Solar Tests of Aperture Plate Materials for Solar Thermal Dish Collectors

Leonard D. Jaffe
Jet Propulsion Laboratory
Pasadena, CA 91109

ABSTRACT

In parabolic dish solar collectors, walk-off of the spot of concentrated sunlight can be a hazard if a malfunction causes the concentrator to stop following the sun. A test program was therefore carried out to evaluate the behavior of various ceramics, metals, and polymers under solar irradiation of about 7000 kW/m^2 (peak) for 15 minutes. The only materials that did not slump or shatter were two grades of medium-grain extruded graphite. High-purity slip-cast silica might be satisfactory at somewhat lower flux. Oxidation of the graphite appeared acceptable during tests simulating walk-off, acquisition (2000 cycles on/off sun), and spillage (continuous exposure of a receiver aperture lip).

INTRODUCTION

If a malfunction occurs in a solar thermal point-focus distributed receiver power plant while a concentrator is pointed at the sun, motion of the concentrator may stop. As the sun moves relative to the Earth, the spot of concentrated sunlight then slowly "walks off" the receiver aperture, across the receiver face plate, and perhaps across adjacent portions of the concentrator. Intense local heating by the concentrated sunlight may damage or destroy these parts.

Methods of protection against walk-off damage are discussed in Ref. 1. Use of materials that can withstand the concentrated sunlight without active cooling has the advantage of providing passive protection, which should increase reliability and may be less costly than alternative techniques.

The peak flux density at the focus is typically 1,000 to 15,000 kW/m^2. With such input, a gray body losing heat only by reradiation may reach an equilibrium temperature as high as 3750°C (6800°F). Because the spot moves at the Earth's rotation rate of 15 deg/h, typical times for the spot to move its own diameter are 5 to 15 minutes (except in polar regions). For passive protection, a material and design that can withstand these conditions is needed.

Ability to withstand walk-off is only one of the requirements for an aperture plate. In most designs, the spot of sunlight traverses the aperture plate each time the concentrator is swung to point it at or away from the sun during normal operation. The exposure time during normal sun acquisition or "deacquisition" is much shorter than during walk-off: typically 1 to 2 seconds for the spot to move its own diameter. However, sun acquisition and deacquisition occur once or several times a day during operation, whereas walk-off occurs only through malfunction. An aperture plate that is exposed to the sun during acquisition should withstand many cycles of acquisition and deacquisition.

An additional requirement of any aperture plate is that it must withstand "spillage" or lip heating. The flux density at the lip during normal operation is usually less than one percent to a few percent of the peak flux density of the spot, but the lip is exposed to this spillage at all times when the concentrator is pointed at the sun.

Some work has been reported on the ability of uncooled materials to withstand concentrated sunlight for short periods of time. Except for some limited tests, this prior effort was not oriented toward dish concentrators, and either the flux densities or exposure times used were lower than those of interest for walk-off of dish concentrators. Considerable work has been done on materials for high-speed reentry bodies and for resistance to nuclear explosions, but applicability of this work to solar concentrators is uncertain because of the different modes of energy transfer. It therefore appeared worthwhile to undertake tests to evaluate candidate materials. In particular, there was interest in finding a suitable aperture plate material for passive protection for the organic Rankine system. A more detailed account of the work, with extensive literature references, is given in Ref. 2.

TYPES OF MATERIALS TESTED

The general types of materials tested included graphite, silicon carbide, silica, silicates, alumina, zirconia, steel, and polytetrafluoroethylene. Also tested were aluminum and copper with temperature-resistant coatings, and graphite with temperature-resistant coatings. About 45 samples were tested.

The preferred sample size selected was 200 x 200 x 25 mm (8 x 8 x 1 in.), to have samples large enough when compared to the solar spot size and thick enough to provide reasonable protection. A few thicker samples were tested to see if greater thickness improved performance. Because many samples were provided free of charge rather than purchased, they were often smaller than preferred. Some were as thin as 0.4 mm (0.017 in.); these samples were provided more because of the supplier's interest in using them for protection during normal operation, acquisition, and deacquisition than for possible walk-off protection.

TEST EQUIPMENT

Solar tests were made on Test Bed Concentrator 1 at J.P.L.'s Parabolic Dish Test Site. As part of the setup for testing a major portion of the organic Rankine module, a water-cooled aluminum shield had been mounted near the focal plane of the concentrator. This shield had a central opening 400 mm (16 in.) in diameter. A water-cooled aluminum sliding shutter, installed on the side of the shield closest to the concentrator mirrors, could be opened or closed to permit concentrated sunlight to pass through the shield opening or to block it off.

