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WORKING EXPERIENCE WITH HIGH-TEMPERATURE STRAIN GAGES

by

A. H. Marchertas, C. Fiala,
and S. H. Fistedis

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Reactor Engineering Division

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ABSTRACT

This report describes experience obtained with the Baldwin-Lima-Hamilton (BLH) Type FNWFB9-50-12 full-bridge, weldable, high-temperature strain gage. Circumstances leading to the investigation and reasons for failing to meet its original objectives are described. Shortcomings of this gage type, which are similar to those of other high-temperature gages, are discussed for the benefit of users of high-temperature gages.

I. INTRODUCTION

At the beginning of 1964, a full-size experimental loop for testing sodium at 1200°F was being built for the then active Fast Reactor Test Facility (FARET)[1] project. Since the sodium technology at 1200°F had not been developed, all conceivable tests of possible importance to the structural safety were considered. In this connection, the utilization of recently available high-temperature strain gages was proposed, although their reliability had not been determined in the field. These gages would be used for evaluating, or trying to evaluate, the behavior of high-temperature piping and the stresses resulting from restraining deformations.

Experimental results of high-temperature piping flexibility tests were unavailable or very scarce, for none could be found in the current literature. This is understandable, since the field use of high-temperature strain gages had been unknown. To add to this, different methods of flexibility analysis predicted varied results for the same piping system. Thus, with the construction of the FARET test loop, it was believed that an attempt should be made to seek results on high-temperature piping flexibility tests.

The main objective of the investigation was thus to obtain experimental verification for the standard piping-stress analyses. Concurrently, experience with high-temperature strain gages would be gained, which, in itself, would be vital to the advancement of reactor technology. In addition,

if the performance of the strain gages was reliable, the effect of creep of the piping system could be investigated. Observation of the piping components and deformation thereof after the completion of the test would also yield some qualitative results.

This report describes the effort expended in the attempt to make use of some of the high-temperature gages. (Due to the currently inadequate level of high-temperature strain-gage development, the analytical and experimental comparison of piping flexibility was not possible.) However, many relevant factors of high-temperature strain gages, which cannot usually be found in technical literature or are just implied, have come to light. These have yielded a useful background to the area of high-temperature strain measurement; thus, the newly acquired experience, which cannot be specified in quantitative terms, should be helpful in future nuclear-technology projects.

II. BACKGROUND INFORMATION

The primary purpose of the proposed investigation was to determine the behavior of the high-temperature (up to 1200°F) piping system during the actual operation of the Fuel Assembly Test Loop of the Fast Reactor Test Facility (FARET). However, the true performance of the gages employed to temperatures above 900°F had not been established previously.

In line with the general scheduling of the loop's construction, the search for commercially available high-temperature strain gages was started during the first half of 1964. Manufacturers were contacted who claimed to have available high-temperature strain gages, or were known to have had experience with them.

After the field was surveyed for available strain gages, the choice at the start of the survey had been narrowed to three basic types of gages, the qualities of which had been described by the manufacturer as follows:

1. The strippable wire gage, using the Rokide* process as the bonding technique. This process made the gage bonding easy, and no curing was claimed to be necessary up to 1000°F. Temperature compensation was to be provided individually in each case. Initial cost of the basic equipment was about $4000.

2. The strippable gage, either wire or foil, using the "brush-and-cure" bonding technique. Gage bonding is difficult and requires great dexterity. The gages must be cured at temperatures higher than those in the test. Individual temperature compensation must be provided separately in each case.

*Trade name for the flame-spraying technique.

3. The weldable gage,* which was claimed to have excellent temperature compensation for apparent strain, leakage errors, and drift. Sensing wire had been attached to the shim with ceramic insulation and precured; as such, it can be spot-welded to the object to be tested.

The decision as to the type of gage to use for this project was influenced by several factors: the anticipated short-range nature of the project, the lack of experience of Argonne personnel in high-temperature strain-gage work, the cost to the project, and, most important, the construction schedule. No time was available to test the gages individually under controlled thermal conditions and examine the apparent strain curves, drift with time, and other effects. Selection of the gages was thus greatly influenced by what had been advertised about the gages by the manufacturer and by direct contact with people who had experience with high-temperature strain gages. It was therefore decided that the weldable full-bridge gages would offer the greatest chances of success for our project. Bonding difficulties and expense would be minimized. Separate temperature compensation of the individual gage would not be required; curing also would not be needed once the gage is attached. (We learned later in the project that curing was indeed necessary. See Section V.)

These advantages were thought to provide us with the best chance of success in our application. Thus, the Baldwin-Lima-Hamilton (BLH) full-bridge weldable (Type FNWFB9-50-12) gages were ordered from the manufacturer** with a specifically matched Type 304 stainless steel shim. This shim material was to provide exact matching with the piping material.

In the summer of 1965 the construction of the piping loop was delayed. Some time before that, Atomics International (AI) had some encouraging results† in their laboratory with a commercially available free-filament gage, bonded by the flame-spraying method. Although a complete evaluation of this BLH Type HT-1212-5A gage was not available, AI was sufficiently encouraged by its performance to propose a thorough investigation. Furthermore, AI had been working with the flame-spraying technique as a means of high-temperature strain-gage bonding and had hopes for it in future use.

Since accessibility of any gages on the surface of the piping would be difficult at best after completion of the loop, the reliability of the selected gages should be the highest possible. Since reliability of none of the available high-temperature strain gages had been fully demonstrated, the use of several kinds of gages, especially of two diverse types, would further improve the chances of success. Thus, since preparation time was available, due to the construction delay of the loop, we decided to enhance the chances

*The weldable gage means the one made by Baldwin-Lima-Hamilton; the Microdot weldable gages and their advantages were unknown to us at that time.

**Additional equipment ordered is enumerated in Appendix C.

†By personal communication with M. M. Lemcoe, Atomics International, Inc.

of success by using the full-bridge weldable and also the free-filament gages. If, quantitative results were not to be destined, then, hopefully, some qualitative comparison of the two types of gages could be made. Thus the BLH Type HT-1212-5A gages were ordered, together with the associated flame-spraying equipment. (For the equipment listing, see Appendix C.)

Two kinds of gages were to be used with the experiment. In preparation for installation, C. Fiala mastered the use of the Rokide equipment, as used by BLH and also with the variations introduced by AI. All gages were applied according to the given instructions and specifications. (Some of the procedures have changed since that time. See Section III.A on gage instrumentation.)

Soon, however, termination of the FARET project brought an end to the high-temperature strain-measurement effort. Hence, the installed gages remained on the piping undisturbed until the loop was readied for flow-testing the prototype fuel assemblies for the Fast Flux Test Facility (FFTF).

III. TEST PREPARATION

The impracticability of instrumenting the entire loop with high-temperature strain gages was realized at the beginning of the effort. A small three-dimensional portion of the piping system, i.e., a section of the 4-in. discharge line, was therefore chosen for this purpose and is shown in Fig. 1. This section alone was to be instrumented with high-temperature strain gages. The test section as it finally looked from the outside is shown in Fig. 2, and the instrument console is shown in Fig. 3. Test preparation for instrumentation is described in the following paragraphs.

A. Gage Instrumentation

The location of the maximum stresses in the test piping section is unknown. If this were known, rosettes, positioned at these locations, would secure the magnitudes of these maximum stresses, which are among the basic quantities sought in the investigation. Because these magnitudes could not be determined before a test, a systematic way had to be found for positioning the gages and yielding the greatest amount of information.

Generally, the greater the number of the gages, the greater will be the number of quantities to be compared with analytical results. This will be even more so if a judicious approach is used at the beginning for positioning the gages on a given cross section. For example, strain readings on the horizontal and vertical cross sections of the pipe would be directly related to the corresponding bending moments usually given in piping analyses. Thus, location of rosettes was restricted to four points along the circumference of the pipe diameter within one station; gages were permitted only

