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REON

ROCKET ENGINE OPERATIONS - NUCLEAR

REPORT NO. 2691 (REVISED)
TO
AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

STRAIN GAGE RESEARCH
AND
HIGH OUTPUT TRANSDUCERS

NERVA PROGRAM

CONTRACT SNF 1

JANUARY 1964

MASTER

AEROJET-GENERAL CORPORATION

AZUSA, CALIFORNIA

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AEROJET-GENERAL CORPORATION
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ABSTRACT

The research and development program was initiated in strain gage technology for two purposes:

- (1) To develop a radiation resistant strain gage for measuring surface strains
- (2) To improve the state-of-the-art of bonded strain gage pressure transducers and accelerometers so that they can be used in radiation environments.

In the course of this development, the method of mounting strain gages using an aluminum oxide spray method (Rokide) was developed. A preliminary radiation test conducted in GTR in October, 1962 on four strain gages and three resistance thermometers mounted by this Rokide method showed great promise. A detailed process specification describing this mounting process using specially designed strain gages was written. A second radiation test was conducted in May, 1963 in GTR at 700⁰F using two test fixtures. In these test fixtures, 72 Rokided gages were tested, representing 11 different types. The test results are summarized in chart form. Further details regarding this test can be found in Vol. II of the Instrumentation Data Book.

Non-radiation tests were performed to demonstrate the ability of flame-sprayed, ceramic-bonded, strain gages to monitor micro strains up to 4000 in graphite compression testing.

A series of exploratory tests was conducted to ascertain the feasibility of operating Rokided gages at output levels of ± 1 volt. These tests showed that the developed strain gages can be operated to produce signal outputs 30 to 40 times as great as those obtained with orthodox gages. An informal development program has been initiated with three instrumentation manufacturers of bonded strain gage pressure transducers. Strain gage elements will be mounted, via the Rokide method, on the pressure sensing elements of pressure transducers. The ultimate objective of this program is to develop a radiation-resistant,

bonded, strain-gage pressure-transducer which is superior to the unbonded type transducer and also, simultaneously, to develop a strain gage pressure transducer which can deliver an output signal much larger than is presently feasible.

It should be mentioned that this development program has benefitted other programs outside the NERVA program. Strain gages mounted via this flame spray development have been installed and used successfully on nozzles in the Apollo and Trans-Stage programs. Several of these strain gages will be mounted in the newly erected, heavy-water-moderated, research reactor (HFBR) at Brookhaven National Laboratory.

W. D. Stinnett
REON Technical System Manager

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APPENDIX A - PROCESS SPECIFICATION, PROCESS FOR ROKIDE BONDING STRAIN
GAGES TO METAL

APPENDIX B - CARBON GAGING REPORT

I. INTRODUCTION

During the search for suitable instrumentation, it became evident that strain-gage type sensing elements should be examined as possible candidates for use in NERVA transducers. This decision was reached from an earlier survey of transducer irradiation tests and from available reports on nonradiation environmental tests. Several desirable attributes of strain sensors were noted among which the following are outstanding.

- A. Excellent linearity
- B. Infinite resolution
- C. Low hysteresis
- D. Simplicity of construction (no bearings, pivots, wipers or contacts)
- E. Operable with ac or dc power
- F. Constant output and input impedance with any stimulus
- G. Low, purely resistive, input and output impedances
- H. Output proportional to excitation as well as stimulus

The main disadvantage of strain gage sensing elements for transducers lies in their low output level. A typical full scale value is 30 mv. This is a particularly acute problem in the NERVA application since the environments are expected to be noisy, and for this reason a poor signal-to-noise ratio obtains. Furthermore, the signal-to-noise ratio is not correctible by amplification because noise would be simultaneously amplified, and secondly, the amplification itself presents a problem at least as difficult as the transducer problem in a high radiation environment.

Since the elemental strain gage is a relatively inexpensive device and is readily available in several configurations, it affords an excellent vehicle for the development of sensing elements. Therefore, strain gages were chosen

not only for their own sake but also as a tool for examining strain sensitive elements for other types of transducers (e.g. pressure and vibration).

II. GENERAL

A method of spraying ceramic materials has been developed by the Norton Company of Worcester, Mass. This process is known by the trade name of "Rokide," and has proved to be quite satisfactory as a means of bonding strippable wire strain gages to parent materials to be tested in high temperature environments. Since such an application results in a completely inorganic installation, this process warranted developmental effort for NERVA use. An effort was undertaken to increase gage output, and tests were planned with this in mind.

III. EQUIPMENT

The Rokide process permits spraying a number of ceramics with varying properties. Rokide A, aluminum oxide, has good electrical insulating properties, handles quite well in rod form, and will withstand strains of 3000 microinches per inch in either tension or compression.

Aluminum oxide can be applied to a parent material by either of two methods: An oxy-acetylene-compressed air gun with a rod feed may be used or a plasma gun may be utilized.

Because of the initial cost of the plasma equipment and since the equipment was not so fully developed, the oxy-acetylene-compressed air gun was selected. This machine develops a high temperature flame through which a Rokide rod is driven by means of an air turbine and reduction gearing. The speed of the rod drive is variable over wide limits, and is held very constant, when set, by means of a governor mechanism coupled to the turbine drive. As the rod reaches the core of the flame, it fuses. A concentric air jet outside the flame then atomizes the molten ceramic and drives it through the gun nozzle at high velocity.

Figure 1 illustrates the Rokide gun used at Aerojet. This unit is a Type R1 gun manufactured by Metallizing Company of America. For clarity, the nozzle assembly is shown disassembled, and a Rokide A (Al_2O_3) rod is also pictured. This unit can handle either 1/8-inch or 3/16-inch diameter rods. Only the 1/8-inch diameter has been used in strain gage application.

Figure 2 shows an extension nozzle assembly available in lengths of six-inch increments. This unit delivers the atomized stream with a 1/8-bend at the end of the extension. The unit is useful in "hard to get at" locations.

Figure 1. R1 ROKIDE GUN WITH Al₂O₃ ROD INSERTED

Figure 2. R1 ROKIDE GUN EXTENSION NOZZLE

IV. PROCESS

After a surface is cleaned and roughened by a suitable means such as sandblasting, a Rokide jet directed at the surface, deposits fine particles of molten ceramic, forming a good bond with the parent material and with the deposited Rokide. A strippable wire gage held in place on top of such an undercoat can be given a second coat and thereby will be secured to the undercoat. A matrix of high-temperature, pressure-sensitive tape is used to secure the gage in place during application of the second coat. After the second coat is applied, this matrix is removed and a third coat is applied to complete the process. Strain gages and surface resistance thermometers can both be mounted by the Rokide process.

