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Astronuclear

WANL-TME-559

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PRELIMINARY REPORT
CY 63

A-1 FUEL ELEMENT TESTS

(Title Unclassified)

D. Wiebe 3-10-64
D. Wiebe, Manager (Date)
Engineering Mechanics
Experimental Engineering

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- III. A-1-5, Tension and Compression Tests
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1.0 INTRODUCTION

1.1 Design-imposed stress concentrations and seemingly minor variations in manufacturing processes may cause significant variations in the strength properties of graphite elements. For this reason, tests were begun on Westinghouse-Cheswick elements to determine dynamic Young's Modulus and fatigue strength. Initial tests to verify procedures and test fixtures were conducted on available elements (developmental quality Cheswick elements and production quality elements of Oak Ridge manufacture). As production quality Cheswick elements have become available, testing has been extended to include dynamic shear modulus determinations, compression and tensile strength tests, and an alternate test for dynamic Young's Modulus using axial rather than lateral deflections. A fuel element vibration-clearance test, a destructive impact-fatigue test, was conducted using the Oak Ridge elements in order to conserve the Cheswick elements available. These tests have been collectively termed the A-1 series of tests and have been described more thoroughly in WANL-TNR-095. This report describes the tests performed as of September 30, 1963 on Westinghouse-Cheswick elements, and the test results and conclusions obtained thus far.

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2.0 PURPOSE

2.1 This test was conducted to determine some of the mechanical properties of Westinghouse-Cheswick fuel elements. A second purpose was to establish the impact strength of Oak Ridge Fuel Elements.

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3.0 OBJECTIVES

3.1 Objectives accomplished in the conduct of this test were the determination of:

1. Dynamic Young's Modulus
2. Compressive Strength
3. Fatigue Strength

for Westinghouse-Cheswick graphite reactor elements.

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4.0 SUMMARY

- 4.1 Dynamic modulus tests conducted on Westinghouse-Cheswick elements at ambient temperature have shown remarkable consistency among similar types of elements. For example, using lateral vibration resonance, the nineteen hole, unfueled, uncoated elements tested had values of dynamic Young's Modulus of $2.60 \pm .01 \times 10^6$ psi. This consistency indicated both homogenous material and good quality control for the elements. The magnitude of the value of dynamic modulus was approximately 25 percent higher than previously indicated. These data will permit a more accurate analysis of reactor performance.
- 4.2 Compression tests (in the axial direction) on Cheswick element specimens yielded values of 12,700 $\begin{smallmatrix} +1400 \\ -2000 \end{smallmatrix}$ psi, approximately 50 percent higher than minimum in WANL-TNR-033; these increased values may permit larger flow cross sections (higher resultant stress on the element material) in future designs.
- 4.3 Cantilever fatigue tests on specimens made from nineteen hole, unfueled, uncoated Westinghouse-Cheswick elements have indicated an endurance strength in excess of 3000 psi.
- 4.4 Test methods have been ascertained for determinations of properties of element, dynamic shear modulus, logarithmic decrement, and fatigue tests in pure bending. Test method and procedure determinations are continuing for tensile tests.

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5.0 TEST SPECIMENS

5.1 Westinghouse-Cheswick manufactured elements

- 5.1.1 Nineteen hole elements, unfueled and uncoated, per WANL drawing number 709J682
- 5.1.2 Nineteen hole elements, unfueled and coated, per WANL drawing number 909E027
- 5.1.3 Nineteen hole elements, fueled and uncoated, per WANL drawing number 909E007
- 5.1.4 Nineteen hole elements, fueled and coated, per WANL drawing number 909E007 w/coating
- 5.1.5 Thirteen hole elements, unfueled and uncoated, per WANL drawing number 909E263
- 5.1.6 Thirteen hole elements, unfueled and coated, per WANL drawing number 936J656
- 5.1.7 One hole elements, Unfueled and uncoated, per WANL drawing number 975D673 not coated
- 5.1.8 One hole element, unfueled and coated, per WANL drawing number 975D673A w/coating

5.2 Oak Ridge Manufactured Elements

- 5.2.1 Nineteen hole elements, unfueled and uncoated, per WANL drawing number 909E324

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6.0 TEST EQUIPMENT

6.1 A-1 Dynamic Modulus and Damping Tests

Tests conducted under this general loading were further broken down as follows:

A-1-1 Dynamic Modulus of Fuel Element and Unfueled Hexagonal Element

A-1-2 Elastic Modulus of Fueled and Unfueled Hexagonal Elements from
Axial Bar Test

A-1-3 Dynamic Shear Modulus of Fueled and Unfueled Hex Elements

A-1-4 Internal Damping Characteristics of Fuel Elements and Unfueled
Hex-Elements

6.1.1 A-1-1 tests utilize lateral resonant frequency as a measure of dynamic Young's Modulus. See Ambient Temperature Test Setup, Figure 1, and Environment Temperature Test Setup, Fig. 3. The test element was supported laterally at the two points 0.5 in. inboard of the fundamental resonance nodes on one pound force electromagnetic generators. One generator was used to produce a sinusoidal input force. The other generator acted as a transducer converting the element deflection into measureable voltage. By varying the frequency of the input force, the frequency of maximum element deflection (maximum induced voltage on the generator), the resonant frequency was obtained. See Instrumentation, Figure 2, for the instruments used on this test and A-1-2

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and A-1-3. The dynamic Young's Modulus was calculated from this frequency (see Appendix A, Sample Calculations, Page 25). For calculation of bluntness of area (A-1-4), frequency inducing voltages corresponding to 1/2 resonant frequency output voltages were ascertained. This procedure was followed for each type of element and element assembly tested at each test temperature. A total of thirty-five elements were tested.