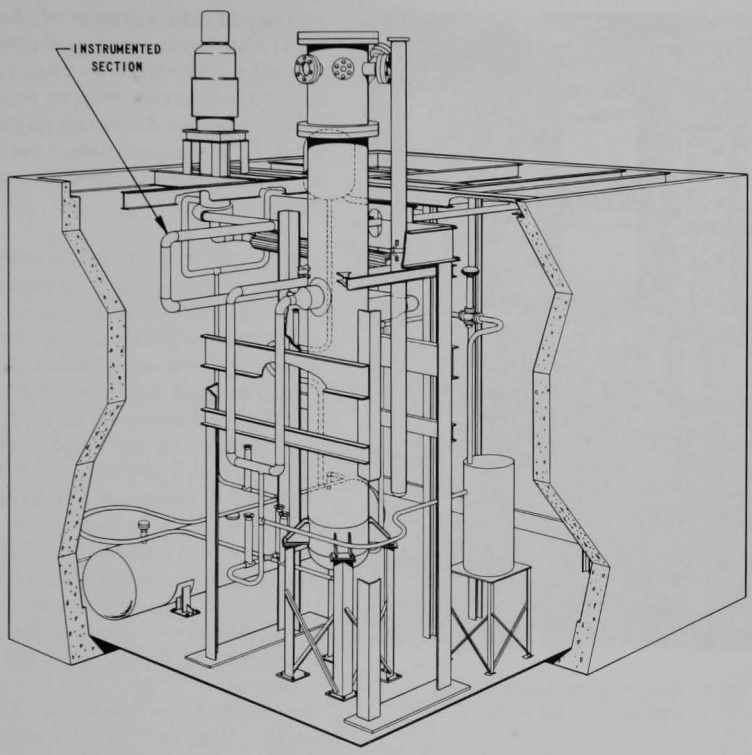


Fig. 1. General View of the CCTL Piping System

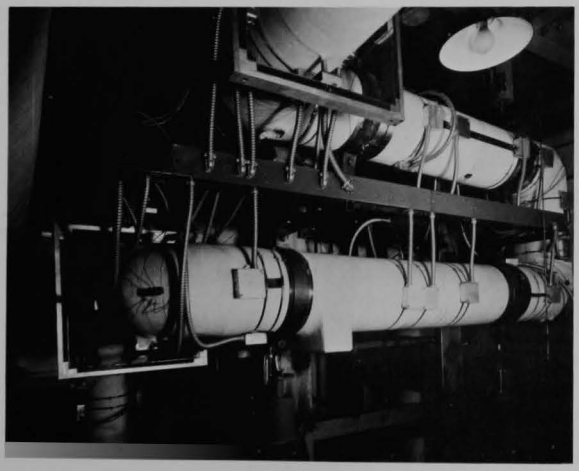
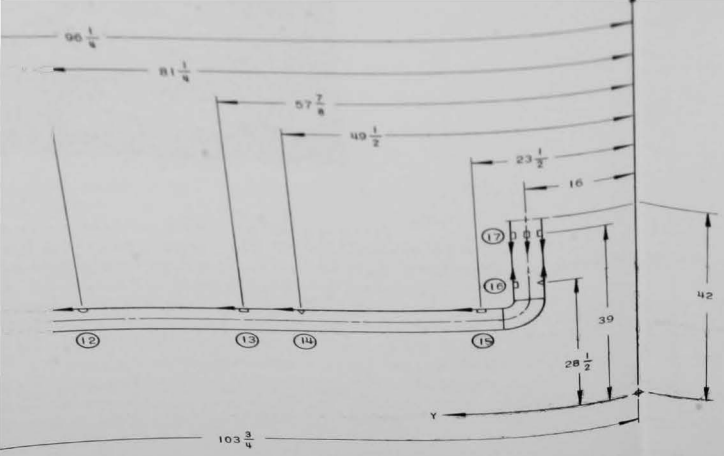


Fig. 2
Outside View of the Test Section. ANL Neg. No. 112-6777.



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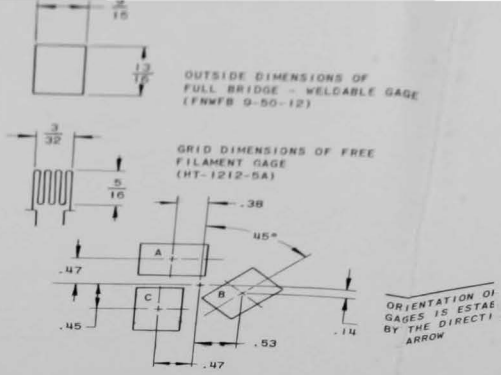


SYMBOLS FOR B-L-H ROSETTE ARRANGEMENTS:

FULL BRIDGE - WELDABLE GAGE (FNWFB-9-50-12)

FREE-FILAMENT GAGE (HT-1212-5A) WITH ROKIDE-BLH-S ALUMINA BONDING

FREE-FILAMENT GAGE (HT-1212-5A) WITH RIKIDE-BLH-H HIGH PURITY ALUMINA BONDING

WHERE THE SIGNIFICANCE OF THE ARROW IS SHOWN IN THE SKETCH ABOVE

Fig. 6. Location of Strain Gages within the Test Section

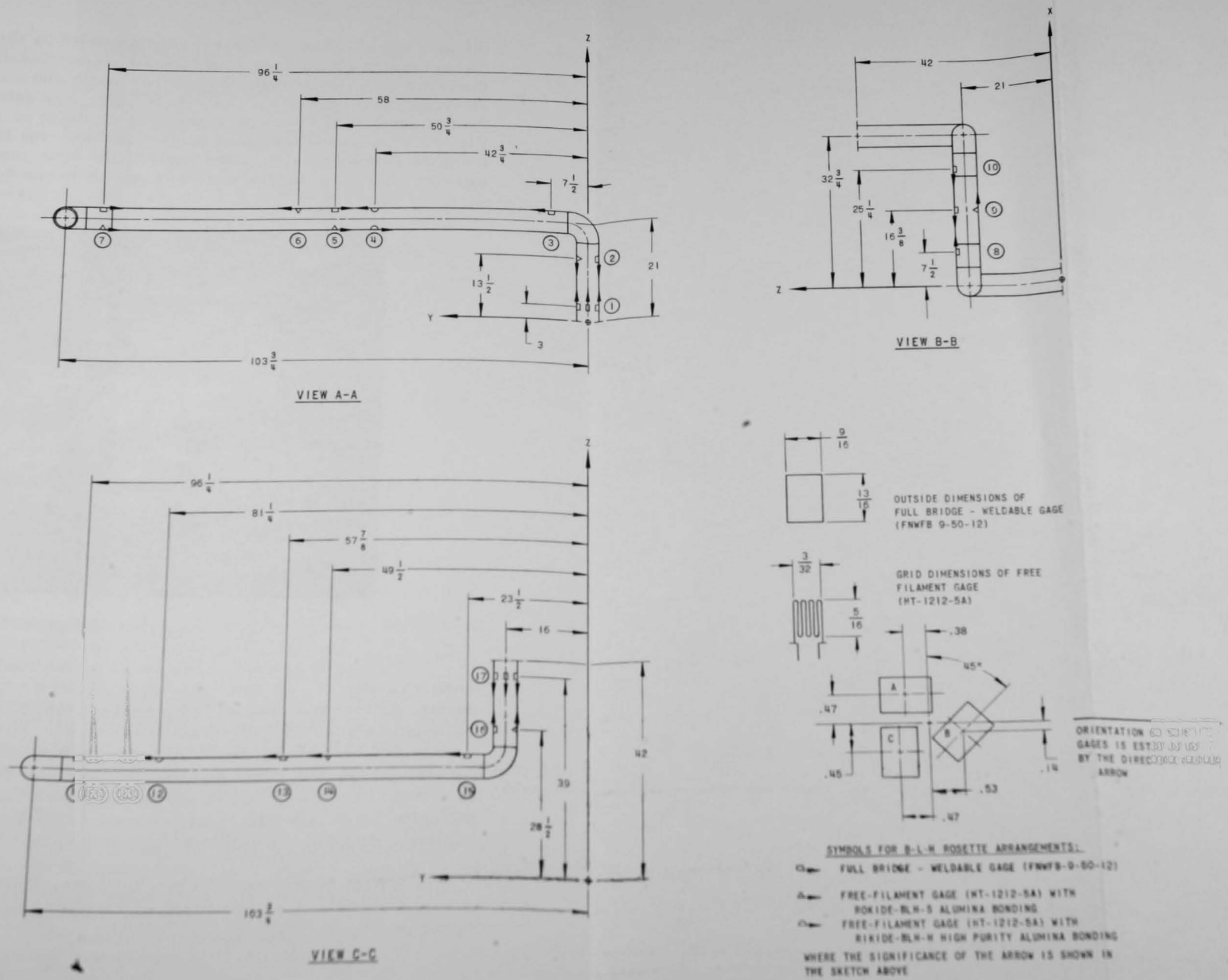


Fig. 6. Location of Strain Gages within the Test Section

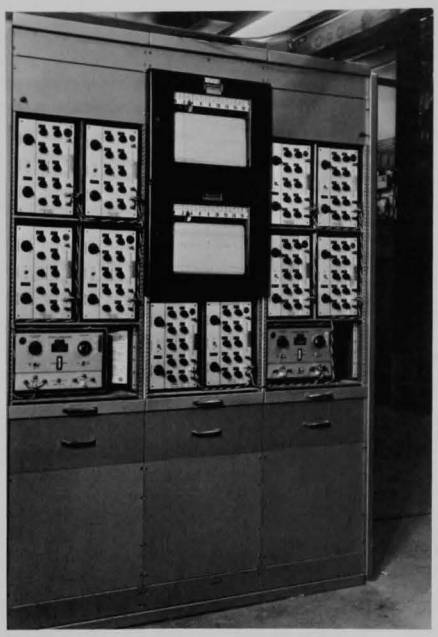


Fig. 3. Strain-gage Instrument Console. ANL Neg. No. 112-6775.

at the outside surface of the vertical and horizontal sections of the pipe. In other words, rosettes could be located only at points where the positive and negative axes of the coordinate system intersected the circumference of the pipe.

The locations of the so-called stations (or instrumented cross sections) were close to junctions between elbows and straight sections of the pipe. (Proper gage location on the test section had been selected for best correlation between experimental results and analysis. The analytical considerations are discussed in Appendix A.) The exact junctions were avoided, because of the proximity of the weld, and with it, the stress concentrations and irregularities. Hence, the rosettes were placed on the straight portion of the pipe $1\frac{1}{4}$ in. from the edge of the weld to the center of the rosette. Figure 4 is a sketch of the gage location at the elbow; Figs. 5 and 6 show the final position of the rosettes, including the type and orientation.

All the active strain gages used in the experiment were arranged in sets of rectangular rosettes; one thermocouple was located at the center of each rosette. The leads extending from the gage to beyond the insulation of

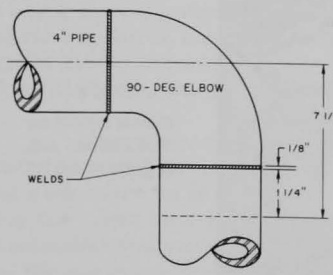


Fig. 4. Location of Gages in the Vicinity of Welds

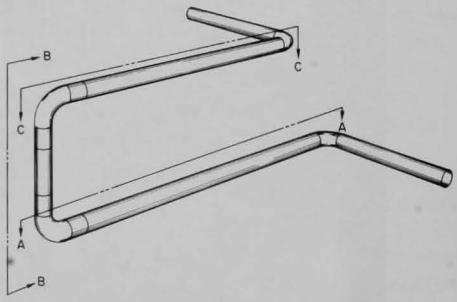


Fig. 5. Schematic Diagram of the Test Section

the pipe were Nichrome V wire, recommended by the manufacturer for the highest test temperatures. All these leads, especially those connected to the same gage, were made of identical length and insulated with fiberglass sleeving. The span of wire next to the gage was deformed into loops and then attached to the surface of the pipe by strips of shim, as shown in Fig. 7. This way of fastening leads minimized the transfer of any movement from the outside portion of the leads to the ends connected to the gages. Regular high-temperature wire was used between the end of the Nichrome V wire and the console.

