there was no sagging observed when applying this coating; thus, no additional screws were necessary.

Coating 4

No reinforcement was required. This coating is ablative and of a proprietary formulation.

Coating 5

The inorganic mineral wool fibers in hydraulic setting inorganic binders was applied to the overcast using two methods, one half requiring reinforcement and the other half having no reinforcement. The reinforced section required the use of 1 in. by 36 in. (hole size by wire width), 20-gauge chicken wire fastened directly to the protruding (high) ribs of the overcast. No spacers were used. Each row of No. 8, l-in. self-drilling, self-tapping screws was placed at a center-to-center distance of

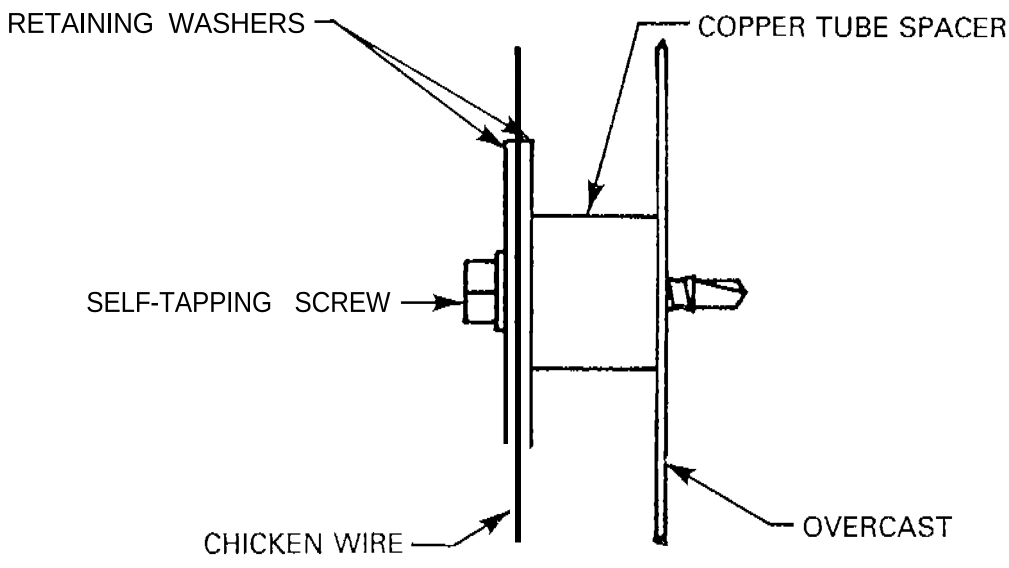

Figure 8. *Coating 2 fastening* detail.