The completed application provides a surface-mounted transducer composed entirely of inorganic materials, and, as such, is appropriate for use in radiation environments over a broad range of temperatures.

Appendix A outlines the tentative procedure used at Aerojet for Rokide strain gage application. Figures 1 through 8 of Appendix A show stages in the process of mounting Rokide gages. Figure 1 of Appendix A shows a gage as it was received from Baldwin Lima Hamilton. The top material is glass fiber fabric impregnated with teflon (3M, X 1132 or equal). The back side of this material is coated with a pressure sensitive silicone adhesive in which the strain sensitive grid is laid. Behind the pressure sensitive adhesive and the grid is a paraffin wax paper backing. Figure 2, Appendix A shows this material partially removed. Figure 3 of Appendix A is a view of a test beam which has been sandblasted in the area which is to receive the gage. Figure 4 of Appendix A shows the sandblasted test beam after the initial Rokide coat has been applied. Figure 5 of Appendix A shows the gage in place ready for the second coat of Rokide (Figure 6). In Figure 7 of Appendix A, the carrier tape has been removed, again exposing portions of the strain wire. A third and final coat of Rokide has been applied as shown in Figure 8 of Appendix A. The gage applied in this way constitutes an assembly that is entirely devoid of organic materials, consisting only of metallic leads, strain wire, and aluminum oxide.

V. TESTS

A. IRRADIATION TESTS

In September 1962, the first Aerojet irradiation test on Rokide coated transducers was performed in GTR. Four strain gages and three surface resistance thermometers were exposed (with several pressure transducers, an accelerometer, and a vibrometer). The test was conducted for approximately 60 hours at temperatures up to 230°F. The integrated neutron flux maximum was 8.92×10^{15} n/cm², E > 2.9 Mev. The gamma dose maximum was 5.62×10^{10} ergs/gm (C). Two of the strain gages were cycled continuously and alternately at strains of approximately +300 and -300 microinches/inch and the other two at +600 and -600 microinches/inch.

All seven of these Rokide coated transducers performed satisfactorily during this first exploratory test. The insulation resistance of the transducers was not measured during exposure but "before" and "after" results showed considerable degradation. Consequently, insulation resistance became and remains the subject of further examination.

Baldwin Lima Hamilton type HT100-5A strain gages were used on two beryllium copper test beams in this test. Fixture 1 containing one beam is shown in Figure 3 and a detail view of the other beam in fixture 2 is shown in Figure 4. In each case, a pneumatic bellows assembly was used to drive the beam against a mechanical stop, and a spring was used to return the beam to a second mechanical stop. Figure 5 is a plot of the output signal vs radiation dose for the two gages of Fixture 1 connected as active gages in a half bridge. Figure 6 is the corresponding plot for Fixture 2. Note that Figure 5 shows an increase in output at about 7×10^{14} n/cm². Post-irradiation examination revealed some fixture warpage which is thought to be the cause of this increase. Note also that Fixture 2 received approximately three times the dose experienced by Fixture 1. Figure 7 gives the measured insulation resistance for the gage pairs on each of the two fixtures before and after irradiation.

A second test was performed on Rokide coated strain gages in May 1963. Seventy-two gages of several alloys, two physical sizes, and four electrical

Figure 3. FIXTURE 1 SHOWING DRIVING AND TOGGLE MECHANISM
 FOR STRAIN GAGE BEAM

Figure 4. BEAM OF FIXTURE 2 SHOWING STRAIN GAGES, RESISTANCE THERMOMETER, DRIVING BELLOWS, AND RETURN SPRING

NPC 17,600

Figure 5. EFFECT OF RADIATION ON STRAIN GAGE OUTPUT, FIXTURE 1

NFC 17,601

Figure 6. EFFECT OF RADIATION ON STRAIN GAGE OUTPUT, FIXTURE 2

Figure 7. INSULATION RESISTANCE OF STRAIN GAGES

Test Fixture	Insulation Resistance (megohms)	
	Preirradiation	Postirradiation
1	1.4	0.80
2	200	1.0

sizes were tested at 700⁰F in the GTR. The test lasted 101 hours. Total integrated neutron flux was a maximum of 2.3×10^{16} n/cm², E > 2.9 Mev and a total maximum gamma dose of 9.7×10^{10} ergs/g (C). Particular attention was given to instrumenting the leakage currents of strain gages to ground in this test. Strain levels were at +1200 to +1500 microinches/inch. These strain levels combined with the higher temperatures and greater radiation levels resulted in substantial degradation in insulation resistance and some gross failures because of open circuits.

A fixture was designed expressly for testing Rokide coated strain gages. Front and rear views of this unit are shown in Figures 8 and 9. The double acting pneumatic bellows actuates a drive rod which, in turn, flexes the test beams. The mechanical stops were set to limit the drive rod travel to +1/4 inch resulting in beam microstrains of +1500 maximum. Each of these fixtures can accommodate 22 test beams or 44 gages. Test beams are 1 inch wide x 5-7/8 inches long x 1/16 inch thick with an effective length of 4 inches. Two of these fixtures, numbered "2" and "4," were used.

Gages were connected in half bridge configurations with completion networks in a nonradiation area. Figure 10 shows the basic schematic for signal output monitoring.

Figure 11 is a schematic diagram of the basic circuit used for measuring insulation resistance leakage current. Note that the guard circuit shunts the leakage current of the shield around the microammeter so that the microammeter current is only that current which passes from strain gages through their own insulation to ground return.

Figure 12 shows the general mechanical arrangement of strain gages on the test beams. Beyond the gage terminals, a steatite terminal block manufactured by the Millen Company of Malden, Mass. was used. These can be seen in Figures 8 and 9.

Figures 13, 15, 17, 19, 21, 23, 25, 27, 29 and 31 show the ranges of total output of the various beams by gage type plotted against the radiation, both netrons and gamma. Preirradiation and postirradiation data are also shown on these curves. Figures 14, 16, 18, 20, 22, 24, 26, 28, 30 and 32 show center position veoltage vs radiation for the various beams by gage type.