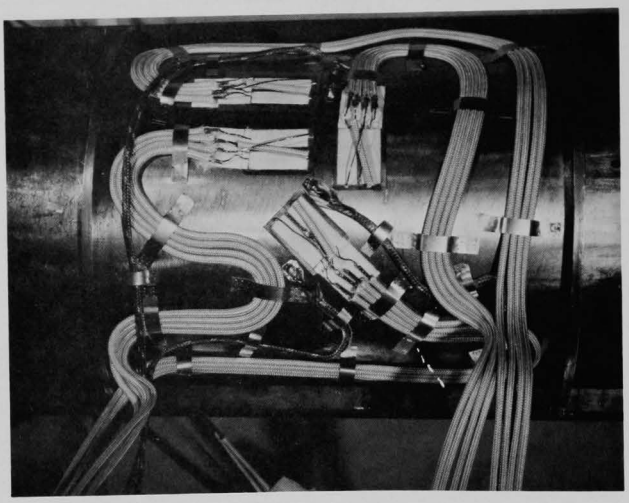


Fig. 7. Positioning of Gages within a Rosette

Proper alignment of the gages with respect to the marked center-lines was also of concern. Since gages were supposed to be arranged in rosette patterns, a special template was made to position three gages of a rectangular rosette configuration as a unit. The template was made so that it provided holes for the welder point. This reduced the possibility of the ceramic insulation coming in contact with the welder point. Welds were extended along the entire length of the ceramic, and not beyond that, as indicated in the specification drawings of BLH. (New specifications state explicitly to weld the entire length of the gage.)

Thus, by the end of 1965, following the instructions of the manufacturer, the chosen portion of the piping had been instrumented with the following types of gages:

No. of Rosettes	Type of Gage	Type of Bond
19	Full-bridge weldable	Spot weld
7	Free-filament	Rokide (S)*
3	Free-filament	Rokide (H)*
29		

A total of 87 active high-temperature gages were dispersed throughout the chosen portion of the piping. Additional gages were also installed: temperature-compensating gages for the free-filament gages (one gage per rosette), and other independent gages for keeping track of the general strain-gage behavior at high temperatures. Location of the gages, together with their orientation and identification, is shown in Fig. 5. The gage locations with respect to the original coordinate system are shown in Table I.

TABLE I. Station Locations of the Strain Gages

Station	X,[a] in.	Y, in.	Z, in.	Station	X,[a] in.	Y, in.	Z, in.
1	0.060	0	3	10	27.750	103.75	21
2	0.270	0	13.5	11	35.395	96.25	21
3	0.570	7.5	21	12	35.695	81.25	21
4	1.275	42.75	21	13	36.163	57.875	21
5	1.435	50.75	21	14	36.330	49.25	21
6	1.580	58.00	21	15	36.850	23.5	21
7	2.345	96.25	21	16	37.150	16	28.5
8	9.995	103.75	21	17	37.360	16	39
9	18.870	103.75	21				

[a]These values have been revised by assuming an averaged slope allowance of 0.02 in./in. for drainage.

B. Difficulty with Switching-Balancing Unit

A check of the leakage resistances of the strain-gage circuits in the BLH Type 225 switching and balancing units showed that the resistances were of the same magnitude. This led to the discovery that the resistances from terminal to ground in the switching and balancing units were all connected in parallel. This meant that the resistance of each gage was influenced by that of others. In effect, the measuring circuit modified the actual strain reading of each gage. A possibility also existed that, if a short-circuit developed in one of the gages during the experiment, the indications of all the other gages could also be lost. Another relevant characteristic of this feature is that the ground resistance of each gage circuit decreases in magnitude approximately by the same ratio as there are resistances in parallel (number of gages in the unit).

*For specifics, see the list in Appendix C.

For reliable strain readings, the leakage resistance (generally called the resistance to ground) has a recommended minimum value. This limiting ground resistance decreases with temperature and becomes quite small close to the originally planned maximum test temperature of 1200°F. The manufacturer recommends the following minimum ground-resistance values (by personal communication with S. P. Wnuk, BLH, Inc.):

Temperature, °F	Min Ground Resistance, megohms
1000	2-3
1100	0.4
1200	0.2

Thus, due to the characteristics of the circuit, the recommended minimum resistance to ground may become difficult to maintain. The measuring instrument, rather than the strain gage itself, may become the limiting factor of strain measurement at high temperatures.

Considering all the circuit disadvantages mentioned above and also its detrimental potential, we decided to modify the standard switching and balancing units. The change amounted to adding another deck to the channel selector switch, thus isolating each gage system from the others.

As an illustration of change in measurement due to the change in circuit modification, several readings were taken with the full-bridge weldable gages; the same four gages were used to read the apparent strain data both with the standard switching and balancing unit and also when the circuit had been modified. Figure 8 shows apparent strain readings with the standard and Fig. 9 with the modified switching and balancing unit. Comparison of the two graphs indicates that the strain data obtained with the modified unit yields higher values. This means that the actual strain experienced by the gage is greater than what is usually shown by the standard BLH Type 225 switching and balancing unit. Also, the gage-to-gage variation of Fig. 8 is greater than that of Fig. 9; however, no reliable quantitative values can be quoted in this respect from data of only four strain gages.

IV. DESIGN OF CALIBRATION EQUIPMENT

Although the manufacturer of high-temperature strain gages makes available average calibration data for the gages, accuracy of the individual gage seems in doubt. Thus, in anticipation of a more rigorous investigation of the relevant properties of high-temperature strain gages, a special loading fixture was designed and constructed and a furnace was designed to accommodate the fixture so that an elevated temperature would be made available. Combination of the loading fixture and the furnace would permit the simultaneous exposure of the strain gages to a predetermined load and a chosen temperature. In such a way, variation of gage factor of the individual

gages could be determined. Characteristics of the fixture and the furnace, both shown in Fig. 10, will be described briefly in the following paragraphs.

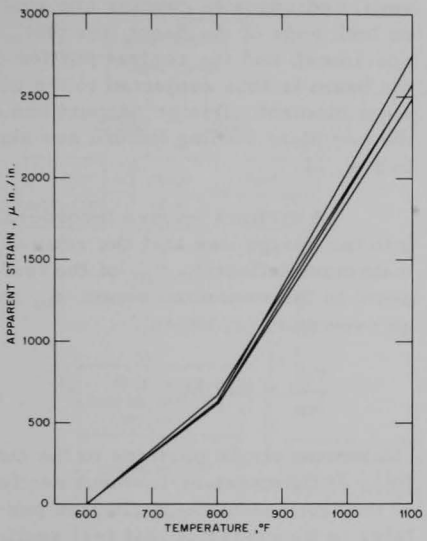


Fig. 8. Sample Strain Reading with Standard Switching-Balancing Unit

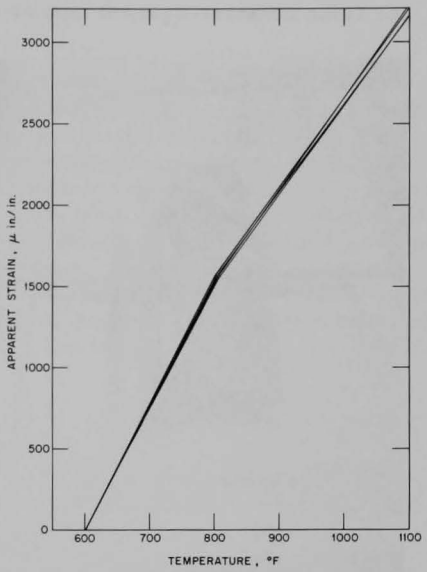


Fig. 9. Sample Strain Reading with Modified Switching-Balancing Unit

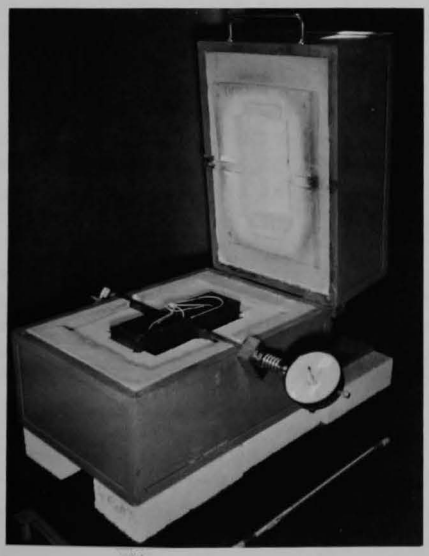


Fig. 10
General View of the Furnace

A. Loading Fixture

The type of loading fixture designed for testing strain gages was of the same constant-moment type as described by Lemcoe.[2] In this fixture, equal and opposite couples are applied on both ends of the beam (the test specimen), and the central portion of the beam is thus subjected to the constant moment. Design proportions of the complete loading fixture are shown in Fig. 11.

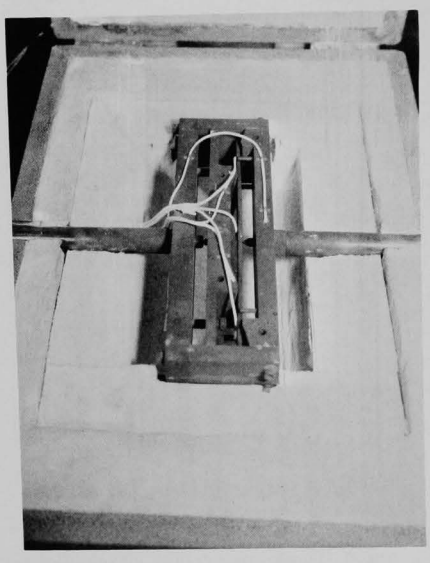


Fig. 11. View of the Loading Fixture

A distinct feature incorporated into the design was that the ratio of maximum deflection y_m of the test beam to the maximum strain ϵ_m was an even number; hence,

$$\frac{y_m}{\epsilon_m} = 100 \text{ in.}$$

(Maximum strain pertains to the outer fiber of the constant-moment section of the test beam; the deflection pertains to the center of that test section.)