Solar Walk-off And Solar Acquisition

For the materials walk-off and acquisition tests a fixture was designed which mounted against the aluminum shield, on the side away from the mirrors. The test fixture was made of graphite in the form of a "window frame" with an opening 230 mm (9 in.) square, in which the sample was placed. The sample was retained by graphite rods 10 mm (3/8 in.) in diameter, which fitted loosely through holes in the upper frame of the fixture and rested in blind holes in the lower frame. During exposure, the center of the solar spot was close to the center of one face of the sample.

The flux pattern used for walk-off and solar acquisition tests was designed to simulate the pattern then planned for use with the organic Rankine module. The distribution of solar flux in the materials test plane was measured with a flux-mapper (Ref. 3). The peak measured flux density in this plane was 9,700 kW/m^2 at an insolation of 1 kW/m^2. The total concentrated solar power at 1 kW/m^2 was approximately 78 kW, as measured by a cold-water calorimeter. In the materials tests the actual insolation was lower than 1 kW/m^2; at an insolation of 720 W/m^2, the peak flux density was 7,000 kW/m^2.

Solar Spillage

For spillage tests, one edge of the samples was tapered and rounded to form a lip. Two chromel-alumel thermocouples, wire diameter 0.25 mm (0.010 in.), were inserted through the back of the 26 mm (1.0 in.) thick samples, terminating 0.5 mm (0.02 in.) from the lip. The samples were mounted at various radial and axial positions to simulate spillage conditions (such as flux levels) that might be encountered with various solar thermal power modules. Samples were mounted off center so that only the edge of the solar spot struck the sample.

TEST PROCEDURES

In all solar tests, the samples were observed on television utilizing a black-and-white TV camera; imagery was recorded on a video cassette recorder. Insolation was recorded digitally using Eppley and Kendall pyroheliometers. Direct normal insolation during tests was 530 to 960 W/m^2.

Walk-off Tests

All of the materials investigated were tested for their ability to sustain walk-off. The test duration was 15 minutes unless the sample failed earlier. The test was more severe than an actual walk-off because the spot of maximum solar flux was held fixed on the sample, whereas in walk-off the spot would traverse across the plate.

Several samples were tested wet to simulate exposure to rain followed by sunlight and walk-off. They were soaked in water at a depth of 15 to 30 cm (6 to 12 in.) for at least 30 minutes prior to solar testing.

Acquisition Tests

Tests aimed at evaluating behavior under acquisition and deacquisition conditions and under spillage conditions were conducted only on graphite. These tests were run because some grades of graphite appeared promising in the walk-off tests, but there was concern that the rate of loss of graphite by oxidation might be excessive under the long cumulative exposures associated with acquisition-deacquisition and spillage.

Two graphite samples were tested under conditions simulating repeated acquisition and deacquisition. They were mounted in the same way as the samples for walk-off testing. The acquisition-deacquisition tests consisted of multiple cycles of opening and closing the shutter, each approximately 1 second open, 10 to 19 seconds closed. Maximum exposure was 2000 cycles. Insolation in these tests was 780 to 960 W/m^2; acquisition and deacquisition in service probably would be primarily at low sun elevation, when insolation would be lower.

Spillage Tests

Solar tests of oxidation of graphite under conditions simulating many thousand hours of spillage exposure were beyond the scope of this work. Instead, to allow estimation of the long-time oxidation rate, measurements were made of the temperature of graphite samples simulating a tapered aperture lip. The lip, with thermocouples inserted, was placed 75 to 175 mm (3 to 7 in.) from the center of the spot of sunlight (representing aperture diameters of 150 to 350 mm, 6 to 14 in.) and at various axial positions. Flux density at the lip position nearest the spot center varied from less than 1 to over 1000 kW/m^2 depending on sample position.

WALK-OFF TESTS: MELTING AND FRACTURE RESULTS AND DISCUSSION

Results of the walk-off tests are summarized in Table 1 and tabulated, with accompanying measurements and photographs, in Ref. 2.