Figure 8. FRONT VIEW OF STRAIN GAGE TEST FIXTURE USED IN
MAY 1963 TEST IN GTR

Figure 9. REAR VIEW OF STRAIN GAGE USED IN MAY 1963 TEST IN GTR

Figure 10. SIMPLIFIED SCHEMATIC DIAGRAM OF GAGE TEST CIRCUIT

Figure 11. SIMPLIFIED SCHEMATIC DIAGRAM OF INSULATION RESISTANCE GUARD CIRCUIT

Figure 12. MECHANICAL ARRANGEMENT OF TEST BEAM WITH GAGES INSTALLED

MPC 17,987

Figure 13. STRAIN GAGE TYPE HT-1235-4A-1, FIXTURE 2: TOTAL OUTPUT VS. RADIATION EXPOSURE

NPC 17,988

Figure 14. STRAIN GAGE TYPE HT-1235-4A-1, FIXTURE 2:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 16. STRAIN GAGE TYPE HT-122K, FIXTURE 2: CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

NPC 17,993

Figure 19. STRAIN GAGE TYPE HT-11K-10A-1, FIXTURE 2:
TOTAL OUTPUT VS. RADIATION EXPOSURE

Figure 20. STRAIN GAGE TYPE HT-11K-10A-1, FIXTURE 2:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 22. STRAIN GAGE TYPE HTD-2K-10A-1, FIXTURE 2:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 23. STRAIN GAGE TYPE HT-11K-10A-1, FIXTURE 4;
TOTAL DOSE VS. RADIATION EXPOSURE

NPC 17,998

Figure 24. STRAIN GAGE TYPE HT-11K-10A-1, FIXTURE 4:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 25. STRAIN GAGE TYPE HTD-2K-10A-1, FIXTURE 4:
TOTAL OUTPUT VS. RADIATION EXPOSURE

Figure 26. STRAIN GAGE TYPE HTD-2K-10A-1, FIXTURE 4:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

NPG 19,001

Figure 27. STRAIN GAGE TYPE HT-1235-4A-1, FIXTURE 4:
TOTAL OUTPUT VS. RADIATION EXPOSURE

NPC 19,002

Figure 28. STRAIN GAGE TYPE HT-1235-4A-1, FIXTURE 4:
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 29. STRAIN GAGE TYPE HT-122K-10A-1, FIXTURE 4:
TOTAL OUTPUT VS. RADIATION EXPOSURE

Figure 30. STRAIN GAGE TYPE HT-122K-10A-1, FIXTURE 4;
CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figure 31. STRAIN GAGE TYPE HTPT-1K-10A-1, FIXTURE 4:
TOTAL OUTPUT VS. RADIATION EXPOSURE

Figure 32. STRAIN GAGE TYPES HT-122K AND HTPT-1K-10A-1, FIXTURE 4: CENTER-POSITION OUTPUT VS. RADIATION EXPOSURE

Figures 33 and 34 show the average insulation resistances for the various types of gages tested. Care in location was taken before, after, and several times during irradiation. Total irradiation is given in each case.

Figure 35 is a summary table of the results of the radiation and high temperature environments combined, with respect to the change in output signal.

Figure 36 is included for comparative purposes only. The insulation resistance of several type HT gages is tabulated to show typical values before connection into the test circuits. High voltage potential in this case was 50 volts. These gages were tested after being mounted on test beams but before beam installation in the fixture. These gages are not directly identifiable as the same units which were irradiated, but they constitute a sample of the group used for irradiation testing.

Figure 36 shows that insulation resistances of the uninstalled Rokide coated gages are high compared with any installed gage. The average gage insulation within this group is greater than 6000 megohms. Two such average gages on a test beam would exhibit a beam insulation resistance of 3000 megohms.

The average, nonirradiated, insulation resistance as shown in Figure 33 or Figure 34 is the 400°F indication recorded before irradiation. The average of these indications is 277 megohms per beam. Therefore, contaminants that are introduced as the result of connecting the installed gages were responsible for the large loss (over 90 percent) in insulation resistance.

It can be shown that further loss in insulation resistance because of the combined radiation and temperature environments is sufficient to cause output changes that are at least as great as those encountered during the test.

The conclusion from the above results is that silver soldering fluxes for electrical connections were probably the major cause of the low insulation resistances experienced and that they were probably a major cause of change in both electrical center shift and in electrical output swing. Spot welding techniques will be used to overcome this problem in future tests.

Run	Fixture 2					Exposure	
	HT-1235-4A (avg of 8)	HT-122K (avg of 8)	HT-122K-10A-1 (avg of 2)	HT-11K-10A-1 (one)	HTD-2K-10A-1 (avg of 2)	Neutron Flux n/cm ²	Gamma Dose ergs/gm(c)
Preirradiation							
400°F	354	258	250	333	292	0.0	0.0
700°F	222	94	67	25	108	0.0	0.0
1 (10 kw)	73	21	112	50	32	1.0(12)	5.2 (6)
2 (100 kw)	34	14	13	25	18	5.9(12)	3.1 (7)
3 (1 Mw)	14	10	10	10	11	3.4(13)	1.8 (8)
5 (3 Mw)	6.3	4.7	4.6	4.55	5.8	6.3(14)	3.3 (9)
5e (0 Mw)	61.4	20.0	15.6	25	31.2	7.4(14)	3.9 (9)
7 (3 Mw)	7.37	6.15	6.51	5	6.97	1.1(15)	5.8 (9)
11 (3 Mw)	5.73	5.26	4.20	4.55	6.12	2.6(15)	1.4(10)
14 (3 Mw)	5.46	4.54	4.02	4.77	5.32	3.9(15)	2.0(10)
15* (3 Mw)	3.21	2.84	2.78	3.13	3.23	4.2(15)	2.2(10)
15a (3 Mw)	5.98	5.49	4.78	5.26	6.28	4.4(15)	2.3(10)
18 (3 Mw)	4.20	3.94	3.24	2.5	3.94	5.8(15)	3.0(10)
20 (3 Mw)	4.37	3.83	3.52	3.13	3.80	6.8(15)	3.6(10)
23 (3 Mw)	3.7	3.3	2.22	2.5	2.58	8.3(15)	4.3(10)
26 (3 Mw)	3.1	2.6	1.5	1.67	1.52	9.9(15)	5.2(10)
29 (3 Mw)	2.1	2.1	1.53	1.39	1.00	1.2(16)	6.0(10)
32 (3 Mw)	2.2	2.2	1.57	1.47	0.87	1.3(16)	6.8(10)
Postirradiation							
33 (700°F)	5.9	3.7	2.70	1.67	1.36	1.3(16)	6.8(10)
35 (250°F)	48	49	27	33.3	33.3	1.3(16)	6.8(10)

* During run 15, the chamber was cooled with gaseous CO₂.