The choice of an even number for the ratio established, to a large extent, the relative proportions of the composite design. Thus, the test specimen is a beam 1/8 in. thick, 1 in. wide, and 8 in. long. The span of the constant-moment section (the location for mounting strain gages) is $4\frac{1}{2}$ in. long.

In line with the material of interest for the test, both the fixture and the test beam were made of Type 304 stainless steel. Matching the material of these components minimized the differences in expansions between them at high temperatures.

Friction in the loading mechanism was one of the more serious sources of trouble at high temperatures. In the initial testing stages of the equipment, galling resulted and complete fusion was experienced in some force-transmitting parts. Subsequent changes of material in some of the mating components eliminated this difficulty. High-temperature lubrication also helped.

B. Furnace

The furnace was designed around the test fixture so that necessary protrusions through the walls could be accommodated. Thus, the screws

activating the load on the test beam and the arm providing the indication of the beam's maximum deflection were positioned outside the furnace. Heating elements of the furnace had the capacity to supply a maximum temperature of about 1500°F.

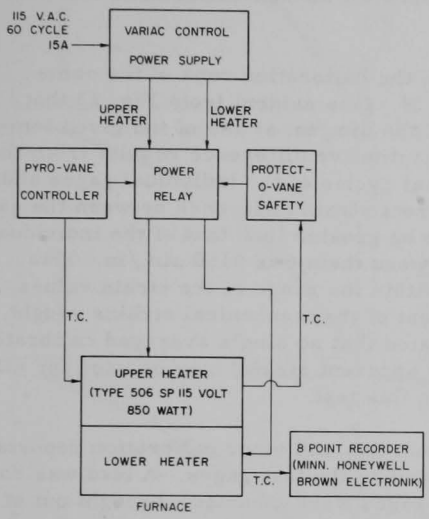


Fig. 12. Schematic Diagram of the Furnace Controls

Controls of the furnace were first made so that an on-off switch of maximum current (15 A) provided the intermittent heating. Although thermocouples within the furnace were insensitive to the on-off changes of full power, strain gages responded remarkably in a damped time-delayed manner. Subsequent change of the furnace controls to a constant-current power supply eliminated this difficulty. (Figure 12 is a diagram of the controls.)

V. GAGE CALIBRATION TESTS

A comprehensive study by Lemcoe[2] disclosed the unsuitability of the free-filament BLH Type HT-1212-5A gage for measuring strain on austenitic stainless steel under high temperatures. Although some minor calibration tests of this gage were made, our main attention turned to the remaining full-bridge weldable gage. Consequently, the effort of calibration described in the present section of this report pertains to the full-bridge weldable gage.

Nine full-bridge weldable gages, subjected to the temperature range 600-1100°F,* were carefully calibrated. These gages had been prepared for the calibration by subjecting them to three heat cycles up to 1100°F before the test runs. All the gages were mounted on Type 304 stainless steel bars just as the previous gages had been on the pipes of the sodium loop and according to the instructions of the manufacturer.

The regular procedure of the calibration test was to stabilize and bring all strain readings to zero at 600°F, where this was to be the reference temperature. Then the temperature was to be increased in 100°F increments up to 1100°F, conditions being stable when the strain readings were taken. Such a procedure would in effect accumulate the drift and show it as part of

*With the revitalization of the piping loop for FFTF, the maximum test temperature was considered to be 1060°F--hence, the change in maximum calibration temperature.

the apparent strain. As a matter of interest, this method of calibration was checked against the more time-consuming way of bringing up to temperature, stabilizing, taking the apparent strain reading, and reducing the temperature to 600°F, always to the same base. This supposedly more accurate way of testing failed to show any difference between the two calibration-test procedures.

The test results obtained from the calibration runs of the same nine gages are shown in Figs. 13 and 14. It is evident from Fig. 13 that, in the individual gages, a variation of ±50 μin./in. at any of the given temperatures could be expected. This quantitative difference results from the fourth, fifth, sixth, and seventh thermal cycles of the individual gages and is shown in Fig. 14. The recorded apparent strain difference between the gages of the same type would be expected to be greater than that of the individual gages, and the averaged variation between them was ±150 μin./in. This magnitude of variation, however, is within the range of the strain values, which is significant in the measurement of the mechanical strains sought. Therefore, the results obtained indicated that no single averaged calibration curve (that is, a correction curve for apparent strain) may be used for all the full-bridge weldable gages used in this test.

To explain the diversity between this and other calibration reports, we also investigated the effect of grounding the test gages. A lead was connected to the test beam (to which the gages were mounted), brought out of the furnace, and grounded. However, no change in calibration was observed.

It recently has been learned that some other factors might have a significant effect on the performance of the full-bridge weldable strain gages, and thus on the apparent strain calibration curves. One factor is the surface preparation before the gages are welded, as reported by Proctor and Mitchell.[3] They found that a fine mirror surface finish before applying the gages produced superior results. This might explain the wide discrepancy between our results and theirs. For an arbitrary group of 10 gages, their apparent strain maximum deviation from an averaged value (for the temperature range 392-1048°F) was less than ±40 μin./in. for mild-steel gages. Thus, surface preparation might explain some of the discrepancy between the apparent strain tests. However, we did not investigate the importance of the surface condition for the full-bridge weldable gages.

Some evidence has been found that the gage-to-gage variation in apparent strain might be reduced with change in temperature. This reduction would be accomplished by effectively canceling the thermal variation in material properties (modulus of elasticity) by suitably changing the properties of the measuring circuit in a predetermined manner. Murray and Stein[4] list different circuit combinations for this purpose. Evidently, such circuit modifications should result in a slightly decreased calibration sensitivity of the system, but the sensitivity then would remain temperature-independent.