6.1.2 A-1-2 tests utilize axial resonance as a measure of dynamic modulus (see Figure 4, Elastic Modulus, Axial Vibration). The test specimen was suspended in the center in axial alignment with the small one pound force electromagnetic generators rigidly mounted at each end of the specimen. A low axial preload was imposed such that a sinusoidal force produced in one generator was transmitted through the specimen to the other generator, acting as a transducer, without impact loss. For a constant input force, the maximum axial displacement of the end of the specimen occurs at the axial resonant frequency. Varying the input generator frequency yielded an element axial resonant frequency whose output produced in the generator-transducer was a maximum voltage output; this frequency was recorded. The dynamic modulus was calculated from this frequency (see Appendix A, Sample Calculations, Page 28).

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For calculation of bluntness of area (A-1-4), the frequency inducing voltages corresponding to one-half resonant frequency output voltages were also ascertained, (see Appendix A, Sample Calculations, Page 30). This procedure was followed for each type of element and element assembly tested. A total of forty elements were tested.

- 6.1.3 A-1-3 tests utilize torsional resonant frequency as a measure of dynamic shear modulus (see Figure 5 Dynamic Shear Modulus Test Setup). The test specimen was mounted as a fixed and pivoted beam with a flywheel attached to the pivoted end of the beam. Small one pound force generators were attached to the flywheel in such a manner that a sinusoidal force output from one generator induced a torsional excitation in the flywheel. The amplitude of excitation was reproduced as a voltage on the other generator. The input force frequency was varied until the maximum angular amplitude, as indicated by maximum induced voltage, indicated torsional resonance of the flywheel-element system. The shear modulus was calculated from torsional resonance of the system. The frequency inducing voltages corresponding to one-half resonant frequency output voltages were ascertained and recorded for calculation of bluntness of area (A-1-4).

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6.1.4 A-1-4 tests involve two specific test procedures in addition to the reduction of data from A-1-1, A-1-2, and A-1-3 for bluntness of area using standard formulas.

(a) Determination of logarithmic decrement (see Figure 6).

Each type of fuel element tested was clamped rigidly, and a strain gage was applied on the element to read strain when the element was deflected. The strain gage output was connected to an amplifier-oscillograph, then the element was deflected and released. The decay of amplitude was recorded and the logarithmic decrement calculated as a function of strain. Preliminary tests only have been completed.

(b) Determination of tensile hysteresis (see Figure 7).

In this portion of A-1-4, the element tensile specimen tested was mounted in a tensile test machine and loaded as noted below:

0-200-0 lb, recording continuously load vs. strain on an automatic strain recorder.

0-400-0 lb, recording continuously load vs. strain on an automatic strain recorder.

The area of resulting hysteresis curves were measured and converted to absorbed energy per inch of element at various stress levels. Preliminary tests only have been completed.

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6.2 A-1-5 Tensile and Compressive Strength of Fuel Elements and Unfueled Center Elements

6.2.1 Compressive Strength Tests (see Figure 7)

These tests were conducted on two inch long specimens cut from production quality Westinghouse-Cheswick elements. These elements had been strain gaged to determine Poisson's ratio and to ensure uniaxial compression. The test specimen was placed in the Wiedemann-Baldwin tensile test machine and loaded to failure. A continuous record of load vs strain to failure was made. A total of twenty tests have been conducted on production quality Cheswick elements; fifteen additional tests have been conducted on specimens obtained from elements of other types (development grade Cheswick and production grade Oak Ridge elements).

6.2.2 Tensile Strength Tests

Eight inch long strain gaged specimens, cut from unfueled uncoated Cheswick elements, with graphite end clamps cemented in place were tested on the Wiedemann-Baldwin Machine. The end clamps were supported on adjustable plates which provided uniaxial tension. The specimen was loaded to a nominal 300 lb load, the support plate adjusted to eliminate bending, and the load was released. The specimen was then loaded in discrete increments to failure. Preliminary tests only have been completed.

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6.3 A-1 Fatigue Tests

6.3.1 A-1-6 Bending Test of the Fueled and Unfueled Element (Room Temperature) (See Figure 8)

Elements of each type tested were cut into ten inch long specimens. The load fixture produced a uniform moment over the central two inch portion of the specimen. In use, the specimen was mounted in the fixture, the preload set with a load cell-turnbuckle arrangement and the alternating load set by adjustment of an eccentric. A strain gage was installed in the region of maximum moment and the instrumentation connected. Cycling was started and continued to failure or to 1×10^6 cycles. Load, strain, and total cycles (total time) were monitored as required. Preliminary tests only have been completed.