Graphites

Grade G-90. Graphite grade G-90 was the only material that consistently survived a 15-minute simulated walk-off without melting, slumping, or cracking. A sample of G-90 survived two 15-minute tests without cracking. Another sample of this material was tested wet, and did not crack.

Grade G-90 is an extruded material that is reimpregnated several times with coal-tar pitch and regraphitized to reduce its porosity and increase its bulk density. Grade G-90 is a premium grade and somewhat expensive for a graphite: about $45/kg ($20/lb).

Grade CS. During the standard walk-off test, all six samples of uncoated graphite grade CS 14 to 37 mm (0.5 to 1.5 in.) thick developed a single crack extending from near the midpoint of an edge to near the center of the specimen. This reproducibility was striking, particularly because the samples came from three different lots of graphite. Of two samples that were 50 mm (2 in.) thick, one survived the simulated walk-off test without cracking or other failure; the other cracked from an edge to somewhat beyond the center. None of the CS graphite specimens fell apart into two or more pieces. Four samples of CS graphite that cracked halfway during initial exposure were retested for total times up to 45 minutes without further observed crack advance. Apparently the first crack, halfway across, was sufficient to relieve the thermal stresses and prevent further cracking. With proper segmenting, this grade should perform satisfactorily. (Bank and Owen (Ref. 4) reached a similar conclusion on the basis of earlier tests.) Grade CS is a commercial grade of extruded graphite that costs about $4.50/kg ($2/lb).

Like most graphites fabricated by extrusion, grade CS has markedly anisotropic properties, with its coefficient of thermal expansion being lower and its strength higher in the direction parallel to the grain (parallel to the extrusion direction) than in the direction perpendicular to the grain (perpendicular to the extrusion direction). It is very likely that cracking occurred perpendicular to the grain.

Effect of Water. Graphite grades G-90 and CS absorbed very little water on immersion and their subsequent performance in simulated walk-off tests was unaffected by this wetting.

Other Graphite Grades. Other grades of conventional graphite tested were 3499, 8826, and HLM-85. All samples of these grades cracked apart or shattered in test; the 3499 at exposure times of 1-1/2 to 8 minutes, the 8826 and HLM-85 in 1 to 1-1/2 minutes.

Walk-off Performance and Other Characteristics of Graphite Grades. Graphite grades G-90 and CS, which performed well, are extruded grades with medium grain size (maximum particle size nominally 750 micrometers). Grades 3499 and 8826 are fine-grained molded graphites (maximum particle size nominally 75 micrometers); they shattered in test. This suggests that fine grain (and possibly molding) is less desirable than medium grain (and extrusion?) in graphites for walk-off protection. Such an interpretation of the grain size effect is consistent with the general belief that coarser-grained graphites have better resistance to thermal shock than fine-grained.

Many graphite grades are available besides those tested. Perhaps some further testing of grades with a wider range of characteristics would be worthwhile.

Graphite Cloth. One sample of a "graphite cloth," graphitized polyacrylonitrile, was tested under simulated walk-off conditions. The sample, 0.43-mm (0.017-in.) thick, developed slits and holed through in 30 seconds. Examination under the microscope indicated that the material had not melted, but that woof fibers, especially, had disappeared, presumably by oxidation. Similar results have been reported (Refs. 4,5).

If one assumes that multiple layers would behave independently, an assembly of 30 plies, 13-mm (0.5-in.) thick, might last 15 minutes. This is rather speculative in the absence of a multi-layer test. Such a graphite cloth assembly would be considerably lighter than conventional graphite of the same dimensions: 4.5 kg (10 lb) for an aperture plate for the collector mentioned above. Material of this type costs about $150/kg ($70/lb).

Coated Graphite. Three samples of graphite were coated with boron nitride, which is white, and two with commercial high-temperature white paints. The samples behaved like uncoated samples of the same grade, except that one CS sample cracked all the way across, rather than halfway.

Silica

Samples of high-purity slip-cast fused silica with fine particle size survived 4 minutes at insolation of 670 W/m^2 and 1-1/2 minutes at 740-790 W/m^2 before slumping. The longer survival at the lower insolation suggests that high-purity slip-cast silica would be satisfactory at somewhat lower flux levels than those used in this test program. The cost of a segmented aperture plate of high-purity slip-cast silica for the collector discussed would be about $12/kg ($6/lb) in quantities of a hundred or so.