Figure 33. DEVELOPMENTAL STRAIN GAGES: INSULATION RESISTANCES BETWEEN GAGES AND BEAMS OF FIXTURE 2

Run	Fixture 4						Exposure	
	HT-1235-4A (avg of 4)	HT-122K (one)	HT-122K-10A-1 (avg of 3)	HT-11K-10A-1 (avg of 6)	HTD-2K-10A-1 (avg of 5)	HTPT-1K-10A-1 (one)	Neutron Flux n/cm ²	Gamma Dose ergs/gm(C)
Preirradiation								
400°F	260	333	170	249	220	333	0.0	0.0
700°F	131	200	49	106	85	250	0.0	0.0
1 (10 kw)	40	50	10	26	17	50	1.8(12)	7.8 (6)
2 (100 kw)	19	25	8	13	12	25	9.9(12)	4.3 (7)
3 (1 Mw)	7	10	4	8	6	10	5.9(13)	2.6 (8)
5 (3 Mw)	3	4.17	2.3	3.3	3.3	4.35	1.0(15)	4.3 (9)
5e (0 Mw)	26	33.3	8.6	20	16	50	1.3(15)	5.7 (9)
7 (3 Mw)	3.2	4.55	2.9	3.90	4.0	4.77	2.0(15)	8.7 (9)
11 (3 Mw)	2.91	4.17	2.41	3.55	3.57	4.35	4.6(15)	1.9(10)
14 (3 Mw)	2.59	4	2.19	3.27	3.18	4	7.0(15)	3.0(10)
15* (3 Mw)	1.8	2	1.31	1.71	1.62	2.13	7.4(15)	3.2(10)
15a (3 Mw)	3.05	4.55	2.60	3.67	1.63	4.55	7.7(15)	3.3(10)
18 (3 Mw)	1.97	2.94	1.97	2.4	2.4	2.94	1.0(16)	4.4(10)
20 (3 Mw)	2.21	3.33	2.3	2.7	2.74	3.57	1.2(16)	5.2(10)
23 (3 Mw)	2.10	3.33	2.0	2.05	2.3	3.03	1.5(16)	6.4(10)
26 (3 Mw)	1.5	2.5	1.59	1.6	1.9	2.5	1.8(16)	7.6(10)
29 (3 Mw)	1.18	2.17	1.11	1.26	1.65	2.17	2.0(16)	8.8(10)
32 (3 Mw)	1.54	2.27	0.92	1.15	1.3	2.38	2.3(16)	1.0(11)
Postirradiation								
33 (700°F)	5.6	10	3.3	3.49	4.2	8.33	2.3(16)	1.0(11)
35 (250°F)	33.3	33.3	17.5	27	29	50	2.3(16)	1.0(11)

* During run 15, the chamber was cooled with gaseous CO₂.

Figure 34. DEVELOPMENT STRAIN GAGES: INSULATION RESISTANCES BETWEEN GAGES AND BEAMS OF FIXTURE 4

Figure 35. SUMMARY OF DEVELOPMENTAL STRAIN GAGE OUTPUT DATA

Fixture	Gage Type	Number of Beams	Number of Failures	Maximum Change in Pre- and Post- irradiation Total Output of Surviving Beams
2	HT-1235-4A	7	2	16%
2	HT-122K	7	2	9%
2	HT-122K-10A-1	2	2	
2	HT-11K-10A-1	1		5%
2	HTD-2K-10A-1	2		7%
4	HT-11K-10A-1	4	1	21%
4	HTD-2K-10A-1	4	1	7%
4	HT-1235-4A-1	4	2	5%
4	HT-122K-10A-1	3	1	3%
4	HT-122K	1		3%
4	HTPT-1K-10A-1	1		5%

**Figure 36. INSULATION RESISTANCE OF TYPE HT
GAGES ROKIDE COATED ON TEST BEAMS**

Type	Megger Voltage	Upper Gage (megohms)	Lower Gage (megohms)
HT-1235-4A-1	250	>100,000	>100,000
↓	↓	>100,000	>100,000
↓	↓	3,000	450
↓	↓	5,000	5,000
↓	↓	80	300
↓	↓	250	800
↓	↓	1,000	250
↓	↓	600	350
↓	↓	150	600
↓	↓	250	1,000
↓	↓	4,000	1,200
↓	↓	10,000	100,000
HT122K-16A-1	250	700	150
↓	↓	2,500	25,000
↓	↓	350	300
↓	↓	2,500	1,500
↓	↓	2,500	800
↓	↓	350	3,000
↓	↓	800	700
↓	↓	500	10,000
↓	↓	5,000	2,000
HT122K-16A-1	250	150	800
↓	↓	1,300	3,500

An interesting incidental discovery was made in connection with strain gages irradiated in GTR in May, 1963.

Electric heaters were used to bring the environmental chamber containing Fixtures 2 and 4 to 700°F. When the reactor was brought to full power, the gamma heat deposited in chamber and fixtures was more than sufficient to maintain the test temperature at 700°F. To hold the temperature down to 700°F, the electric heaters were turned off and carbon dioxide was released into the chamber. Run 15 (Figures 33 and 34) shows the insulation resistances encountered under these conditions. Run 15a was made shortly after run 15 but the chamber had been purged with N₂. It will be noted from Figures 33 and 34 that insulation resistances nearly doubled when the CO₂ was replaced with N₂.

Subsequent insulation resistance readings were made during each run after nitrogen purging. Unfortunately, sufficient nitrogen could not be delivered to the chamber to provide the required cooling. Hence there is no assurance that the CO₂ was very completely exhausted from the chamber.

Visual examination of Fixture 2 and Fixture 4 was made in November 1963. Both fixtures and their beams were in apparent good order and appeared to be in operating condition. Since the gamma levels are quite high and likely to remain so for some time, no further post-mortem examination is planned.