6.3.2 A-1-7 Fatigue Strength of Fuel Element and Unfueled Hex-Element (see Figure 9)

Specimens of each type to be tested were cut to approximately thirteen inch lengths from full-length elements. The specimen was clamped in place, a strain gage attached at the root of the clamp, and the connecting rod fastened in place. The pre-load was adjusted with a turn-buckle arrangement; the alternating load, with a cam eccentric or eccentric load, depending on the type of fatigue machine. Cycling was commenced and continued to failure or to 1×10^6 cycles, monitoring load, strain, and cycles (total time) as required. A total of sixty specimens have been tested.

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6.4 A-1-8 Fuel Element Vibration Test Clearance Study

Unfueled elements were attached in the vibration test fixture using all combinations of classic end conditions, i.e., free, hinged, and clamped. The clearance between each side of the element and the adjacent surface of the test fixture was adjusted to discrete clearances from 0.010 in. to 0.200 in. The element was subjected to input acceleration levels to a maximum of 15 "g" at element resonant frequencies. The empirical curve of element life vs. input acceleration level at the discrete clearances was obtained. The total number of elements tested was fifty-one. A picture of the test setup is included as Figure 10.

A more complete description of these tests is found in WANL-TNR-095, A-1 Tests.

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7.0 TEST RESULTS AND DATA

7.1 Al-1 Dynamic Modulus, Lateral Resonant Vibration

The data obtained on Westinghouse-Cheswick and other elements has been tabulated in Table I. For the unfueled, uncoated Cheswick elements, the standard deviation of the resonant frequency was less than 0.1 cps. This corresponded to less than 0.5% variation in values of E among the same type of element. For the elements tested of other than Cheswick production quality, the resonant frequency standard deviation was .36 cps for similar types of elements, corresponding to 4.2% variation in values of E.

The data shows three different current inputs; generator power inputs from 0.3 amperes to 0.01 amperes have been tried. From the maximum current to the minimum caused approximately a 2% increase in the resonant frequency. The 0.3 ampere input caused the support hangers to drift; the 0.01 ampere input, although most accurate for determinations of dynamic Young's Modulus at strains approaching zero, was susceptible to errors resulting from ambient electrical noise. As of the day of this report, a nominal value of 0.05 ampere is being used. This corresponds to a stress level of approximately 100 psi.

Inaccuracies inherent in the test setup, other than instrumentation errors, are:

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- 1) Hanger, attaching wire, and armature mass
- 2) Air damping
- 3) Fixture resonances

All of these inaccuracies tend to lower the value of Young's Modulus obtained and increase the apparent material damping. The combined effect of these errors and the instrumentation errors was estimated to be less than 1%.

The calculated values of dynamic modulus obtained from resonant frequency determinations of coated elements and unfueled hexagonal elements with inner hardware did not represent the dynamic modulus of the graphite material. These values, as high as 3.05×10^6 psi, were the result of using a constant I (element moment of inertia), not accounting for a change in I due to the coating, and not adding the stiffness of inner hardware into the calculation. This test has been conducted to determine the effective Young's Modulus of the various types of elements as installed in the reactor. The value of Young's Modulus desired is not that of the material per se, but the modulus of the material, in the element configuration and with the coating and/or hardware included. This is the value that has been recorded. See Figures 11 and 12.

Limited high and low temperature tests conducted have confirmed the shape of the Young's Modulus curve presented in TNR-033; the values obtained have been approximately 20% higher (see Figure 13). The minimum test temperature obtained, -250°F , was the lower limit of the environmental test fixture as presently designed.

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Al-1 data is presented for five Oak Ridge elements. These elements, used in Al-8 impact tests, show a lower dynamic modulus, higher damping, and greater standard deviation of resonant frequencies (hence Young's Modulus) than the Cheswick production quality element.

The stress level during Al-1 testing was verified with measurements of element tip amplitude converted to stress using the formula in Al-1, Calculation of the Bending Stress, Appendix A. The calculated value of stress obtained for a 19 hole element for 0.15 ampere input current was 250 psi; for 0.05 ampere input, 100 psi. Dynamic measurement difficulties on the small amplitudes involved (less than 0.1 in.) made the confidence in dynamic stress accuracy $\pm 20\%$. Figure 2 shows the relative values of the fundamental resonant frequencies and amplitudes at constant input current for the types of 19 and 13 hole elements tested. The 19 hole fueled elements tested had lower resonant frequencies because of the added weight of the fuel. Frequency is proportional to $\frac{1}{2L} \sqrt{\frac{EI}{\rho}}$; adding fuel to the element serves to

increase the value of ρ , decreasing the resonant frequency, hence any deleterious effect of the fuel on the graphite was not demonstrated. The effect of the coating on the lateral resonant frequency of the fueled elements tested was apparently due only to the weight of the coating material, i.e., the strengthening effect of the thin-walled cylinders of niobium coating was not noticeable.