Other Materials

None of the other materials survived more than 3 minutes. Most failed within a few seconds. Comparison of the behavior of the various materials in the walk-off tests emphasizes the importance of melting point. The only materials tested that did not melt or slump were graphite and silicon carbide. Neither of these materials melts at atmospheric pressure. Silicon carbide was nevertheless unsatisfactory because it shattered in thermal shock. Silicon carbide has lower thermal conductivity than graphite, which is doubtless a major factor in its poorer performance.

WALK-OFF TESTS: OXIDATION RESULTS AND DISCUSSION

During walk-off tests the loss in thickness due to oxidation for grades CS and G-90 varied from 0.2 mm (0.008 in.) to 8 mm (0.3 in.) per 15 minutes of exposure. The corresponding loss in mass was 2 to 22% (normalized to a standard sample size, 25 x 200 x 200 mm (1 x 8 x 8 in.), assuming that the mass loss in grams is independent of sample size). This loss rate will probably be acceptable for walk-off protection because walk-off is expected to be an infrequent event and the test was more severe than the expected service.

The effect of wind speed on the oxidation loss was significant (Fig. 1), and accounts for a large part of the variation in loss between samples. Interestingly, insolation did not have a significant effect upon mass loss rate. The literature indicates that, at the temperatures encountered in walk-off, the rate-limiting process is mass transfer through the boundary layer. Insolation level would be expected to have only a small effect on mass transfer, whereas wind speed would have a major effect.

The difference in mass loss rate between grade CS graphite and grade G-90 was not statistically significant. Neither a boron nitride coating nor prior immersion in water had a statistically significant effect.

ACQUISITION TEST RESULTS AND DISCUSSION

The repeated on-sun/off-sun cycles used for some samples of grade CS graphite were intended to give an indication of the extent of graphite oxidation during normal sun acquisitions and deacquisitions. In 700 to 2000 cycles, which might represent a year or two of service, the samples lost 5 to 7 mm in thickness and 0.15 to 0.2% of their weight (normalized to a thickness of 25 mm, 1 in.). This appears to be tolerable. Wind speed during the simulated acquisition-deacquisition test was 2 to 10 m/s, 4.5 to 22 mi/h), representative of the wind conditions likely to be encountered during operation.

SPILLAGE TEST RESULTS AND DISCUSSION

The various positions of the sample edge in the spillage tests were used to indicate the temperatures attained by the lip of a graphite aperture plate exposed to various levels of spillage. One test represented, approximately, the conditions that were planned for the organic Rankine receiver with an aperture diameter of 350 to 380 mm (14 to 15 in.). The flux density at the lip was about 10 kW/m^2; the lip temperature was 107°C (225°F). At this temperature the oxidation of graphite would be negligible even over periods of many years.

Tests of other samples represented conditions on receiver aperture plates having diameters of 150, 200, and 250 mm (6, 8, and 10 in.), positioned close to the focal plane. Flux densities at these positions were approximately 400, 70, and 40 kW/m^2. Temperatures reached were, respectively, 312, 173, and 133°C (594, 343, and 271°F). According to data of Ref. 6, the oxidation rate for grade CS graphite below 750°C (1400°F) is given by

$$dm/dt = 5.26 \times 10^8 e^{-42,900/RT_K} \qquad (1)$$

where dm/dt = mass loss, g/m^2s

R = universal gas constant = 1.986 cal/K-mol

T_K = temperature, K

For the 200 and 250 mm (8 and 10 in.) apertures, the calculated oxidation rate is negligible. For a 150 mm (6 in.) aperture, the calculated rate of less than 1 μm/y certainly appears acceptable.

According to the literature, graphite oxidation at temperatures up to 750 to 850°C (1400 to 1600°F) is reaction-rate limited. Loss rates due to spillage, therefore, should not be significantly affected by wind speed.

SUMMARY AND CONCLUSIONS

A test program was carried out to evaluate behavior of materials under conditions simulating walk-off of a parabolic dish solar collector. Each test consisted of exposure to concentrated sunlight at a peak flux density of about 7,000 kW/m^2 for 15 minutes. Types of materials tested included graphite, silicon carbide, silica, various silicates, alumina, zirconia, aluminum, copper, steel, and polytetrafluoroethylene. Of these, the only material that neither cracked nor melted was grade G-90 graphite, a premium grade. Grade CS graphite, a lower cost commercial grade, cracked half-way across, but did not fall apart. Both of these grades are medium-grain extruded graphites. A graphite cloth (graphitized polyacrylonitrile) showed fair performance when tested as a single thin ply; it might be useful as a multi-ply assembly.