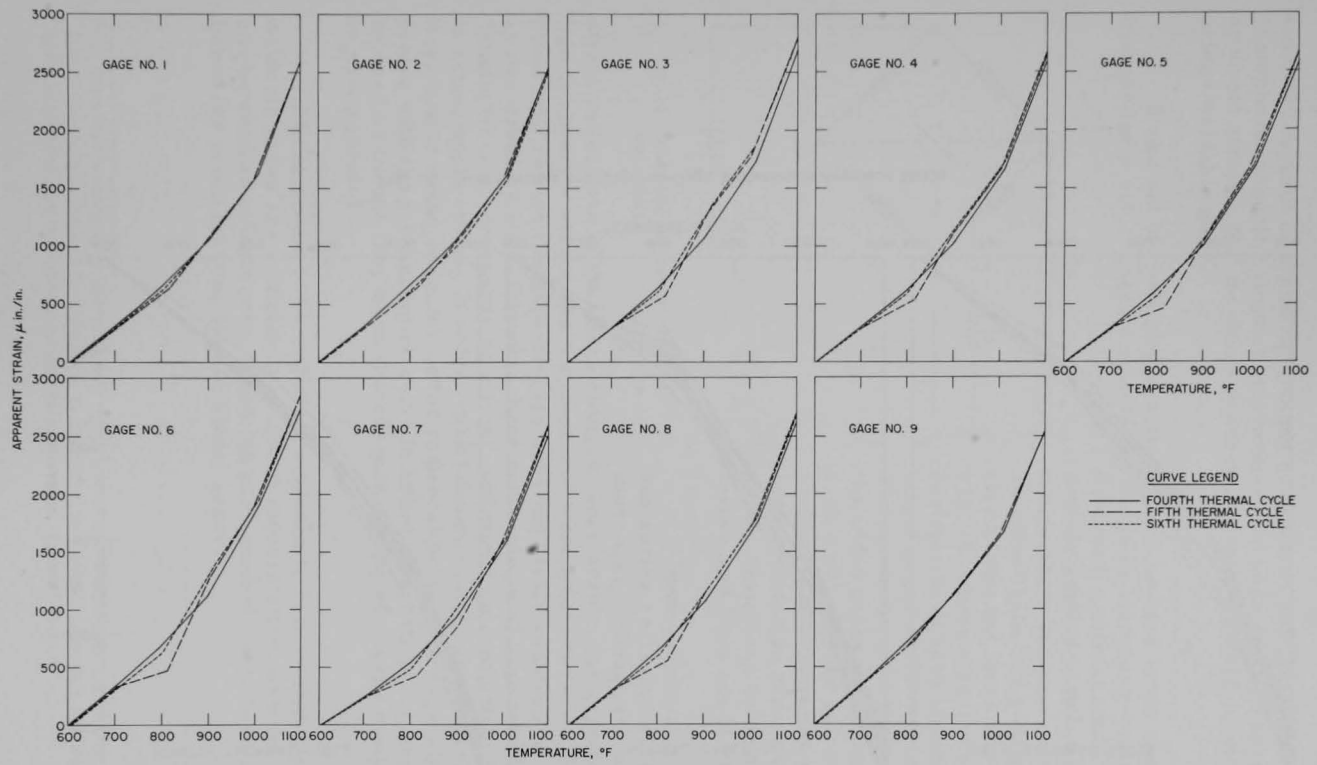


Fig. 13. Calibration Curves of Apparent Strain for Individual Strain Gages

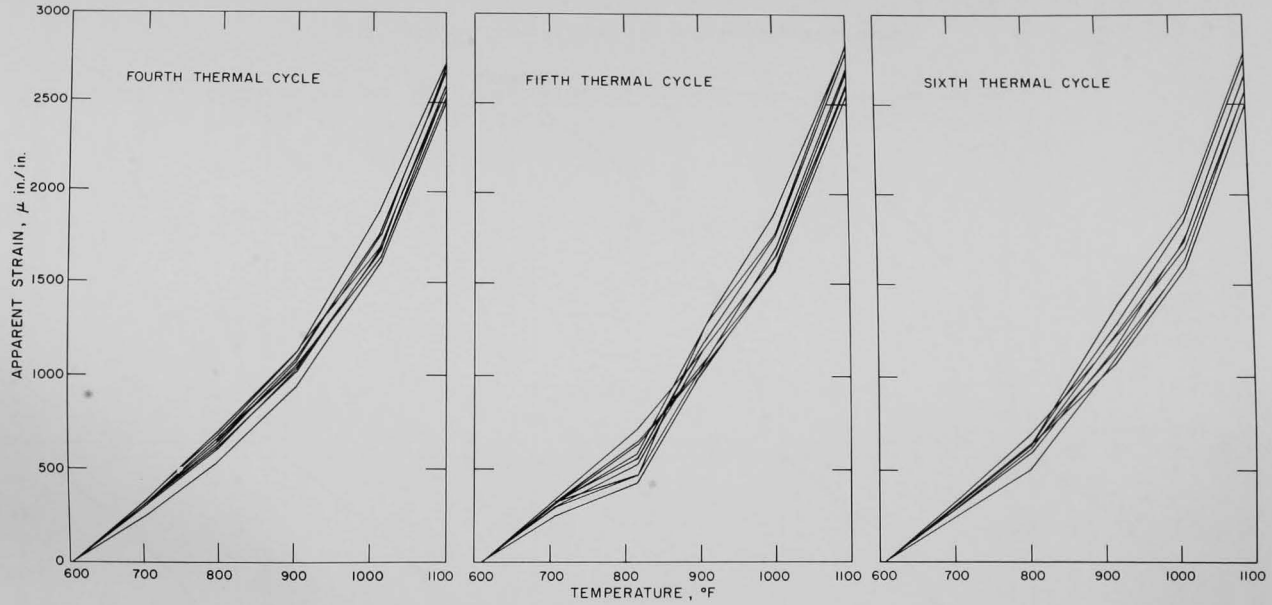


Fig. 14. Plots Showing the Gage-to-Gage Variation in Apparent Strain

Lemcoe[2] reports on some advantages of this sort and, referring to it as the "completion circuit," implies improvement in gage-to-gage variation in apparent strain. Wu[5] mentions desensitization in connection with the full-bridge weldable gage.

If one set of modifying resistors could be used in the above described manner for a set of gages connected to the same switching-balancing unit, then such a circuit could be advantageously applied in practical high-temperature strain measurements.* To investigate this possibility, a circuit was set up as illustrated in Fig. 15, where a series and a parallel resistor have been added to one of the active gages of the original circuit. The combination of the magnitudes of the added gages was maintained in such a way that the balance of the bridge did not change at all. In the experiment, this same parallel-series resistance combination was maintained for a set of four gages.

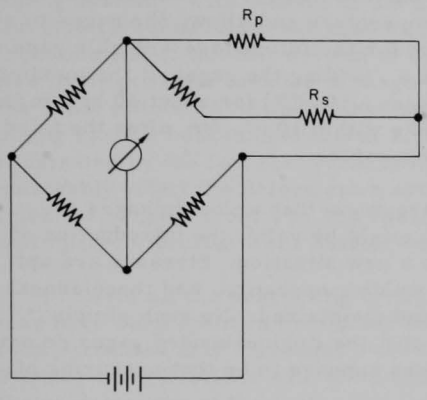


Fig. 15. Schematic Diagram of Modified Gage Circuit

Upon variation of the parallel and series resistances, it became clear that, although the total apparent-strain indications of the gages changed considerably, the gage-to-gage variation of apparent strain was not improved. Individual desensitizing circuits could still reduce the gage-to-gage apparent strain readings to ±50 μin./in. as described by Wu.[5] However, here each individual gage would have a "custom-made" desensitizing circuit, and would be completely impractical in actual applications. If an individual desensitizing circuit is the alternative, then it would seem far better to precalibrate each gage without tampering with the measuring circuit. In either alternative, the gages would be used as though they were transducers, where each gage would need to be precalibrated.

There seems to be sufficient evidence to believe that the full-bridge weldable gages are sufficiently stable at moderate temperature so that they can be used as transducers. Then, an easy method would have to be established for precalibrating the individual gages.

*One extra lead is necessary in such a circuit. This meant that in a full-bridge connection, five (instead of four) leads would be required from the gages to the readout instrument. Since only four leads were available in the installation, this method was not used here.

VI. TEST CONDITIONS AND RESULTS

For the Rokide-bonded free-filament gages and the full-bridge weldable gages the manufacturer maintains that, at least to the design temperature, precuring of these gages is unnecessary. However, our calibration experience showed that data of the first three thermal cycles are not repeatable. Moreover, other users of these gages also prefer precalibration. For example, Lemcoe[2] subjects the Rokide-bonded free-filament gages to 25°F above the expected maximum temperature and allows the gages to soak for 16 hr. A similar curing procedure for the full-bridge weldable gage is mentioned by Proctor and Mitchell,[3] i.e., holding the gages at the maximum expected temperature (for their purposes ~1049°F) for about 30 hr. In this way, they report repeatability of results within 10 μin./in. after the third thermal cycle up to the maximum temperature.

Although the manufacturer's argument that weldable gages are precured in the as-received condition might be valid, the introduction of welds during bonding seems to create a new situation. Stresses are apt to occur in the spot welds during the welding operation, and these anneal out as the temperature is increased and maintained. No such simple explanation can be made of the claim that the Rokide-bonded gages do not need precuring. Consensus of the users appears to be that precuring of both types of gages is a prerequisite.

Thus, conforming with the consensus of the users, numerous thermal cycles were imposed on the sodium loop and thus on the strain gages attached to the pipes. To provide heat to the sodium loop heaters had been previously affixed to the sides of the pipes. Preliminary testing of these heaters had been started at the end of 1966. Although the preliminary testing was mainly for checking out the control equipment and the integrity of the loop, it also served for partly curing the high-temperature strain gages. These preliminary dry-run tests extended only to about 400°F. At these temperatures, excessively high and unexpected strain readings came to light. This caused a premature termination of the preliminary loop test until the reliability of the gages could be checked. However, at this time also, the termination of the FARET project ended any effort in the area of the high-temperature strain gages.

With the revitalization of the sodium loop as the Core Component Test Loop (CCTL) for the Fast Flux Test Facility (FFTF) project, there also was a rejuvenation of the high-temperature strain-gage effort. Precycling of the sodium loop was resumed again in the middle of 1968; consequently, more than 2 yrs had elapsed since the gages had been installed. Dry runs were resumed with air and also helium inside the piping, for checking leakage through the joints in the piping components. Localized heating of selected sides of the pipes (the location of heaters) caused

nonuniform expansion of the pipes and thus of the entire loop. The thermal lag from the heater side of the pipe to the opposite side was quite large, creating nonuniform expansion and subsequently causing excessive strain within the system. No attempt was made to record strains at these preliminary thermal trials.

Subsequently, thermal cycling was performed with sodium inside the piping system. With sodium in the piping system, heat distribution around the pipe circumference was uniform; the maximum temperature variation from one end of the test section to the other was only a few degrees. This was made possible because of large thermal conductivity of sodium and also the great efficiency of the piping insulation; heaters in the side loops of the piping system held temperatures at very constant level. This is further illustrated by the fact that velocity of sodium flow inside the pipes did not noticeably affect the deformation state. The sodium pump speed was tried out ranging from 0 to 900 rpm, and no notable differences due to anticipated vibration were detected in the strain readings.

With all the precycling conducted on the loop, insufficient effort may have been spent in the curing stage of the test. Safety of the sodium loop permitted only a gradual increase in the temperature of the entire loop. Further complications with the sodium pump provided other limitations on the performance of the loop. The maximum temperature of the test (~1060°F) could not be reached as part of the soaking or preconditioning of the gages. Meeting of contract schedules on the overall operation of the CCTL at maximum design test temperature also played a major role. The control of test conditions of such a major undertaking as the CCTL has many variables and sometimes unfortunate limitations. Gages cannot be simply exposed to the desired conditions as they can under laboratory conditions; other factors can come into play and must be considered. On the other hand, insufficient prestabilization of the strain gages could at least partly account for discrepancies reported later in the actual tests of the gages.

Before the actual test was performed, the pipe hangers of the loop were adjusted to values used in the analytical results, which corresponded to zero load at room temperature. To further eliminate some of the unknowns, or at least minimize their effect, certain test procedures were planned. One of the main factors was the selection of a reference temperature to which the piping system could always be returned. The choice of this temperature was limited in our test because of unforeseen difficulties with the sodium pump and the associated leak tests. The entire temperature range of the test extended from 600 through 1060°F. The lower temperature was established to be 600°F; 1060°F was the maximum design temperature of interest to FFTF.

The step-by-step procedure of the actual strain test would be as follows:

1. Establish thermal equilibrium at reference temperature; zero-balance all strain readings.
2. Go to the desired temperature, and again establish thermal equilibrium; take the strain readings.
3. Return to reference temperature, and establish thermal equilibrium; take the strain readings.

The cyclic procedure of testing could eliminate some of the accumulative errors during the test. Limitation of the reference temperature to 600°F provided some additional restraints. It was hoped that, for comparison purposes with analytical results, these data could be extended to temperatures at which analytical results were available.

The actual history of the recorded strain data is approximately illustrated by the graph of Fig. 16. Recorded data were taken at times and temperatures shown by the data, which then were connected by straight lines to form the graph. Thus, slopes of these straight lines should not be taken as the actual rates of heat increase or decrease in the loop.