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7.2 Al-2 Dynamic Modulus, Axial Resonant Vibration

The data obtained on Westinghouse Cheswick and other elements has been tabulated in Table II.

The data shows four different current inputs; generator power inputs from 0.3 amperes to 0.01 amperes have been tried. As was the case with the Al-1 tests, from the maximum current to the minimum caused approximately a 2% increase in the resonant frequency.

Inaccuracies inherent in the test setup, other than instrumentation errors, are:

- 1) Armature mass
- 2) Slippage and compression of the wooden dowels used as end supports
- 3) Fixture resonances

All of these inaccuracies tend to lower the value of Young's Modulus obtained and increase the apparent material damping. The combined effect of these errors and the instrumentation errors was estimated to be less than 1%.

As in Al-1 tests, the relative resonant frequencies of different types of 19 hole elements followed the expected pattern of decreasing frequency with increasing element weight - see Figure 14. The 13 hole element required a slight modification of the wooden dowels in order

to perform the tests, hence values of resonant frequency for 13 hole elements may not be in the correct position relative to the 19 hole elements. Values among 13 and 1 hole elements would be in the correct relative position, as the wooden dowels would be the same type.

Tests of 13 hole elements with center hardware and shim rods installed showed the effect on modulus and bluntness of those hardware additions - see Figure 15. The increase in resonant frequency with addition of center hardware was due to the increased stiffness afforded the element by the stainless steel sleeve and the pyro tile graphite sleeves. Note that the indicated bluntness with the addition of the sleeves was higher than element bluntness without the sleeves. Shim rods did not increase the element stiffness, as did the stainless and pyro sleeves, because of the additional end play in the shim rods. The friction of the shim rods in the element passages did noticeably increase the bluntness, however.

Values of bluntness and dynamic modulus determined from Al-1 and Al-2 tests on the same element showed slightly lower values of dynamic modulus on the Al-2 tests and values of the same order of magnitude for bluntness (bluntness measurements were less accurate than resonant frequency because of greater error due to output voltage fluctuation at lower voltage levels. Estimated error in bluntness is about $\pm 25\%$)

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7.3 Al-3 Dynamic Shear Modulus

Only preliminary data has been obtained thus far in tests for G, the shear modulus perpendicular to the axis of extrusion. Current inputs to the drive generator shall be maintained at 0.05 amperes (this level of power has shown approximately the same order of magnitude of stress as Al-1 and Al-2 tests).

Inaccuracies inherent in the test setup, other than instrumentation errors, are:

- 1) Pivot friction
- 2) Drive wire friction and play
- 3) Clamps on flywheel and fixed ends

All of these inaccuracies tend to lower the calculated shear modulus obtained and increase the apparent material damping. The combined effect of these errors and the instrumentation errors was estimated to be less than 1%.

Data for G, the shear modulus perpendicular to the axis of extrusion, will be presented in the next report on Al, Mechanical Tests.

7.4 Al-4 Internal Damping Characteristics of Fuel Elements and Unfueled Hex-Elements

Preliminary tests have been conducted to verify procedure. Tests shall be conducted on samples of each type of element at ambient temperatures and pressure and at ambient temperature and vacuum to determine logarithmic decrement from approximately 2000 psi to 0 psi. No data are available.

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7.5 A1-5 Tensile and Compression Strength of Fuel Elements and Unfueled Center Elements

Results of tests conducted on compression specimens of Cheswick production quality and other elements were summarized in Table III. The test fixture was the same as presented in a previous report on element properties - see Figure 7. A typical fractured specimen was photographed - see Figure 18.

Compressive hysteresis was measured on Cheswick and other elements using the Wiedemann-Baldwin automatic recorder. Curve of stress versus strain showing hysteresis near the fracture stress was obtained for a Cheswick elements specimen and a specimen of an Oak Ridge element - see Figure 16. For a Cheswick element, a curve of hysteresis versus stress was also obtained - see Figure 17.

Results of compression tests show Cheswick production quality elements to exhibit higher compressive strength and lower hysteresis than other types of elements (Oak Ridge and development grade Cheswick elements).

Tensile tests are preliminary. The method utilized thus far (preloading the specimen on three-point supports, adjusting the supports to eliminate bending, and conducting the tensile test) seems able to produce pure tensile fractures, as opposed to a combination of bending and

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tensile fractures. Tests shall be conducted with various methods of support until a method producing consistently good results is obtained. Ultimate tensile strengths obtained thus far have been approximately 50% of the values expected.

7.6 Al-6 Bending Test of the Fueled and Unfueled Hex-Element

Preliminary tests to check the fixture performance at room temperature have been conducted; no data are available. The number and types of specimens and the stress levels to be tested are the same as Al-7 tests. The test frequency for this machine shall be 3 cps as the high moving mass does not allow accurate load measurements at higher test frequencies.

7.7 Al-7 Fatigue Strength of Fuel Element and Unfueled Hex-Element

Data on cantilever fatigue tests performed on 19 hole, unfueled, uncoated Cheswick production quality elements have been summarized in Table IV. The results of these tests show fatigue strengths of 3 cps and 30 cps tests were similar - see Figure 19. Maximum static flexural strength of the 19 hole unfueled, uncoated element averaged approximately 5500 psi.