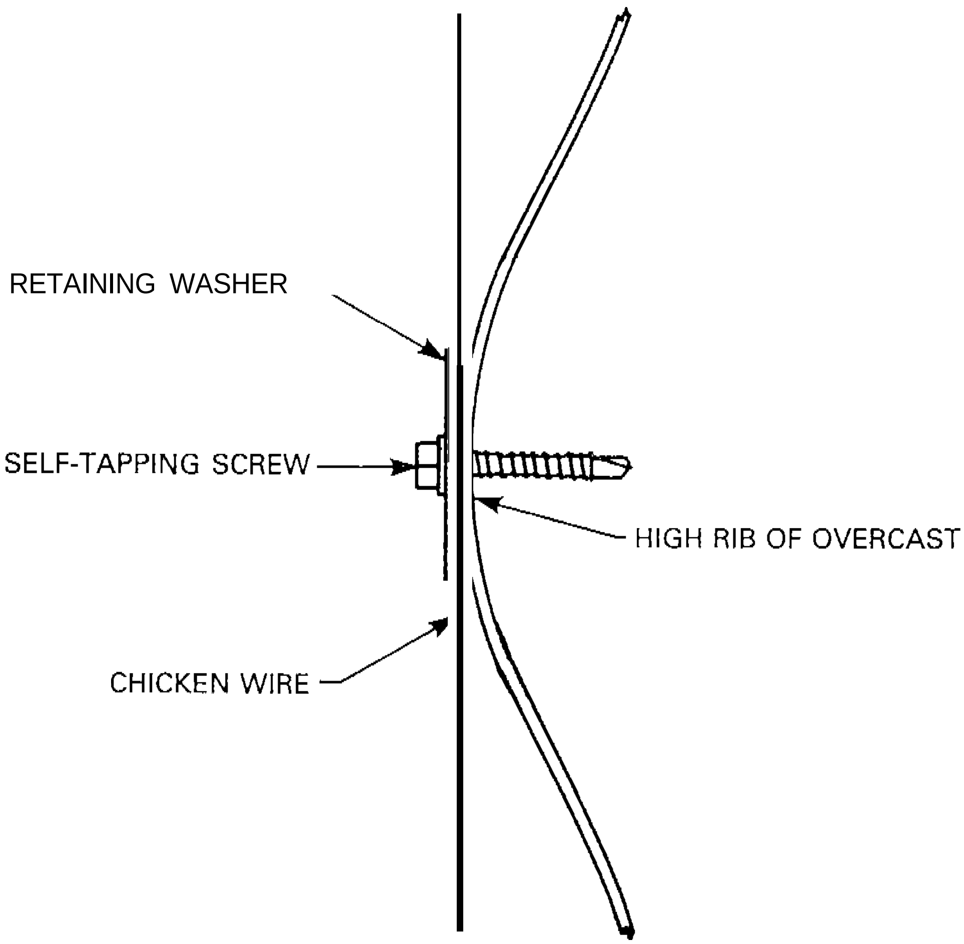

Figure 9. Coating 5 fastening detail.

1 ft; therefore requiring 66 self-tapping screws and retaining washers (Figure 9).

Coating 6

The vermiculite, portland cement, and limestone coating was reinforced with two criss-crossed layers of 1 in. by 36 in. (hole size by wire width), 20-gauge chicken wire. These dual layers of wire were then fastened onto the overcast at each of the protruding (high) ribs with *No.* 8, l-in., self-drilling, self-tapping screws and retaining washers. The rows of the rib-mounted screws were aligned symmetrically around the overcast to offer maximum support. After the application of the coating, the wire began to sag in the top portions of the overcast. Therefore, 70 additional screws were used in the required areas to alleviate the sagging, bringing the amount of screws needed for sufficient support to 195.

Coating 7

The cement-based insulating plaster with polystyrene beads was reinforced in the method similar to that used for Coating 2. The only difference was the type of wire used for this coating, 1 in. by 36 in. (hole size by wire width), 20-gauge wire, rather than the 2 in. by 60 in. (hole size by wire width), 20-gauge wire used for Coating 2.

Coating 8

The fiberglass-reinforced surface-bonding mortar was reinforced in a method similar to that used for Coating 7. However, this coating was heavier and required more support; therefore, the center-to-center distances for the rows of the supporting screws were reduced from 1 ft to 6 in.

Coating 9

The cellulose sodium silicate-based coating did not require reinforcing. This coating was applied in 0.25-m layers with one week allowed between applications to allow for curing,

Coating 10

The phenolic spray foam was applied to an overcast using 1 in by 36 in, 20-gauge wire; washers, and sheet-metal screws. One half of the overcast employed spacers as detailed in the reinforcing strategy for Coating 2.

Test Results and Discussion

An important consideration when evaluating fire-resistant products is the prevention of the spread of fire to an area above the overcast. Temperatures of 320°F (160°C) are hot enough to ignite certain bituminous coal dusts.[3] Coatings/coverings utilized for fire protection should ideally prevent this temperature from being reached on the unexposed side of the overcast during a fire on the underside for as long as possible.

Another consideration is the structural integrity of the aluminum under fire conditions. The yield and tensile strengths of aluminum alloys 3004 and 5052 at various temperatures are shown in Table 2. At elevated temperatures, these alloys begin to show reductions in their strength properties, dependent upon the specific alloy and its temper. Prediction of the temperature at which a particular aluminum structure would begin to fail in a fire is **a** complex, inexact endeavor, dependent upon variables such as alloy, temper, construction method, loading, etc. The fact that the coatings evaluated in this program tend to be self-supporting upon drying and that the overcast, per se, is not required to support any type of loading, offers an added margin of safety from a structural-failure standpoint, in the event of fire exposure.

The temperature data from the tests that were conducted were analyzed with these two considerations in mind. Selected temperature data for coatings tested under both regimes are shown in Tables 3 and 4.

In addition, a test was also conducted on an uncoated aluminum overcast. The data for this test is also presented in Table 3. The test involving the uncoated aluminum overcast was terminated in about 30 minutes. Temperatures in excess of 320°F were recorded on the unexposed side in about 6 minutes. The first visual indication of melting occurred at the 12-minute mark. At this point, a large hole began to form in the overcast, on the east side, which allowed flames to pass through.

Unexposed (outside) thermocouple temperatures, generated in tests with coated or covered aluminum panels, were generally lower when compared with corresponding coating/overcast interface data due to temperature gradients in the metal, which are primarily caused by the cooling effect of air passing over the top.