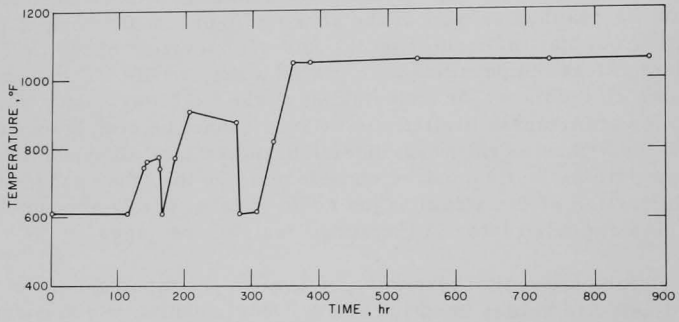


Fig. 16. Temperature-Time History of the Test

Several concurrent tests were performed. Controls of the tests were governed by many factors other than those connected with the high-temperature strain gages. The long extent of the peak-temperature (1060°F) test was controlled by the need of endurance information on the entire loop. This would effectively prove or disprove the usefulness of the loop for FFTF. The resulting data at the end of the third thermal cycle were never taken. This may be of little consequence, since averaging between the two ends of the loop would probably be unreasonable due to the length of the test and the expected accumulation of drift.

VII. INTERPRETATION OF EXPERIMENTAL READINGS

It has been inferred in Section V that, due to the unfavorable results on apparent strain, useful quantitative results were not expected in this experiment. Although quantitative data for comparison with analytical results would not be available, some qualitative comparison could still be expected. It would be anticipated that, at least on the statistical basis, certain trends of behavior should still persist.

As an example of such an expected trend, let us suggest an example: Since there were three cycles (third one incomplete) of increasing temperature in the experiment, the mechanical strain on the pipe would be expected to be proportional to change in temperature at least to some extent. If this trend is expected from the analytical point of view, the strain values at the peak temperature of each cycle could be compared. In conducting the comparison, we should correct the recorded strain values in at least two respects: one correction due to the change in gage factor, the other due to the presence of apparent strain.

In continuation of examining only the weldable strain gages, their strain readings at 775, 910, and 1050°F (the approximate thermal peak conditions of the first, second, and third cycles, respectively) were selected for comparison. Table II lists strains of the individual full-bridge weldable gages; the first column shows the recorded strain, the second column shows the strain that has been corrected by the prescribed change in gage factor, and the third column lists the strain where the correction due to an "averaged" apparent strain has been introduced.

TABLE II. First Sample of Strain Results

	775°F			910°F			1050°F		
	A	B	C	A	B	C	A	B	C
1(+X)A	696	1453	883	436	1755	615	951	2964	864
1(+X)B	318	1030	460	25	1285	145	909	2888	788
1(+X)C	317	1180	610	-206	1301	161	553	2887	787
1(+Y)A	537	1275	705	282	1579	139	942	2944	944
1(+Y)B	593	1338	768	-123	1116	-24	789	2745	645
1(+Y)C	528	1265	695	-43	1208	68	582	2512	412
1(-X)A	701	1458	888	415	1731	591	1130	3159	1059
1(-X)B	644	1395	825	-130	1108	-32	759	2706	606
1(-X)C	-54	763	193	-635	811	-329	1334	3788	1688
1(-Y)A	624	1372	802	620	1965	825	562	2542	442
1(-Y)B	671	1425	855	548	1883	743	623	2610	510
1(-Y)C	475	1356	786	-221	1284	144	563	2894	794
2(-X)A	591	1335	765	-52	1197	57	748	2702	602
2(-X)B	538	1275	705	150	1428	288	740	2704	604
2(-X)C	515	1250	680	-209	1018	-122	383	2281	181
2(-X)D	-46	624	54	-179	1052	-88	-425	1375	-725

TABLE II (Contd.)

	775°F			910°F			1050°F		
	A	B	C	A	B	C	A	B	C
3(+Z)A	826	1598	1028	180	1462	322	945	2939	839
3(+Z)B	421	1145	575	-308	905	-235	563	2475	375
3(+Z)C	217	918	348	-545	634	-506	275	2136	36
5(+Z)A	929	1713	1143	201	1486	346	784	2751	651
5(+Z)B	520	1256	686	-212	1014	-126	549	2461	361
5(+Z)C	180	1027	457	-632	814	-326	336	2614	514
7(+Z)A	668	1421	851	159	1438	298	823	2693	393
7(+Z)B	539	1277	707	648	1997	857	882	2909	809
7(+Z)C	-85	580	10	-95	1148	8	318	2331	231
8(+Z)A	683	1438	868	-28	1225	85	616	2557	457
8(+Z)B	421	1145	575	-314	898	-242	798	2735	635
8(+Z)C	232	934	364	-305	908	-232	263	2140	40
9(+Z)A	792	1560	990	378	1689	549	1004	3014	914
9(+Z)B	660	1412	842	184	1467	327	936	2928	828
9(+Z)C	100	787	217	-449	744	-396	378	2253	153
9(+Z)D	30	709	139	30	1291	151	-162	1687	-417
10(+Z)A	649	1400	630	-28	1225	85	988	2973	873
10(+Z)B	654	1556	986	-59	1469	329	762	3124	1024
10(+Z)C	375	1244	674	-217	1288	48	631	2976	874
11(+Z)A	1433	1165	595	-6	1250	110	832	2800	700
11(+Z)B	468	1198	628	-246	976	-164	755	2693	593
11(+Z)C	-137	522	-48	-646	519	-629	245	2099	-1
13(+Z)A	835	1608	1038	238	1529	389	877	2857	757
13(+Z)B	590	1334	764	-111	1130	-10	719	2661	561
13(+Z)C	399	1271	701	-326	1164	24	351	2647	647
15(+Z)A	582	1325	755	-90	1154	14	572	2505	405
15(+Z)B	702	1460	890	290	1588	448	647	2625	525
15(+Z)C	132	823	253	-377	826	-314	327	2210	110
16(+X)A	643	1393	823	243	1534	394	931	2926	826
16(+X)B	685	1440	870	691	2046	906	892	3345	1245
16(+X)C	-25	647	77	-798	345	-795	258	2095	-5
16(+X)D	74	758	188	9	1267	127	-266	1572	-528
17(+X)A	-99	565	-5	-25	1228	88	38	1914	-186
17(+X)B	-99	565	-5	-26	1227	87	39	1915	-185
17(+X)C	-103	560	-10	-28	1225	85	34	1909	-191
17(+Y)A	-104	559	-11	-25	1228	88	32	1907	-193
17(+Y)B	440	1167	597	283	1580	440	479	2426	329
17(+Y)C	258	963	393	-78	1168	28	564	2499	399
17(-X)A	-102	561	-9	-28	1225	85	36	1912	-188
17(-X)B	-107	556	-14	-28	1225	85	34	1909	-191
17(-X)C	-102	561	-9	-26	1227	87	33	1908	-192
17(-Y)A	-99	565	-5	-24	1229	89	34	1910	-190
17(-Y)B	-105	558	-12	-24	1229	89	36	1911	-189
17(-Y)C	-118	544	-26	-33	1219	79	28	1902	-198

A--Recorded strain.
B--Strain corrected for change in gage factor.
C--Strain corrected for change in gage factor and apparent strain.

The correction for the change in gage factor was made according to the recommendations of BLH, described in Appendix B. The correction in strain for the variation in apparent strain was determined as follows: Three different calibration runs of the same strain gages were averaged, results being shown in Fig. 14. The resulting three averages were again averaged to yield the final "averaged" apparent strain-correction curve shown in Fig. 17.

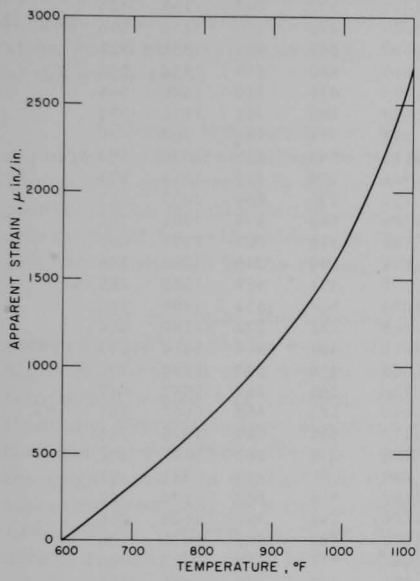


Fig. 17. Average Apparent Strain Curve of the Test

The tabulated results show that the anticipated proportionality of the calculated mechanical strains with change in temperature cannot be confirmed. Furthermore, the consistency of diverse results in the third column is too persistent. If statistical variations were dealt with, then at least a portion of the number of gages would be consistently proportional to temperature.

To further investigate this point, another table was made showing the results of strains taken as the first reading of each cycle. Thus, strain readings at 742, 770, and 820°F for all weldable gages are enumerated in Table III. The trends observed here are similar to those in Table II. However, all the search for an explanation thus far could not dissolve this "consistent inconsistency."

TABLE III. Second Sample of Strain Results

	742°F			770°F			820°F		
	A	B	C	A	B	C	A	B	C
1(+X)A	509	1102	972	430	1134	584	627	1544	804
1(+X)B	295	865	735	353	1048	498	601	1502	762
1(+X)C	303	993	863	241	1069	519	390	1453	713
1(+Y)A	412	995	865	389	1088	538	604	1513	773
1(+Y)B	454	1041	911	304	994	444	508	1396	656
1(+Y)C	409	991	861	245	928	378	357	1231	491
1(-X)A	568	1168	1068	463	1171	621	686	1604	864
1(-X)B	481	1071	941	307	997	447	507	1393	653
1(-X)C	24	683	553	47	852	302	213	1248	508

TABLE III (Contd.)