The maximum stress values that were indicated in Table IV were derived from $S = \frac{Mc}{I}$. This formula assumed an isotropic material (fuel element graphite is anisotropic). A revised formula for maximum stress may be developed if later tensile tests show the compressive and tensile strength versus strain curves for Cheswick fuel element to vary significantly.

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Tests are continuing on fatigue strength determinations of other types of Cheswick elements, both fueled and coated.

7.8 Al-8 Fuel Element Vibration Test - Clearance Study

Elements of Oak Ridge manufacture (these were used in lieu of Chewwick elements for expediency) tested under various end conditions, end clearances and accelerations resulted in the curve shown in Figure 20. This empirical curve does not indicate element strength in a quantitative fashion - conclusions can be drawn, however, on the relative element life at a particular input "G" load for various combinations of end conditions and clearances.

The tests indicated the poorest lateral support system is one supporting the elements in a cantilever beam fashion; approximately 3 1/2 G's can be sustained continuously. Other support systems were better (for example, a support system equivalent to clamped ends can sustain 15 G's continuously) - the 15 G upper limit of the curve is a machine limitation.

Tests were conducted at the fundamental resonant frequency or at the first harmonic resonant frequency, whichever resulted in a higher impact load on the element (the shaker employed had a total travel limit of ± 0.5 in., hence at frequencies less than approximately 20 cps, the full 15 G acceleration could not be imposed).

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Strain gage readings during tests were recorded for initial cantilever support tests. The resultant data, because of impact conditions, could not be correlated with the loading conditions imposed. Additional tests are planned using accelerometers in a further attempt to obtain an analytical and experimental correlation of stress and/or strain with loading conditions.

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8.0 CONCLUSIONS

- 8.1 The dynamic modulus tests conducted to date have indicated consistent values of resonant frequencies (hence consistent values of Young's Modulus and/or shear modulus) for production quality Cheswick elements. Other elements tested in initial checkout studies of the apparatus, and for A-1-8 tests, showed a much wider variation of frequency. The calculated values of Young's Modulus, obtained testing unfueled Cheswick production quality graphite elements in the temperature range -250°F to 1000°F, were approximately 25 per cent higher than values reported in WANL-TNR-033. However, the shape of the curve (increasing slightly with temperature) was similar.
- 8.2 Damping and hysteresis values obtained for Cheswick elements demonstrate that a significant difference exists between production quality Cheswick elements and the elements used initially in fixture and procedure checkout studies.
- 8.3 The compressive strength of unfueled element Cheswick graphite has as much as 50 per cent more strength than WANL Materials for Design (TNR-033) data indicate.
- 8.4 Fatigue strength data indicate 1×10^6 cycle fatigue strengths in excess of 3000 psi for production quality Cheswick elements.
- 8.5 Fuel element vibration-clearance tests, conducted on Oak Ridge, unfueled, uncoated elements demonstrate satisfactory element life at clearances approximating these in the reactor for input accelerations below 10 g and any element support system other than cantilever.

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9.0 RECOMMENDATIONS

- 9.1 Production quality elements should be tested as soon as possible for a verification of the data obtained in the current series of A-1 tests.
- 9.2 The A-1-1 method of test at room temperature should be considered as a quality assurance test for elements used in mechanical tests.
- 9.3 Environmental temperatures in either A-1-1 and A-1-2 testing should be extended to reactor operating temperatures to ascertain dynamic Young's Modulus variations as accurately as possible.
- 9.4 Higher strains for dynamic moduli tests should be included where the test method permits.
- 9.5 The fuel element vibration test (A-1-8) should be continued with production quality Cheswick (Westinghouse Division) elements. The original lot of Oak Ridge elements have noticeably different properties from production quality Cheswick elements, particularly in damping, hence tests of production quality Cheswick elements should be performed to verify the data obtained thus far.

10.1 APPENDIX A

Sample Calculations

A-1-1 Dynamic Modulus of Fuel Element and Unfueled Hexagonal Element

The relationship between the natural frequency and the dynamic modulus of elasticity is:

$$f = \frac{a}{2\pi} \sqrt{\frac{EIg}{L^3W}}$$

or

$$E = \frac{4\pi^2 L^3 W f^2}{a^2 I g}$$

where

E = elastic modulus (lb/in.²)

L = length (inches)

W = weight (lb)

a = constant = 22.4 for 1st mode free-free beam

I = element cross section moment of inertia (in.⁴)

g = acceleration of gravity = 386.4 in./sec²

f = natural frequency (cps)

Calculation of dynamic modulus for a typical 19 hole element.

The moment of inertia and the weight are different for the thirteen and single hole elements; the calculations are similar.