The only other material tested which appeared promising was high-purity slip-cast silica; samples survived one and one-half to four minutes. This duration is inadequate for walk-off protection, but the material may well be satisfactory at flux densities somewhat lower than those used in these tests.

The other grades of graphite and silica tested, and all the samples of other materials, either melted, slumped or shattered quickly during the walk-off tests.

Coatings of white high-temperature paint or boron nitride did not improve the performance of graphite samples. Immersion in water prior to test, simulating rain, did not affect their performance.

Oxidation of grades CS and G-90 graphite per 15-minute simulated walk-off varied from 0.2 to 8 mm (0.008 to 0.3 in.) of thickness, from 2 to 22% of the mass (normalized to 25 mm (1 in.) thickness). The amount of oxidation varied strongly with the wind speed.

Grade CS graphite was tested for up to 2000 cycles simulating 1-second periods of acquisition at the same flux density as the walk-off test. Loss in moderate to high winds was about 5 mm in thickness or 0.15% of the sample mass. Tests under simulated spillage conditions were limited to measurements of the temperature of the lip of a simulated aperture plate of grade CS graphite. They indicate that the oxidation rate of this material will be negligible at a flux density of 400 kW/m^2 on the lip, for the graphite geometry and flux distribution used in test.

ACKNOWLEDGMENTS

William Owen, Richard Smoak, and Terry Hagen contributed to planning of the work. George Lynch helped greatly in arrangements to obtain and prepare samples. John Woodbury and Dennis Maciej provided major support in the solar testing. Toshio Fujita, Frank Surber, Robert Hale, and Wayne Phillips suggested significant improvements in the manuscript.

Test materials were provided by Maurice Argoud, Herman Bank, J. A. Barry, David Lawson, William Owen, Wayne Phillips, Kudret Selcuk, and Jack Stearns of JPL, Joseph Harris of Georgia Institute of Technology, Wilson Schramm of Lockheed Missiles and Space Company, David Wells of United Stirling, Inc., John Davidson of Airco-Speer Carbon Co., Y. Harada of Illinois Institute of Technology Research Institute, and David Page of Union Carbide Corp.

REFERENCES

1. L.D. Jaffe, R.R. Levin, P.I. Moynihan, B.J. Nesmith, W.A. Owen, E.J. Roschke, M.K. Selcuk, D.J. Starkey, and T.O. Thostesen, "Systems Approach to Walk-off Problems for Dish-Type Solar Thermal Power Systems," JPL Doc. 5105-97, 1981, and Proc. I.E.C.E.C., Orlando, FL, Aug. 1983, Am. Soc. Chem. Eng.

2. L. D. Jaffe, "Solar Tests of Aperture Plate Materials for Solar Thermal Dish Collectors," JPL Doc. 5105-121, 1983.

3. W. A. Owen, Internal communications, JPL, 1981-1983.

4. H. Bank and W. Owen, Internal communication, JPL, 1980.

5. R. Smoak, Internal communication, JPL, 1980.

6. Carbon Products Division, Union Carbide Corp., "Oxidation of CS-312 in Dry Air," Union Carbide Corp., Palma, Ohio.

Table 1
Summary of Results of Walk-off Tests

Material Type		Thickness mm	Failure Mode	Time
Graphite	3499	26	Shattered	1 to 8 min
	8826	26	Shattered	1 to 1-1/2 min
	CS	14-50	Cracked halfway (1 of 10 survived)	10 s to 14 min
	HLM-85	24-26	Shattered	1 to 1-1/2 min
	G-90	24-25	(Survived)	30 min
	Cloth	0.4	Holed	30 s
SiC		6-32	Shattered	1 s
SiO_2	Slipcast, high purity	18-21	Slumped	1-1/2 to 4 min
	Slipcast, commercial	20-26	Dripped	10 s
	Fibrous, glazed	41	Dripped	7 s
Silicates	Mullite	32-38	Melted	1 to 4 s
	Processed kaolin	27	Melted	3 s
	Cordierite	25	Melted	2 s
	Alumina-boria-silica	0.5-0.7	Melted	1 s
Al_2O_3	Paper	0.4-1.4	Melted	2 to 6 s
ZrO_2	Cast and sintered	29	Melted	20 s
	Fibrous board	25	Melted	1 min
	Cloth	0.5	Melted	8 s
Copper		26	Melted	1 to 3 min
Aluminum		1.8	Melted	1 s
Steel		2	Melted	2 s
Polytetrafluoroethylene		38	Melted	2 min