B. HIGH OUTPUT GAGE TEST

Many of the transducers which will be used on the NERVA engine will probably require artificial cooling to compensate for the heat deposition resulting from the radiation environment. The use of larger amounts of excitation power for sensors would therefore be tolerable since the heat generated by the large excitation current would be dissipated by the same mechanism used to cool the transducer against gamma heating. A strain sensor operating at a microstrain of 3000 with a gage factor of four would have an incremental resistance change ratio of

$$\frac{\Delta R}{R} = 4 \times 3000 \times 10^{-6} = 0.012$$

To develop a one volt output, such a gage would require a power supply voltage of

$$E = \frac{1}{0.012} = 83 \text{ volts}$$

This approach requires first that the gage have sufficiently good insulation from its parent material to preclude breakdown. Typical Rokide gages installed at Aerojet sustain "hi-pot" testing at 300 volts or more and are therefore considered to be adequately insulated.

A second requirement is that the gage itself be able to dissipate the required power, P.

where

$$P = \frac{E^2}{R_g}$$

and

R_g = gage resistance

If 1000 ohms is used as an arbitrary maximum gage resistance (since it would be desirable to limit output impedance to 1000 ohms) the power to be dissipated per gage is

$$P = \frac{E^2}{R_g} = \frac{(83)^2}{1000} = 7 \text{ watts}$$

Several 2000 ohm gages (1000 ohm gages were not available at the time) mounted on 5-7/8 inches long x 1 inch wide x 0.063 inch thick test beams of 17-7 PH steel were energized with regulated dc in open air. These gages were of Alloy 1200 wire (90-92% Pt, 8-10% W). Tests showed that these gages can withstand the continuous application of 300 volts under these conditions. The dissipated power was:

$$P = \frac{E^2}{R_g} = \frac{(300)^2}{2000} = 45 \text{ watts}$$

Using the same type of gages and beam, two gages were mounted on opposite sides of a beam and connected as a half bridge. This assembly was placed in a bread-board fixture arranged to flex the beam to maximum microstrain values of ± 3000 . Actually, that portion of each gage nearest the beam support experienced about 2900 microinches per inch while that portion at the opposite end of each gage saw a microstrain of

$$2900 - \left(\frac{1-1/8}{5-7/8} \right) 3000 = 2030$$

Thus the gages saw average microstrains of

$$\frac{2900 + 2030}{2} = 2465$$

The above calculations are estimates based on an active beam length of 3-7/8 inches with the two gages, each one inch long, mounted 1/8 inch from the beam support point.

After balancing the bridge, the beam was deflected and the excitation voltage was increased until the half bridge output reached 1 volt. The supply required was 115 v per gage. This equipment was operated for 16 hours and the beam was flexed in both directions several times each hour without any sign of failure. A photograph of the test fixture with beam installed is shown in Figure 37.

C. MISCELLANEOUS SURFACE TRANSDUCER TESTS

Minor, exploratory, nonradiation tests were conducted on several parent materials and with various inorganic materials. In certain surface transducer applications, sandblasting, or otherwise roughening the parent surface, appears to be inadvisable. To preclude this need, an undercoat of metal is sometimes used. Molybdenum was tried and was moderately successful. A nickel-chromium alloy was more successful and will be considered for certain NERVA applications.

Satisfactory deposits of aluminum oxide, Rokide A, were made on 17-4 PH and 17-7 PH steels several aluminum alloys, titanium, mild steel, copper, beryllium copper, brass, and ceramics.

In addition, 15 alloy-1200 gages were installed on samples of ATJ graphite, oriented with the strain sensitive axis with the graphite grain. Rokide A was the bonding agent. Alloy 1200 is a high temperature alloy usable to 2000°F and possessing a gage factor of approximately 4.0. These graphite samples were tested to destruction and the Rokide coated gages were operative to microstrains of 4000 or more. Appendix B contains detail results of the tests on ATJ graphite.

FIG 37 TEST BEAM AND GAGES
S = 2500 N INCHES/IN, E = 115V DC
OUTPUT = $\pm$ IVDC, GAGE-HT122K-16A-

An informal cooperative program has been conducted with the Baldwin Lima Hamilton Corporation to improve the matrix backings used on strippable wire gages intended for ceramic spray applications. During the Aerojet learning period, gage mortality was particularly high and remained unsatisfactorily high even after the mounting technique had been developed. Much of the difficulty appeared to be in handling the gage in the free state and in removing the temporary backing used to protect the strain wire during shipping and handling. Aerojet is not equipped to manufacture gages but experiments with several pressure sensitive tapes and technical assistance from the Minnesota Mining and Manufacturing Company led to the discovery of several matrix improvements. The Baldwin Lima Hamilton Company is incorporating these changes in developmental gages. Meanwhile, the Minnesota Mining and Manufacturing Company, at Aerojet request, has experimented with a variety of release materials for pressure sensitive tapes. Two of the materials are promising and will be incorporated in developmental gages to be supplied by BLH.

Typical, maximum size, off-the-shelf strain gages suitable for Rokide coating are about $1/4$ inch long and $1/8$ inch wide. In order to increase the ability of strippable wire gages to dissipate power, several developmental gages 1 inch long and $3/4$ inch wide were tested. These gages cover 24 times the surface area of the smaller gages but do not have proportionately larger insulation leakage currents.

VI. CONCLUSIONS

Irradiation Tests

The two previously described irradiation tests resulted in two very useful general conclusions. First, surface mounted transducers, installed by the Rokide process are suitable candidates for radiation environments. Second, insulation resistance leakage is the greatest remaining problem, but present evidence indicates that this problem is correctible. An explanation of the second conclusions is given below.

Strain gage transduction suffers in two ways when leakage current becomes high. First, it results in an attenuation of the output signal for a given

stimulus and this is reflected as a change in sensitivity. Second, leakage current, especially if unbalanced between bridge arms, results in a shift in the electrical center of the bridge. This shift is particularly deleterious in the transduction of static strain.

Certain precautions are required in measuring insulation resistance leakage in radiation environments. Because of the length of signal and power supply lines, the transducer leakage currents are normally obscured by the parallel leakage paths of the power supply lines. In the second radiation test, a method of "guarding" was used to make leakage current measurements. Not only did this method prove to be very effective, but a means of verifying its efficacy during test was devised. Furthermore, this guarding technique can be used in NERVA applications under certain conditions and, with some wiring changes, could become quite generally useful.