Minor problems were experienced with the fuel-delivery system in Tests 5 and 7, resulting in temporary extinction of the tray fire for 3.5 and 7 minutes, respectively. The duration of these tests was increased to compensate for this.

In every instance but one, Test 4-Coating 4, the coatings/coverings protected the aluminum overcast from melting, sagging, or other signs of visual deformation for the one-hour duration of the test. Coating 4, a proprietary ablative coating, began to burn about six minutes into the test, resulting in intense temperature development within the fire zone and ultimate failure of the overcast in about nine minutes.

Table 2. Strength characteristics of two aluminum alloys at various temperatures (after 10,000 hours at testing temperature) - tensile and yield strength expressed in percent of room temperature (75°F).

Alloy/ Temper	Property	212°F	300°F	400°F	500°F	600°F	700°F
3004-0	TS	100	81	55	38	27	18
	YS	100	100	94	68	46	28
3004-H32	TS	99	83	63	43	24	16
	YS	100	92	65	31	21	13
3004-H34	TS	99	82	62	41	22	14
	YS	100	87	56	25	17	10
3004-H36	TS	98	79	57	35	20	13
	YS	100	79	47	22	15	9
3004-H38	TS	97	76	52	29	18	12
	YS	100	74	41	20	14	8
5052-O	TS	99	87	63	45	30	19
	YS	100	100	90	60	38	23
5052-H32	TS	98	82	62	36	24	15
	YS	99	87	53	26	17	10
5052-H34	TS	97	81	62	33	22	14
	YS	99	87	46	23	14	9
5052-H36	TS	97	80	60	31	20	13
	YS	98	80	42	21	13	8
5052-H38	TS	96	79	58	30	20	12
	YS	98	77	40	20	12	8

Source: *Alcoa Structural Handbook,* Aluminum Company of America, 1958.

Coating 10, the phenolic spray foam, was particularly impressive. The interface temperatures did not significantly increase above ambient and the char depth was found to be only about 1 to 1.5 in. Unburned foam remained behind the supeficial char layer.

Temperatures high enough to ignite coal dust (320°F) were not observed on the unexposed side of the overcasts, coated with all but three coatings: Test 4 (Coating 4) and Test 7 (Coatings 7 and 8) for the 60-minute duration of the test.

Coating 7 (1 in. of cement-based insulating plaster with added polystyrene beads) and Coating 8 (1 in. of fiberglass-reinforced surface bonding mortar) prevented temperatures of 320°F or higher from being developed on the unexposed side for only about 30 and 50 minutes, respectively. In addition, temperatures in excess of 900°F were recorded, within 60 minutes, at the metal/coating interface in tests involving both of these coatings. At these temperatures, the tensile and yield strength properties of aluminum alloys would be practically nonexistent.

Table 3. Selected time/temperature data -Regime I.

KEY: MIT = Maximum Interface Temperature (°F);
AIT = Average Interface Temperature (°F);
MOT = Maximum Outside Temperature (°F);
AOT = Average Outside Temperature (°F);
MINT = Maximum Inside Temperature (°F);
AINT = Average Inside Temperature (°F);
TIME = Minutes; and
(R) = Reinforced.

	TIME	MINT	AINT	MOT	AOT
Test-Base Uncoated Aluminum Centerline Temperatures					
	5	390	359	286	226
	10	788	735	671	494
	15	1071	1027	1027	792
	20	1213	1175	1004	739

	TIME	MIT	AIT	MOT	AOT
*Test I-Coating 1 (R)**					
	10	77	77	77	77
	20	174	124	104	88
	30	338	243	131	120
	40	397	302	158	150
	60	436	380	221	186
*Test 2-Coating 2(R)***					
	10	127	100	77	77
	20	212	178	109	83
	30	266	216	172	160
	40	383	261	194	194
	60	626	386	194	194
Test 3-Coating 3(R)†					
	10	72	72	72	72
	20	172	118	82	82
	30	239	197	167	151
	40	347	243	212	168
	60	540	334	208	181
Test 4-Coating 4††					
	2	140	122	95	82
	4	234	201	192	145
	6	360	303	298	213
	8	802	622	518	427
	10	1398	1163	1263	1233

*Composition: No. 6 ceramic blanket; 3.0 in. thickness.
**Composition: vermiculite/portland cement/limestone; 1.5 in. thick; 85 days cure time.
† Composition: fiber-reinforced bonding mortar; 1.5 in. thick; 74 days cure time.
†† Composition: ablative coating; 0.187 in. thick; 6 days cure t.ime.