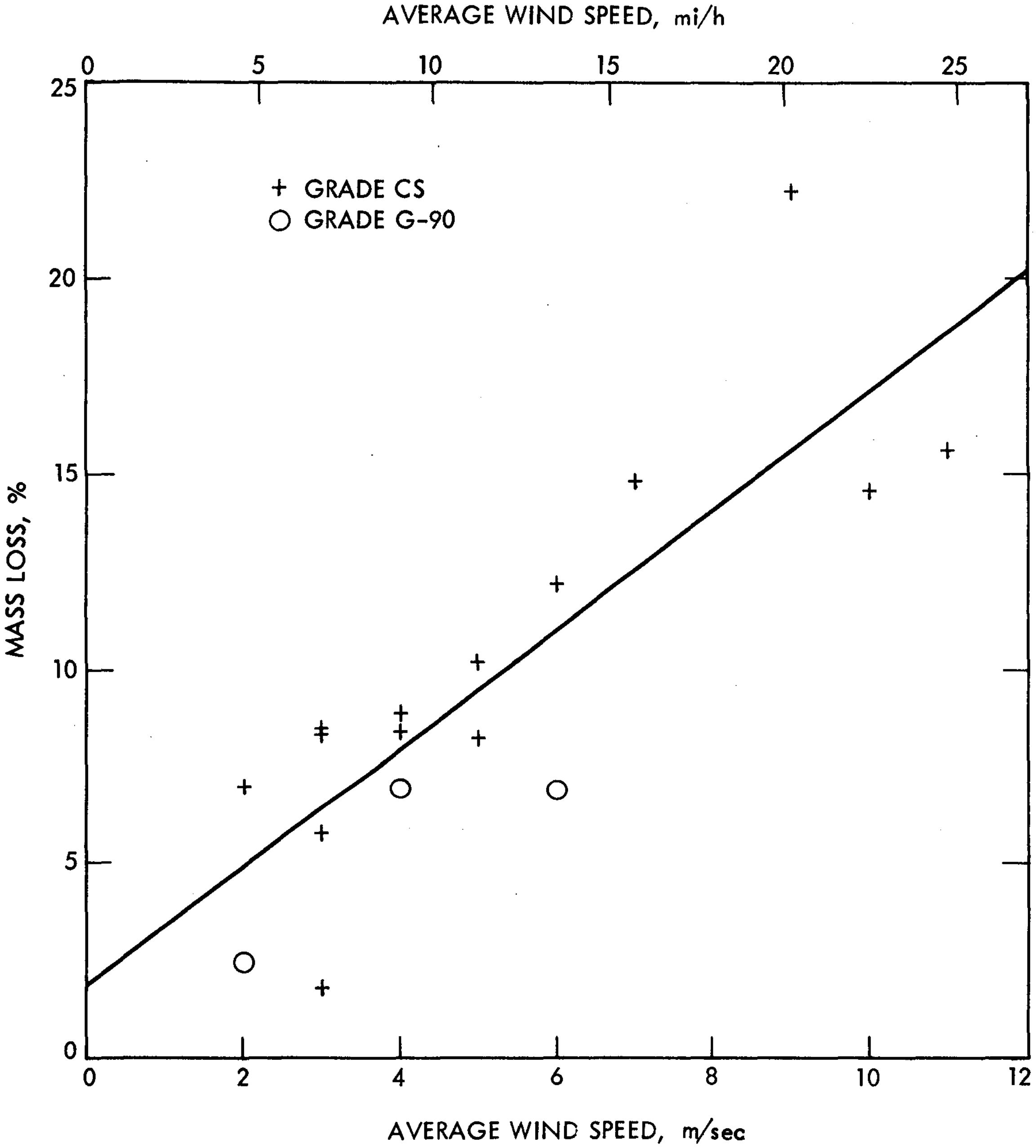

Fig. 1 Effect of wind speed upon mass loss by oxidation, for graphite, Grades CS and G-90, in walk-off tests. (Mass losses normalized to 15 minutes exposure and 25 x 200 x 200 mm (1 x 8 x 8 in.) sample.