	742°F			770°F			820°F		
	A	B	C	A	B	C	A	B	C
1(-Y)A	318	890	760	361	1057	507	277	1165	425
1(-Y)B	396	977	847	328	1020	470	359	1256	516
1(-Y)C	393	1093	963	262	1092	542	405	1468	728
2(-X)A	441	1027	897	319	1010	460	538	1432	692
2(-X)B	402	984	854	330	1023	473	510	1406	666
2(-X)C	386	966	836	165	838	288	251	1112	372
2(-X)D	-68	462	332	-105	537	-13	-130	702	-38
3(+Z)A	621	1227	1097	411	1113	563	629	1538	798
3(+Z)B	351	927	797	233	914	364	438	1315	575
3(+Z)C	193	752	622	90	755	205	206	1053	313
5(+Z)A	667	1278	1148	402	1103	553	596	1501	761
5(+Z)B	403	985	855	279	966	416	467	1349	609
5(+Z)C	206	885	755	89	899	349	249	1286	546
7(+Z)A	510	1104	774	404	1105	555	619	1525	785
7(+Z)B	366	944	814	398	1098	548	533	1450	710
7(+Z)C	77	623	493	114	782	232	272	1140	400
8(+Z)A	467	1056	926	320	1011	461	518	1414	674
8(+Z)B	417	1000	870	315	1006	456	557	1442	702
8(+Z)C	214	775	645	91	756	206	167	1017	277
9(+Z)A	585	1187	1057	465	1173	623	688	1607	867
9(+Z)B	502	1095	965	410	1112	562	619	1526	786
9(+Z)C	155	709	579	121	789	239	291	1147	407
9(+Z)D	9	547	217	-13	640	90	-17	831	91
10(+Z)A	509	1102	972	407	1108	558	682	1590	720
10(+Z)B	531	1246	1116	364	1206	756	585	1669	899
10(+Z)C	334	1028	898	242	1070	520	406	1470	700
11(+Z)A	335	909	779	365	1062	512	619	1523	753
11(+Z)B	424	1008	878	297	986	436	548	1436	696
11(+Z)C	-11	525	395	19	675	125	171	1013	273
13(+Z)A	607	1211	1181	448	1154	604	669	1582	842
13(+Z)B	478	1068	938	308	998	448	507	1394	654
13(+Z)C	312	1003	873	198	1021	471	344	1400	660
15(+Z)A	427	1011	981	260	944	394	433	1318	548
15(+Z)B	492	1084	954	280	967	417	407	1304	564
15(+Z)C	125	676	546	105	771	221	234	1091	351
16(+X)A	495	1087	957	404	1105	555	630	1540	800
16(+X)B	465	1054	924	5411	6692	6142	585	1700	960
16(+X)C	58	602	472	53	713	163	215	1054	314
16(+X)D	9	547	217	-69	577	27	-94	747	7
17(+X)A	-67	463	333	-47	602	52	-82	754	14
17(+X)B	-66	464	334	-48	601	51	-81	755	15
17(+X)C	-69	461	331	-51	597	47	-84	752	12
17(+Y)A	-72	457	327	-50	599	49	-87	749	9
17(+Y)B	244	808	678	255	939	380	270	1150	410
17(+Y)C	215	776	646	204	882	332	303	1173	433
17(-X)A	-67	463	333	-48	601	51	-81	755	15
17(-X)B	-72	457	327	-49	600	50	-83	753	13
17(-X)C	-68	462	332	-50	599	49	-85	751	11
17(-Y)A	-66	464	334	-49	600	50	-83	753	13
17(-Y)B	-69	461	331	-50	599	49	-76	761	21
17(-Y)C	-81	447	317	-53	595	45	-87	749	9

A--Recorded strain.
B--Strain corrected for change in gage factor.
C--Strain corrected for change in gage factor and apparent strain.

VIII. CONCLUSION

The main objective of the high-temperature strain test has not been accomplished. In the main, this failure was attributed to the apparent gage-to-gage strain variation of identical gages. This large apparent strain variation would not permit average "calibration curves" to be used for all gages of the same type.

Although the purpose of the test has not been achieved, much experience has been gained in the use of high-temperature strain gages. The actual experience is difficult to avail to others, but a number of valuable points can be mentioned that might be useful. Although many or all of these points might be self-evident to users of high-temperature strain gages, they are not mentioned in the technical literature.

For example, the labeling of a strain gage as being "temperature-compensated" might be easily misunderstood. A person without previous high-temperature strain-gage experience might well take it to mean that temperature effect is compensated for and is of no concern. However, he finds out eventually (and sometimes through costly and bitter experience) that the temperature effect is a problem and may even be detrimental to the gage itself. In reality, the apparent strain correction due to high temperatures may be much greater than the mechanical strain to be measured. Thus, a mere fractional gage-to-gage variation in this apparent strain reading amounts to the same change as that of the mechanical strain.

Another point claimed by the manufacturer is that stabilization of at least the free-filament Rokide-bonded gage and the full-bridge weldable gage is not necessary. Nevertheless, experience shows that this is not exactly the case. This misconception is important to realize at the beginning of the test, especially when dealing with gages in the field. If gages are installed and covered up by insulation in a piping loop, stabilization of the gages in the subsequent stages of work may be inconvenient. Stabilization in that case would necessitate increasing the temperature of the whole loop to at least its design value and thus curing the gages before actual use. If stabilization is necessary at the beginning, curing can be done easily on an individual basis by means of an ultraviolet lamp. Thus, if such information is not made available before the gages are installed, then proper use of the gages will be impossible.

Even such a simple-appearing procedure as the correction for the change in gage factor with a change in temperature might also become confusing. The manufacturer supplies an "averaged correction" for all gages of the same type. However, the proper way to incorporate this into the strain reading is not specified. The user can do this in two ways: through the dial of the instrument by changing the gage-factor reading for each

corresponding temperature, or by accounting for the change analytically. An attempt to correlate the two methods of correction may be quite frustrating. An inquiry to the manufacturer, however, makes it clear that the gage-factor correction according to his data can only be done analytically.

Another important factor, which came to light accidentally, was the discovery of the peculiarity of the circuitry of the switching and balancing units. The characteristic of the circuitry is such that the instrument indicates a lesser strain reading than that really experienced by the strain gage. Other characteristics of this switching and balancing unit, as mentioned in Section III.B, make it imperative that the user of high-temperature strain gages be aware of this.

As other points of importance to the field of high-temperature strain gages, the accuracy of the gage factor from gage to gage might be investigated. Although the averaged correction is given by the manufacturer, the possible variation and its effect on the strain reading are still in doubt.

Another point for future investigators to check is the part surface preparation plays in the performance of the gages. Although the manufacturer insists that no special care need be taken before applying weldable gages, other users have claimed the opposite.[3]

Most of the reporting on high-temperature strain gages has been on tests conducted in laboratory environments. However, the controlling elements in the field can be completely different. The differences between the two environments should at least partly reflect the inconsistencies between the two.

It is by no means implied that if we had to do the test over again, we could resolve all the answers and yield correct and undisputable results. Certainly, the approach would be changed and other questions asked, but no assurance can be made with respect to sufficiently reliable and reasonably accessible results.

APPENDIX A

Derivation of Strain-Stress-Load Relationships

One purpose of the experimental results is to compare them with analytical predictions. To do that, one must relate strain readings to other quantities that can be directly compared with calculated values. Thus, relationships between strain and stress, and between strain and load at the section, must be determined.

As is usually the case in more complicated experiments, one value of strain does not yield one corresponding value of stress or load. Usually several strain readings must be made before one stress or load value can be deduced; the more complicated the test structure, the more strain readings are required to yield a given number of stress and load values.

Since all the active gages in the piping loop have been arranged in rosettes, the information that can be deduced for comparison from one of them will be analyzed first. Secondly, advantages of particular rosette arrangements with respect to each other will be pointed out.

1. One Rectangular Rosette

One rectangular rosette provides all the necessary information for calculating the maximum shear (τ_{max}) and principal stresses (σ_{max} and σ_{min}) at the location of the rosette. The relationships for making the calculations are standard:[6]

$$\left.\begin{aligned} \tau_{max} &= \frac{E}{2(1+\nu)}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2}; \\ \sigma_{max} &= \frac{E}{2(1-\nu)}(\varepsilon_A + \varepsilon_C) + \tau_{max}; \\ \sigma_{min} &= \frac{E}{2(1-\nu)}(\varepsilon_A + \varepsilon_C) - \tau_{max}; \end{aligned}\right\} \qquad (1)$$

where E, ν, and ε are the modulus of elasticity, Poisson's ratio, and strain, respectively, and the subscripts A and C refer to the axial and circumferential positions as shown in Fig. 6. Although the above maximum strain values can be easily calculated from the recorded strain data, the results seldom can be directly compared with calculated results; usually maximum stresses of the entire cross section of the piping are of greater concern and are generally given in standard piping flexibility calculations, and the results calculated from Eqs. 1 pertain only to the location of the rosette. For the range 600-1100°F, the variation of the modulus of elasticity is illustrated[7] in Fig. 18. A corresponding straight-line relationship is $E = 29.17 \times 10^6 - 6.2 \times 10^3 T$, where T is temperature in °F.