Table 4. Selected time/temperature data - Regime II. *See Table 3 for Key.*

	Unreinforced					Reinforced				
	TIME	MIT	AIT	MOT	AOT	TIME	MIT	AIT	MOT	AOT
*Test 5-Coating 5**										
	10	203	114	113	92	10	118	101	100	91
	20	289	169	167	127	20	127	118	108	102
	30	320	190	172	150	30	176	140	131	118
	60	446	280	293	223	60	329	247	194	169
	70	552	337	338	253	70	410	303	216	196
*Test 6-Coating 6 (R)***										
	10	54	54	59	59	10	86	63	59	57
	20	118	82	86	86	20	198	157	153	112
	30	212	181	158	140	30	279	221	198	188
	40	212	212	205	188	40	360	256	234	211
	60	212	212	212	197	60	540	347	319	235
*Test 7- Coating 7(R) ****										
	–	–	–	–		10	194	158	113	110
	–	–	–	–		20	356	285	239	229
	–	–	–	–	–	30	518	440	338	314
	–	–	–	–	–	40	662	568	446	429
	–	–	–	–	–	60	1022	810	608	568
	-		–	–	–	68	1026	870	653	608
Test 7-Coating 8(R)†										
	–	–	–	–	–	10	113	88	86	73
	–	–	–	–	–	20	320	206	158	125
	–	–	–	–	–	30	554	322	185	167
	–	–	–	–	–	40	689	416	230	207
	–	–	–	–		60	914	681	392	343
		–		–	–	68	986	759	464	394
Test S-Coating 9††										
	10	82	55	50	50	10	82	82	50	50
	20	158	121	122	98	20	149	131	86	74
	30	203	188	176	149	30	176	152	122	93
	40	234	206	183	163	40	194	187	149	101
	60	311	252	176	158	60	208	203	158	107
Test 9-Coating l0(R)†††										
	–	–	–	–		10	68	68	68	68
		–	–	–	–	20	95	79	77	70
	–	–	–	–	–	30	104	88	90	84
		–	–	–		40	108	98	95	85
	–	–	–	–	–	60	136	98	104	93

* Composition: fibers/inorganic binder; 1.0 in. thick; 67 days cure time.

** Composition: Vermiculite/portland cement/limestone; 2.0 in. unreinforced thickness, 1.0 in. reinforced thickness; 115 days cure time.

*** Composition: cement/polystyrene beads; 1.0in. thick; 93 days cure time.

† Composition: fiber-reinforced bonding mortar; 1.0 in. thick; 93 days cure time.

†† Composition: cellulose/sodium silicate; 1.0 in. unreinforced thickness, 1.5 in. reinforced thickness; 35 days cure time.

††† Composition: phenolic foam; 3.5-8.0 in. thick; 16 days cure time.

Conclusions

The fire testing conducted on the aluminum overcast test panels has demonstrated that certain coatings/coverings can be applied to these structures to protect them against structural failure due to fire and to prevent the breach of fire from one airway to another. The test fire employed in this program exercises a standard heat input and, for this reason, may not accurately predict the behavior of the coatings/coverings under all types of fire conditions. Test results do indicate, however, that certain commercially available products can be effectively utilized to cover aluminum overcast constructions in underground mines and should serve to provide protection against fire for extended time periods, which primarily depend upon the nature and magnitude of the fire.

The following materials were particularly effective as a fire-resistant barrier on aluminum in the fire tests that were conducted:

1. 4-in. phenolic spray foam-with wire lath support;
2. 3-in., 6-lb. density, ceramic-fiber blanket attached with stainless-steel fastening system;
3. l-in. vermiculite, portland cement, limestone coatings with or without glass fibers-with wire lath support;
4. 1.5-in. fiberglass-reinforced surface bonding mortar-with wire lath support;
5. l-in. inorganic mineral wool fibers in a hydraulic inorganic binder-with or without wire lath support; and
6. 1-in. cellulose mixed with sodium silicate applied in layers-no lath support required.

References

[1]Luzik S. J., Performance of Selected Coatings Applied to Polystyrene Block Walls Under Simulated Mine Fire Conditions," *Fire Tech., 22, 4,* November 1986, p. 311.

[2] *Alcoa Structural Handbook*, Aluminum Co. of America, Pittsburgh, Pa., 1958.

[3]Nagy, J., 'Explosibility of Carbonaceous Dusts," U.S. Bureau of Mines, Report of Investigations (RI) 6597,1965, 30 pp.