Regarding the conclusions drawn from leakage current test results, the evidence seems to demonstrate quite clearly that most of the trouble is associated with the gage terminals. Although the mechanism in radiation environments is not well understood, contaminants such as small bits of organic material and soldering flux are believed to be the cause of this terminal leakage. Additional tests should be conducted to determine more about this condition.

Gamma radiation induced currents, which take the form of leakage in surface mounted transducers, are polarized. Hence, their effect causes an unbalance or center shift in gage output. This effect could probably be eliminated or reduced by achieving complete electrical and mechanical symmetry in the gage installation. Fortunately, such circuits lend themselves to the guarding techniques described above and these should be tried in subsequent tests.

High Output Gage

The high output gage tests were very limited and were only exploratory in nature. For the minimum effort expended, the results have been gratifying and warrant further consideration. It seems quite likely that a radiation resistant strain sensing element, with at least a ± 1 volt full scale output, is practical if power supply voltages of up to 100 volts can be used and if power dissipations

of up to 10 watts can be tolerated. Aerojet recommends that an elemental pressure transducer be fabricated using such a sensor and that this transducer be evaluated for various appropriate environmental conditions including irradiation.

APPENDIX A

PROCESS SPECIFICATION

PROCESS FOR ROKIDE BONDING
STRAIN GAGES TO METAL

AGC-10192
30 July 1963

PROCESS SPECIFICATION
BONDING, ROKIDE, STRAIN GAGES
TO METAL, PROCESS FOR

CODE IDENT NO. 70143

July 1963:746:FB:jad

AGC-10192
30 July 1963

CODE IDENT NO. 70143

PROCESS SPECIFICATION

BONDING, ROKIDE, STRAIN GAGES TO METAL, PROCESS FOR

1. SCOPE

1.1 This specification establishes the procedures for surface preparation of, and ceramic bonding of strain gages to metal surfaces by the Rokide process.

2. APPLICABLE DOCUMENTS

2.1 Aerojet-General documents.- Unless otherwise specified the following document of the latest issue in effect forms a part of this specification to the extent specified herein.

SPECIFICATION

AGC-36237

Sandblasting to Clean Metal
Surfaces, Requirements for

3. REQUIREMENTS

3.1 Materials and equipment.- The following materials and equipment, or their approved equivalents, shall be required.

3.1.1 Materials

3.1.1.1 Adhesives

- (a) Pressure-sensitive, adhesive waterproof tape
- (b) Glass cloth tape (Minnesota Mining and Manufacturing Co. XL132 or approved equivalent).

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3.1.1.2 Process materials

- (a) Trichloroethylene
- (b) Sand blasting abrasive
- (c) Ceramic bonding material (Rokide or approved equivalent)

3.1.2 Equipment

- (a) Sandblaster
- (b) Ceramic spray gun (Rokide gun manufactured by Metallizing Co. of America; Plasma gun by Plasmadyne Corp., or approved equivalent)

3.1.3 Strain gages.- The applicable strain gage (see figure 1), to be bonded, shall be clean and free from any contaminants, broken wires, or other defects that would indicate a defective gage. Figure 2 shows some of the wires of the gage exposed (see 3.3.3)

3.2 Preparation for bonding.- Prior to the ceramic bonding operation, the faying surface shall be prepared as follows:

3.2.1 Surface preparation.- The faying surface and surrounding area shall be free from oil or grease, and shall be vapor-degreased or hand-wiped with a clean cloth moistened with trichloroethylene and allowed to dry.

3.2.2 Protective covering.- The exposed area adjacent to the faying surface shall be masked with pressure-sensitive tape. Ports or openings that might be adversely affected by the operations herein should be capped or closed.

3.2.3 Degreasing.- The faying surface shall again be hand-wiped with a clean cloth moistened with trichloroethylene, and allowed to dry for a minimum of 5 minutes. The degreased faying surface shall be kept clean and free from any contaminants.

3.2.4 Sandblasting.- The faying surface shall be sandblasted with No. 36 size grit in accordance with Aerojet-General Corporation Specification AGC-36237 (see 2.1). The sandblasted surface, as shown in figure 3, shall be kept clean and free from any contaminants.

3.3 Ceramic application.- The application of the ceramic bond shall be accomplished with minimum interruption between successive operations, so as to prevent oxidation or the deposit of contaminants on the coated surface.

The complete bonding operation interval should not exceed 4 hours. During the bonding operation, the bonding area shall be kept clean and free from oil, grease, or other contaminants that could prevent adhesion between bonding areas.

3.3.1 Temperature of the faying surface.- The faying surface shall be heated to approximately 200°F (as determined by a quick touch) before applying the ceramic bond. The ceramic spraying gun may be used for heating.

3.3.2 Preliminary ceramic application.- Following the sandblasting operation (within a period not to exceed two hours), the faying surface shall be sprayed, using a Rokide gun, or equivalent ceramic spraying device, with a ceramic bonding material consisting of aluminum oxide or equivalent, (hereinafter referred to as ceramic) for approximately 5 to 10 seconds or until the entire faying surface is covered with a light ceramic coating having a buildup of .003 to .005 inch approximately, as shown in figure 4. Good results have been obtained using a 1/8-inch diameter Rokide "A" rod, fed through a Rokide gun at a speed of 3.0 to 3.5 inches per minute. The ceramic rod shall be free from dirt, clay, or other deleterious substances. The ceramic shall be projected from the gun onto the faying surface at a distance from the nozzle to the faying surface of approximately 3 to 5 inches.

3.3.3 Positioning gage.- The protective release material shall be carefully removed from the underside of the gage (see figure 2). The gage shall be positioned (prefitted) on the ceramic-coated faying surface with the strain element down and parallel to the axis of strain to be measured (see figure 5). The dummy (compensating gage), if any, shall be perpendicular to the axis of strain. The leads shall be positioned approximately parallel to each other and held with pressure-sensitive tape to prevent their movement during the application of ceramic (see figure 6).

3.3.4 Gage bonding.- The prefitted gage shall be bonded to the ceramic-coated faying surface as follows:

- (a) The preliminary ceramic coating shall be preheated to approximately 200°F (quick touch).
- (b) With the nozzle of the gun 10 to 15 inches from the gage, spray the gage with ceramic (see figure 6).
- (c) The glass cloth tape holding the gage to the faying surface shall be removed (see figure 7).
- (d) A final ceramic application shall be made to the gage to bond those areas exposed by removal of the glass cloth tape in 3.3.4 (c) (see figure 8).