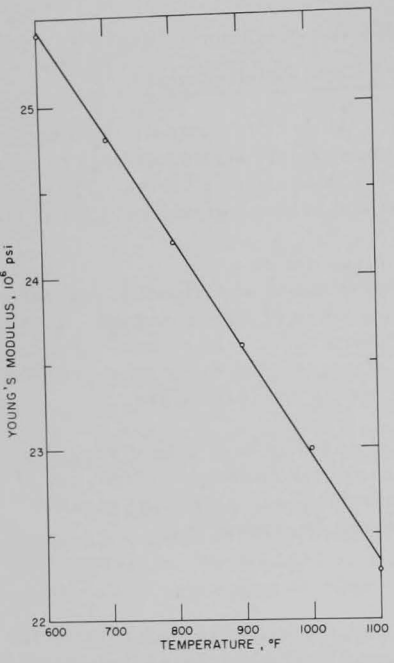


Fig. 18. Variation of Young's Modulus with Temperature for Type 304 Stainless Steel

Of greater value for comparison are the original strain readings (of the rectangular rosette) in the axial and circumferential directions. Because the pipe surface can be approximated closely by a biaxial stress field, the axial and circumferential strain do provide stress values in the corresponding directions. The biaxial stress-strain relationships[8] are

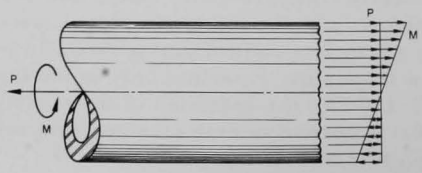
$$\left.\begin{aligned} \sigma_A &= \frac{E}{1-\nu^2}\,(\varepsilon_A + \nu\,\varepsilon_C); \\ \sigma_C &= \frac{E}{1-\nu^2}\,(\varepsilon_C + \nu\,\varepsilon_A). \end{aligned}\right\} \quad (2)$$

Usually, the axial stress value would be due to a combination of an imposed axial load P and a bending moment M, as shown in Fig. 19; this stress might also be affected by a high internal pressure p. Hence, the top and the bottom surface stresses of the pipe can be related to the loads as follows:

$$\sigma_A = \frac{P}{A} + p\,\frac{r_i^2}{r_o^2 - r_i^2} \pm \frac{M r_o}{I}, \quad (3)$$

where A, I, r_i, and r_o are the cross-sectional area, moment of inertia, inside radius, and outside radius of the pipe, respectively. Consequently, Eq. 3 enables some comparison of the experimental results with those of piping calculation. Nevertheless, there are insufficient data from one rosette to define completely the magnitudes of the axial load and the bending moment at the cross section; only the composite effect of both can be compared with the calculated values. Thus, the axial stress determined experimentally by the first of Eqs. 2 can be compared with that derived analytically using Eq. 3.

Fig. 19
Combination of Axial Load and Bending Moment



Similarly, the circumferential stress expression of Eqs. 2 can be related to the internal pressure of the pipe. This stress,

$$\sigma_C = 2p \frac{r_i^2}{r_o^2 - r_i^2}, \tag{4}$$

would come into consideration if high internal pressure were a factor.

In addition to the above, the same rosette data can also be related to the shear strain at the point, and hence to the torque M_T acting on that cross section. This relation has also been derived elsewhere[6] and is given here for reference:

$$M_T = \frac{E r_o}{4(1+\nu)} (2\varepsilon_B - \varepsilon_A - \varepsilon_C). \tag{5}$$

2. Two Rosettes on Opposite Sides of Same Cross Section

In addition to the information yielded by each individual rosette as outlined in Section 1, a combination of rosettes can provide additional data. One such useful combination is that of two rosettes on opposite sides of the same cross section, i.e. on top and bottom of the pipe in Fig. 19. The additional information gained from this combination of rosettes is the explicit expressions and thus the quantitative values of the axial load P and the bending moment M. These expressions are derived by using Eqs. 3 and 4 when applied to opposite sides of the cross section, which become

$$\left.\begin{aligned} M_H &= \frac{I}{2r_o}[\sigma_{A1} - \sigma_{A3} - \tfrac{1}{2}(\sigma_{C1} - \sigma_{C3})]; \\ P &= \frac{A}{2}[\sigma_{A1} + \sigma_{A3} - \tfrac{1}{2}(\sigma_{C1} + \sigma_{C3})]; \end{aligned}\right\} \tag{6}$$

where subscripts 1 and 3 pertain to top and bottom of the pipe, respectively.

Another point pertaining to any two rosettes at the same cross section, and not necessarily located opposite each other, is that each rosette will provide sufficient data to calculate the explicit magnitude of the torque or internal pressure. The calculated values should be the same under ideal conditions. Hence additional means are available for checking purposes.

3. All Four Rosettes in Position (two pairs at right angles to each other)

First, the four rosettes will provide all the information outlined in Sections 1 and 2 of this appendix. In addition, the knowledge of bending moments perpendicular to each other enables one to determine the maximum

bending moment of the entire cross section. This maximum bending moment is given by the vectorial sum of the two components, or

$$M_{max} = \sqrt{M_H^2 + M_V^2}, \tag{7}$$

where subscripts H and V refer to horizontal and vertical moments. The corresponding maximum and minimum bending stresses become

$$\left.\begin{aligned} \sigma_{b\,max} &= \frac{P}{A} + p\,\frac{r_o^2}{r_o^2 - r_i^2} + \frac{M_{max} r_o}{2I}; \\ \sigma_{b\,min} &= \frac{P}{A} + p\,\frac{r_o^2}{r_o^2 - r_i^2} - \frac{M_{max} r_o}{2I}; \end{aligned}\right\} \tag{8}$$

the shear strain (which is the same for the entire cross section) is

$$\tau = \frac{4M_T I}{r_o}. \tag{9}$$

With the above information available, the extremum shear and normal stresses on the cross section may be given as follows:

$$\left.\begin{aligned} \tau_{max} &= \sqrt{\tfrac{1}{4}(\sigma_{b\,max} - \sigma_{b\,min})^2 + \tau^2}; \\ \sigma_{max} &= \tfrac{1}{2}(\sigma_{b\,max} + \sigma_{b\,min}) + \tau_{max}; \\ \sigma_{min} &= \tfrac{1}{2}(\sigma_{b\,max} + \sigma_{b\,min}) - \tau_{max}. \end{aligned}\right\} \tag{10}$$

APPENDIX B

Gage Factor and Indicated Strain Correction

The manufacturer of the high-temperature strain gages provides information as to the variation of the gage factor with change in temperature. For the full-bridge weldable BLH gage Type FNWFB9-50-12, he suggests* a gage-factor (GF) drop of 1.5% per 100°F increase in temperature. Thus, taking the GF straight-line variation as shown in Fig. 20, the relation can be expressed as

$$\%\Delta\ GF = \frac{1.5}{100}(T-78) \tag{11}$$

and

$$\text{True GF} = \text{Indicated GF} \times \frac{100 - (1.5/100)(T - 78)}{100}. \tag{12}$$

The expression for corrected strain becomes

$$\text{True strain} = \frac{\text{Indicated strain}}{1 - 0.00015(T - 78)}. \tag{13}$$

Thus, the true strain at an elevated temperature using a full-bridge weldable gage would be modified by Eq. 13. This would correct the indicated strain reading due to the GF change with temperature.

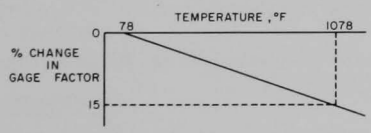


Fig. 20
Variation of Gage Factor with Temperature

A similar correction for the free-filament gage, the BLH gage Type HT-1212-5A, is obtained from the results given by Wnuk.[9] This variation was divided into two ranges of temperatures: one from room temperature (78°F) to 600°F, another from 600°F and above. Straight-line relationships were assumed for the two regions. As a result, for the range from room temperature to 600°F, the equation becomes

$$\text{True strain} = \frac{\text{Indicated strain}}{1 - (0.08/522)(T - 78)}, \tag{14}$$

*From private communication with S. P. Wnuk, Section Head, Strain Gages, BLH Electronics, BLH Corporation, Waltham, Mass.

and the corresponding equation for the temperature range 600°F and up becomes

$$\text{True strain} = \frac{\text{Indicated strain}}{1.05 - (0.13/600)T} \tag{15}$$

Thus, correction for the change in GF due to change in temperature is accomplished in accordance with the information supplied by the manufacturer. The accuracy of these corrections, as they apply to the individual gage, is unknown.

APPENDIX C

Instrument and Material Specifications

This appendix lists strain- and temperature-measuring equipment used in the high-temperature strain test. Grouping is according to general use of the equipment.

Strain Gages and Thermocouples

a. Full-bridge weldable, BLH Type FNWFB9-50-12.
b. Free filament, Rokide boundable, BLH Type HT-1212-5A.
c. Thermocouple, Type C.A.

Strain and Temperature Recorders

a. Strain indicator, BLH, Model 120.
b. Switching and balancing unit, BLH, modified* Model 225.
c. Temperature recorder, Brown "Electronik," 16 point, 0-1600°F range.

Gage Bonding Equipment

a. Spot welder and associated equipment, BLH, Model VTW-34, 15-W-sec capacity.
b. Ceramic spray gun and associated equipment, Metallizing Co. of America, Type R-3 (sold by BLH).
c. Sandblast generator, Metallizing Co. of America "Midget" type, 50-lb sand capacity.
d. Abrasive, Alundum Dynablast, 36 grit.
e. Ceramic rod, BLH, Rokide, H high-purity alumina rod for operation up to 1400°F.
f. Ceramic rod, BLH, Rokide, S alumina rod for operation up to 700°F.

Wiring and Insulation

a. Thermostat wire, Consolidated Wire & Associated Corp., American Wire Gage 16-2 conductor, twisted, solid bare, insulation 1/64 in.
b. Thermostat wire, Rome Cable Corp. Rose synthinol, American Wire Gage 16-5 conductor, solid bare, insulation 1/64 in.
c. Nichrome V, No. 20 gage, Driver Harris Co.
d. Fiberglass sleeving, Complete Reading Electric Co., Type NHT-18.

Furnace and Controls

a. Fire brick, Type WR-28, high-temperature.
b. Refractory cement, No. 20 high-temperature, Johns-Manville.
c. Voltage controller, General Radio "Variac," Type V-20.
d. Temperature safety controller, Brown "Protecto-Vane," range 0-2400°F.

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*See Section III.B.

e. Temperature controller, Brown "Pyro-Vane," range 0-2400°F.
f. Heater, heavy-duty Type 506 SP, 115 V, 850 W.

Additional Equipment Used

Megohmmeter, Keithley, Model 501.

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