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$$f = 32.29 \text{ cps}$$

$$W = 548.6 \text{ grams} = \frac{548}{453.6} \text{ lb}$$

$$L = 52.00 \text{ in.}$$

$$a = 22.4$$

$$I = 0.014 \text{ in.}^4$$

$$g = 386.4 \text{ in./sec}^2$$

$$E = \frac{4 \times (\pi)^2 \times (52.00)^3 \times 548 \times (32.29)^2}{(22.4)^2 \times 0.0140 \times 453.6 \times 386.4}$$

$$E = 2.58 \times 10^6 \text{ lb/in.}^2$$

Bluntness

The bluntness is computed by:

$$b = \frac{\Delta f}{f} \sqrt{\frac{A^2}{A_n^2 - A^2}}$$

where

b = bluntness

Δf = frequency bandwidth near f for some value of A

f = resonant frequency

A = magnification factor on either side of f

A_n = magnification factor at resonance

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selecting $A = 1/2$ and $A_n = 1$;

$$b = \frac{\Delta f}{f} \sqrt{\frac{1/4}{1-1/4}} = \frac{\Delta f}{f} \sqrt{1/3} = 0.577 \frac{\Delta f}{f}$$

where

$$\Delta f = f_2 - f_1$$

f_1 = frequency preceding resonance at one-half amplitude attained at resonance

f_2 = frequency following resonance at one-half amplitude attained at resonance

Calculation of bluntness for 19 hole element

The calculations are the same for thirteen hole and single hole elements.

$$f = 32.29 \text{ cps}$$

$$f_1 = 32.19 \text{ cps}$$

$$f_2 = 32.55 \text{ cps}$$

$$b = 0.577 \frac{(32.55 - 32.19)}{(32.29)}$$

$$b = 6.43 \times 10^{-3}$$

Calculation of the Bending Stress

The element undergoing test in the A-1-1 procedure is in the

"free-free" state of vibration; the formula is:

$$\sigma_{\max} = \frac{Ea\pi^3 c}{2L^2}$$

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where

$\delta_{\max}$ = maximum bending stress, psi

E = dynamic Young's Modulus, psi - 2.6×10^6 psi

I = moment of inertia of cross-section of the element, in.⁴ =
0.014 in.⁴

C = distance from the neutral axis of the element cross-
section of the outermost fiber, in. = 0.377 in.

L = element overall length, in. = 52.00 in.

a = single amplitude of vibration of the end of the element
with reference to the nodal points, in. = 0.045 in. for
0.15 ampere current into the input generator substituting,

$$\begin{aligned}\delta_{\max} &= \frac{E a \pi^3 c}{2 L^2} \\ &= \frac{2.6 \times 10^6 \times 0.045 \times (3.142)^3 \times 0.377}{2 \times (52)^2} \\ &= 253 \text{ psi}\end{aligned}$$

A-1-2 Elastic Modulus of Fueled and Unfueled Hexagonal Elements from
Axial Bar Test

The relationship between the natural frequency and the modulus of
elasticity is:

$$f = \frac{n}{2L} \sqrt{\frac{Eg}{\rho}} \quad \text{or} \quad E = \frac{AWL}{n^2 g A} f^2$$

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where

f = natural frequency (cps)

n = mode (no. of half waves)

L = length (inches)

E = elastic modulus

g = acceleration of gravity 386.4 (in./sec²)

ρ = density (lb/in.³)

and

$$\rho = \frac{W}{V} = \frac{W}{AL}$$

where

V = volume (in.³)

A = cross-sectional area (in.²)

W = element weight, lb

Calculation of elastic modulus for a typical 19 hole element

$$f_n = 1148.1 \text{ cps}$$

$$W = 548.6 \text{ grams} = \frac{548.6}{453.6} \text{ lb}$$

$$L = 52.00 \text{ in.}$$

$$n = 1$$

$$g = 386.4 \text{ in./sec}^2$$

$$A = 0.347 \text{ in.}^2$$

$$E = \frac{4 \times 548.6 \times 52.00 \times (1148.1)^2}{(1)^2 \times 386.4 \times 453.6 \times 0.347}$$

$$E = 2.47 \times 10^6 \text{ lb/in.}^2$$

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The bluntness is computed by the same formula as in A-1-1, namely:

$$b = \frac{\Delta f}{f} \sqrt{\frac{A^2}{A_n^2 - A^2}}$$

or, selecting $A = 1/2$ and $A_n = 1$:

$$b = 0.577 \frac{\Delta f}{f} = 0.577 \frac{f_2 - f_1}{f}$$

Calculation of bluntness for 19 hole element:

$$f = 1148.1 \text{ cps}$$

$$f_1 = 1142.2 \text{ cps}$$

$$f_2 = 1156.7 \text{ cps}$$

$$b = 0.577 \frac{(1156.7 - 1142.2)}{(1148.1)}$$

$$b = 7.28 \times 10^{-3}$$

A-1-3 Dynamic Shear Modulus

The formula relating system resonant frequency and shear modulus is:

$$G = \frac{f^2 \times (2\pi)^2 L \times i_f}{I_p}$$

where

G = dynamic shear modulus, psi

f = torsional resonant frequency, cps

L = effective length of element = 49.25^2 in.