3.4 Reliability.- Reliability of the bond shall be commensurate with the bonding requirements and all service environments. Care should be taken to

avoid catastrophic failure or degradation of the strain gage in the bonding process.

3.5 Workmanship.-- The workmanship shall be of sufficiently high grade to insure satisfactory operation, quality, reliability, and durability consistent with the requirements of this specification. Particular attention shall be given to cleanliness, neatness, and thoroughness of the bonding process.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection.-- Inspection shall consist of visual inspection of the bonded gage and in-process inspection as necessary for assurance of conformance to the requirements of Section 3, including attention for broken wires. The bonded gage shall be visually inspected for indications of improper alignment, incomplete bonding, poor adhesion, and wires protruding above the ceramic. Any such evidence shall require correction or removal and reprocessing.

4.2 Instrumentation calibration.-- Gages and recorders used in the tests shall have been calibrated within a maximum period of 90 days from start of the following tests, in accordance with applicable Aerojet-General Corporation procedures. Calibration certification shall be conspicuously affixed to each instrument.

4.3 Tests.-- Testing shall consist of checking each gage bonded as shown in Section 3 in the order as specified:

- (a) Electrical continuity
- (b) Insulation voltage breakdown
- (c) Insulation resistance

Failure of any of the tests shall result in rejection of the installed gage. The lead ends of the gage shall be secured to the area adjacent to the fayed surface during the tests, with pressure sensitive tape.

4.3.1 Electrical continuity.-- The gage shall be tested for electrical continuity. The working current employed for the test shall adequately test the gage, without damage to the gage.

4.3.2 Insulation voltage breakdown.-- The gage shall be tested for insulation voltage breakdown while in a thoroughly dry condition. The electrical supply used for this test shall have an output impedance limiting its current to a value that will not damage the gage.

4.3.3 Insulation resistance. - The gage shall be tested for insulation resistance concurrently with or after the insulation-voltage-breakdown test. The working current limitation for this test shall be the same as for the insulation-voltage-breakdown test.

5. PREPARATION FOR DELIVERY

(This section is not applicable).

6. NOTES

6.1 Intended use. - This specification establishes the procedures for the bonding of strain gages to metal surfaces and the testing of the bonded gage.

Authorized for Release:

H. S. McQueen, Department Manager
Engineering Specifications
Rocket Engine Operations, Nuclear
Azusa

Figure 1. PACKAGED STRAIN GAGE AS RECEIVED

Figure 2. STRAIN GAGE WITH RELEASE BACKING PARTIALLY REMOVED

Figure 3. TEST BEAM, SANDBLASTED FOR GAGE APPLICATION

Figure 4. TEST BEAM WITH INITIAL COAT OF ROKIDE APPLIED

Figure 5. STRAIN GAGE IN PLACE FOR SECOND COAT OF ROKIDE

Figure 6. STRAIN GAGE WITH SECOND COAT OF ROKIDE APPLIED

Figure 7. STRAIN GAGE CARRIER REMOVED AFTER SECOND COAT OF ROKIDE

Figure 8. COMPLETED STRAIN GAGE APPLICATION (THIRD COAT
OF ROKIDE APPLIED)

APPENDIX B

CARBON GAGING REPORT

Section V, Strain Gage Tests on ATJ Carbon Samples

STRAIN GAGE TESTS ON ATJ CARBON SAMPLE

A. GENERAL

A group of strain gages were installed on graphite samples by means of the Rokide process. These samples were then tested at ambient temperatures to destruction, in compression, while the gage output signals were monitored. Loads were applied with the graphite grain.

Results of this investigation are included herein, together with a print of a typical recorder strip chart.

It is concluded that HT121K-16A2 strippable wire strain gages can be successfully Rokided to graphite, and are usable up to microstrain levels of 4000 minimum at ambient temperatures. Prior irradiation test results were also favorable on this type of gage, and temperature tests indicate that it is usable to at least 700°F. In addition, an exploratory test using this gage on 17-7 PH steel at ambient temperature employed 115-volt dc excitation, yielding an output swing of greater than 2 volts with a stimulus of +3000 micro-inches per inch.

It is the opinion of REON that strippable wire Rokided strain gages are one of the better candidates for strain measurement on graphite in radiation environments. It is also felt that further evaluation should be made at elevated and cryogenic temperatures.

B. TEST

1. Test Equipment

A compression test fixture (Figure 1) was utilized for testing. This fixture consists of a hydraulic cylinder powered with a Blackhawk hand operated pump with an actuating cylinder diameter of 4 in., resulting in a cross sectional area of 12.57 in.². A chuck is connected to the piston rod of the cylinder to provide a flat, anvil surface perpendicular to the direction of motion of the piston rod.

A 12,000-lb BLH load cell, also fitted with a chuck which provides a flat anvil, is mounted with its axis coincident with the cylinder axis.

Figure 1
Compression Test Fixture
for ATJ Graphite

The cylinder body and load cell body are secured to a common, rigid frame.

Cylinder pressure, load cell pressure, and strain gage output were recorded on a Type M Dynagraph Recorder (Offner).

2. Carbon Samples

The carbon samples were made of ATJ type graphite by the National Carbon Co. Test pieces were 4-in. long x 1-1/2-in. dia with an active center section 2-in. long by 1-in.-dia, as shown in Figure 2. The ends of each sample were surfaced in a vertical mill in one setup to assure parallelism of the end surfaces engaging the piston-rod anvil and the load-cell anvil.

3. Strain Gages

A developmental strain gage, manufactured by Baldwin Lima Hamilton Company to REON specifications, was used. This gage employs Alloy 1200 wire (approximately 92% Pt and 8% W). The active gage width is 3/4-in. and the active gage length is 1-in. When used in production units, Alloy 1200 gives a mounted gage factor of 3.7 to 4.3. Since the gages used in this test were developmental, the mounted gage factor is not accurately known, but is taken to be 3.7.

Rokiding was performed in accordance with REON procedures, using an R1 gun, manufactured by the Metallizing Co. of America. This gun employs an oxyacetylene flame for fusing ceramic rods, and compressed air for subsequent atomization. Rokide A, Al_2O_3 , was used in this test.

Figure 2
Typical Carbon Samples

4. Test Procedure

A secondary standard load cell was placed between the anvils of the test fixture and loaded in compression to set the dynagraph system gain for a usable scale factor.

Carbon samples were inserted between the anvils, and the mounted gage (Figure 3) was connected with an identically mounted gage on an unstressed dummy sample (Figure 4). The half bridge thus formed was connected to a Type 9403 strain-gage coupler, which in turn supplied the recorder input. Briefly, the 9403 coupler contains a completion network consisting of two 400-ohm resistors, and a calibration resistor network.

With the recorder in operation and calibrated, the pressure was increased on the sample (by hand pump) until the gage failed, and then continued until the sample fractured.

Samples 7, 8, 9, 11, 13, 14, and 15 were tested in the first group. This group had the gages installed on the graphite samples with no surface preparation beyond the lathe machining of the samples.

Samples 1, 2, 4, 5, and 6 were tested in the same manner, except that a different surface preparation was used. Sandblasting and helical grooving (threading), 0.005 and 0.010 in. in depth, were employed. The grooving can be seen in Figures 5 and 6.

Figure 7 is a copy of a typical dynagraph chart with pertinent events and time scale noted.

Figure 3

ATJ Graphite Sample
with Rokided HT 121K-16A2 Gage Installed

Figure 4

Dummy Sample with Gage Installed
Used for Bridge Completion

Figure 5

Failed Samples with 0.005-in.
Helical Grooves, ATJ Graphite

Figure 6

Failed Sample with
60° x 0.010-in. x 16 per inch Helical Grooves

Figure 7
Sample Dynagraph Chart

C. TWST RESULTS

Table I shows the unit pressure on the sample at gage failure, the ultimate strength, and the microstrain at gage failure for samples 7, 8, 9, 11, 13, 14, and 15. The samples were gaged with no surface preparation. A typical calculation for the above results on sample No. 7 follows:

From the strip chart, calibration position No. 5 showed 5.4 major divisions of deflection. The equivalent micro strain, E, for calibration settings with a two gage bridge is

$$S = \frac{1}{N} \cdot \frac{106}{F} \cdot \frac{400}{Rc} + 400$$

where

N = the number of active gages = 1

F = the gage factor = 3.7

Rc = the calibrating resistor = 12,000 ohms at Position 5.

Solving;

$$\begin{aligned} S &= \frac{1}{1} \cdot \frac{106}{3.7} \cdot \frac{400}{12,000 + 400} \\ &= 8720 \text{ microinches/in.} / 5.4 \text{ divisions} \\ &= 1613 \text{ microinches/in.} / \text{major division} \end{aligned}$$

At gage failure, the gage output reads 2.6 major divisions. The microstrain is therefore

$$2.6 \times 1613 = 4190$$

From the strip chart, the pressure on the load cell at the point of gage failure was 2800 lb. Table II shows the diameter of Sample No. 7 as 1.0028 in. The cross section area was therefore

$$\begin{aligned} A &= \frac{\pi d^2}{4} \\ &= \frac{\pi (1.0028)^2}{4} \\ &= .789 \text{ sq in.} \end{aligned}$$

and the unit stress was $\frac{2800}{A} = \frac{2800}{.789} = 3550 \text{ psi.}$

TABLE I

UNIT PRESSURE AND MICROSTRAIN
AT GAGE FAILURE AND PSI ULTIMATE STRENGTH

<u>Sample No.</u>	<u>Psi at Gage Failure</u>	<u>Microstrain at Gage Failure</u>	<u>Psi Ultimate Strength</u>
7	3550	4190	10380
8	3820	4130	9300
9	4070	4360	9670
11	3670	4210	9300
13	4030	4980	9820
14	4180	5290	9120
15	3670	4980	Saved for photo
1	4190	3880	9130) .010 Grooves
2	4560	5400	9270) 16/in.
3			.005 Grooves
4	5330	5740	8620 16/in.
5	3550	4380	9890) Light
6	3680	3810	9130) Sandblast

TABLE II

SAMPLE DIMENSIONS

<u>Test Sample Number</u>	<u>Sample Length Inches</u>	<u>Sample Diameter Inches</u>
1	3.950 in. to 4.005 in.	1.0015
2		1.0007
3		1.004
4		1.0010
5		1.0010
6		1.0030
7		1.0028
8		1.0005
9		1.0002
10		1.0030
11		.986
12		1.0060
13		1.0020
14		1.0019
15		1.0033
16		1.0037

Figure 8 is a stress-strain curve obtained by reduction of data from a typical sample, No. 11.

The second group of samples was tested to determine whether an increase could be obtained in the gage failure point. Results were inconclusive; Figures 5 and 6 show grooving of samples in this group.

All gage failures exhibited considerable graphite remaining on the Rokide deposit, indicating graphite failure in areas adjacent to the gage mounting. Figure 9 depicts this condition by showing the forward and reverse sides of failed gage fragments.

In some cases the gages remained intact after separation from the parent material. Figure 10 shows a gage fracture of this nature and Figure 11 shows the complete separation after which the gage continued to exhibit continuity.

Figure 8

Stress-Strain Curve
For ATJ Sample No. 11

Figure 9

Typical Failed Pieces
ATJ Graphite and Gages

Figure 10

Typical Gage Failure
at 4000 Micro Strain
ATJ Graphite

Figure 11

Separation of Bonded (Rokide)-Gage Assembly
from ATJ Graphite Sample

D. CONCLUSIONS

With no special surface preparation, machined graphite can be gaged using the Rokide process. Microstrains to 4000 can be read consistently before gage failure.

Prior experience indicates that strippable wire gages installed by use of the Rokide process are usable to temperatures of at least 700°F, and will survive radiation in excess of 10^{17} N/cm² (E > 2.9) and 10^{11} ergs/g (C) gamma.

The gage used in this testing was Type HT 121K-16A2, made by BLH. This gage is a developmental type made to REON specifications and is not now an off-the-shelf item. Mounted gage factor has not yet been determined accurately, but can be taken as 3.7 for developmental purposes.

This gage is available with a miniature thermocouple incorporated directly into the gage, and tests show that this arrangement can be Rokided as conveniently as the strain gage alone.

It is recommended that development be continued in this area, particularly at elevated and depressed temperatures.