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I_f = mass moment of inertia of the fly-wheel plus one-third the mass moment of inertia of the element, in.-lb-sec²

I_p = polar moment of inertia of the element cross-section, in.⁴

Calculation for a typical 19 hole element.

Calculation was similar for 13 hole and 1 hole elements.

$$f = 41.8 \text{ cps}$$

$$L = 49.25 \text{ in.}$$

$$I_f = 0.0066 \text{ lb in./sec}^2$$

$$I_p = 0.028 \text{ in.}^4$$

$$G = \frac{(41.8)^2 \times (6.28)^2 \times (49.25) \times 0.0066}{0.028}$$

$$= 0.8 \times 10^6 \text{ psi}$$

Bluntness

The bluntness was computed using the same formula as in A-1-1, namely:

$$\text{Bluntness} = b = 0.577 \times \frac{\Delta f}{f} = 0.577 \frac{(f_2 - f_1)}{f}$$

where

f = resonant frequency = 41.80 cps

f_2 = frequency above resonance where amplitude was one-half resonant amplitude = 42.26 cps

f_1 = frequency below resonance where amplitude was one-half resonant amplitude = 41.48 cps

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$$b = 0.577 \frac{(42.26 - 41.48)}{41.80}$$

$$b = 10.7 \times 10^{-3}$$

A-1-4 Internal Damping Characteristics of Fuel Elements and Unfueled Hexagonal Elements

Logarithmic decrement is given by:

$$\delta = \frac{1}{n} \ln \frac{X_0}{X_n}$$

where

δ = logarithmic decrement

n = number of cycles from X_0 to and including X_n

X_0 = initial amplitude

X_n = n^{th} cycle amplitude

Stress level is determined by:

$$\sigma = \frac{PLC}{I}$$

where

σ = stress (lb/in.²)

P = force (lb)

L = element length (inches)

C = distance from element neutral axis to outermost fiber in direction of bending (inches)

I = moment of inertia of element cross-section (in.⁴)

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Calculation of logarithmic decrement and stress level for a 19 hole element.

Thirteen and single hole elements differed only in stress level calculations where the proper value of I was substituted.

$$n = 1$$

$$X_o = 31.2$$

$$X_n = 28.4$$

$$\delta = \frac{1}{n} \ln \frac{31.2}{28.4} = 0.095$$

$$P = 2.07 \text{ lb at } n = 0, \text{ and } 1.88 \text{ lb at } n = 1$$

$$L = 50.5 \text{ in.}$$

$$C = 0.3765 \text{ in.}$$

$$I = 0.014 \text{ in.}^4$$

$$\delta_o = \frac{2.07 \times 50.5 \times 0.3765}{0.014} = 2810 \text{ psi}$$

$$\delta_n = \frac{1.88 \times 50.5 \times 0.3765}{0.014} = 2560 \text{ psi}$$

The logarithmic decrement between 2560 psi and 2810 psi was equal to 0.095 for the element tested.

A-1-5 Tensile and Compression Test

Young's modulus is defined as:

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$$E = \frac{\sigma}{\epsilon} = \frac{P}{A}, \text{ where}$$

E = Young's Modulus, psi

σ = Element Stress, psi

ϵ = Element Strain, in./in.

P = Load on Element, lb

A = Element cross-sectional area, in.²

Poisson's Ratio is defined as:

$$\mu = \frac{\Delta_{\text{lateral}}}{\Delta_{\text{axial}}}$$

μ = Poisson's Ratio

Δ_{lat} = Change in strain in the direction perpendicular to the direction of loading, in./in.

Δ_{axial} = Change in strain in the direction of loading, in./in.

Calculation of Young's Modulus and Poisson's Ratio for a 19 hole element (Calculations were similar for 13 and single hole elements except that the proper value of area must be used).

<u>Load</u> <u>lb</u>	<u>Axial Strain</u> <u>μ in./in.</u>	<u>Lateral Strain</u> <u>μ in./in.</u>	<u>Area</u> <u>in.²</u>	<u>Stress</u> <u>psi</u>
0	0	0	0.3519	0
100	115	16	0.3519	284
200	240	30	0.3519	569
300	375	53	0.3519	853

$$E_{(100 \text{ to } 200)} = \frac{569 - 284}{(240 - 115) \times 10^{-6}} = 2.28 \times 10^6 \text{ psi}$$

$$\mu_{(100 \text{ to } 200)} = \frac{30 - 16}{240 - 115} = 0.112$$

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Young's Modulus between 284 psi and 569 psi was 2.28×10^6 psi;
Poisson's Ratio over the same range of stress was 0.112.

No signs for strain are indicated; the calculations held for both
tensile and compressive tests.

A1-6 Bending Test of the Fueled and Unfueled Hex-Element (Case of Pure
Bending)

The formula relating stress and load is:

$$\sigma = \frac{PLc}{I}$$

where:

σ = Maximum Stress, psi

P = Load from load cell, lb

L = Length of fixture moment arm = 2.125

I = Moment of Inertia of element cross-section, in.⁴

Calculations for the stress in a 19 hole element (calculations for
13 and single hole elements were similar except that the proper
value of I was substituted).

$$\sigma = \frac{100 \times 2.125 \times 0.377}{0.014} = 5,730 \text{ psi}$$

A1-7 Fatigue Strength of Fuel Element and Unfueled Hex-Element

The formula relating stress and load is:

$$\sigma = \frac{PLc}{I}$$

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Where:

σ = Maximum stress, psi

P = Load from load cell, lb

L = Length of element from clamp to point of load cell attachment, in.

c = Distance from neutral axis to intermost fiber, in.

I = Moment of inertia of element cross-section, in.⁴

Calculation for the stress in a 19 hole element (Calculations for 13 and single hole elements were similar except that the proper value of I was substituted).

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Figure 1

A-1-1 Dynamic Modulus Test Fixture

The test cables leading from the electro-mechanical shakers are attached to an oscillator, amplifier, and frequency counter on the input, and on oscilloscope and VTVM, on the output. Either shaker may be used as the input.

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Figure 2
Instrumentation
A-I Dynamic Modulus Tests

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Figure 3

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Figure 4

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Figure 6

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Figure 7

A-1-5 Compression Test Setup

The two inch specimen is placed on a flat plate balanced on spherical washers to eliminate bending. On the left side is the Wiedeman-Baldwin strain gage recorder pickup.

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Figure 8

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Figure 9
A-1-7 Fatigue Strength Test Fixture and Instrumentation

From left to right are pictured the Sanborn two channel recorder (for the load cell output and the specimen-mounted strain gage output), the eccentric motor drive and test specimen mount, and the variable DC power supply.

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Figure 10

A-1-8 Fuel Element Vibration Clearance Test Fixture

The 1200 pounds force electro-mechanical shaker with the element support fixture attached is shown in the foreground oriented properly with the "strongback". The automatic sweep control chassis is shown in the background.

Figure 11

A1-1 VARIATION OF FREQUENCY RESPONSE AND AMPLITUDE OF UNFUELED-UNCOATED, FUELED-UNCOATED, AND FUELED-COATED 13 AND 19 HOLE ELEMENTS AT AMBIENT TEMPERATURE (CONSTANT INPUT CURRENT)

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Figure 12

A1-1 VARIATION OF FREQUENCY RESPONSE OF UNFUELED-UNCOATED 13 HOLE ELEMENT WITH AND WITHOUT PYRO, STAINLESS STEEL SLEEVES, PLUGS, AND SHIM RODS AT AMBIENT TEMPERATURE

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Figure 13

A1-1 YOUNG'S MODULUS VS TEMPERATURE

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A1-2 VARIATION OF FREQUENCY RESPONSE AND AMPLITUDE OF UNFUELED-UNCOATED, FUELED-UNCOATED, AND FUELED-COATED 13 AND 19 HOLE ELEMENTS AT AMBIENT TEMPERATURE (CONSTANT INPUT CURRENT)

Figure 14

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Figure 15

A1-2 VARIATION OF FREQUENCY RESPONSE, UNFUELED-UNCOATED 13 HOLE
ELEMENT WITH AND WITHOUT PYRO, STAINLESS STEEL SLEEVES, PLUGS,
AND SHIM RODS AT AMBIENT TEMPERATURE

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Figure 16

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FUEL ELEMENT HYSTERESIS ENERGY / CYCLE VS STRESS LEVEL PRELIMINARY DATA

Figure 17

Figure 18

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Figure 19
S-N Curve for 19 hole Cheswick elements, unfueled and uncoated

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Figure 20
A-1-8 Preliminary Data

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TABLE I
10.2.1 DYNAMIC MODULUS TESTS

ELEMENT SERIAL NO.	MANF. AND DESIGNATION			FREQUENCY			LENGTH	WEIGHT	TYPE OF TEST	TEST TEMP.	Element Moment of Inertia	GENERATOR INPUT	Dynamic YOUNG'S MODULUS	BLUNTNESS (b)
				1/2 Ampl.		f _n								
	coating	fuel	Manf.	cps	cps	cps	inches	grams		°F	(inches) ⁴	amperes	psi x 10 ⁶	x 10 ⁻³
AC-09-4474	UC	UF	Ches.	32.26	32.83	32.35	52.00	550.9	A1-1	Ambient, 76°	0.014	0.01	2.60	10.16
AC-09-4476	"	"	"	32.23	32.53	32.33	"	551.0	A1-1	"	"	"	2.60	5.36
AC-09-4477	"	"	"	32.16	32.49	32.36	"	549.7	A1-1	"	"	"	2.59	5.865
AC-09-4478	"	"	"	32.37	32.70	32.47	"	550.5	A1-1	"	"	"	2.61	5.86
AC-09-4483	"	"	"	32.32	32.62	32.42	"	549.7	A1-1	"	"	"	2.60	5.315
AC-09-4484	"	"	"	32.29	32.59	32.41	"	549.7	A1-1	"	"	"	2.60	5.34
AC-09-4485	"	"	"	32.24	32.55	32.36	"	549.6	A1-1	"	"	"	2.59	5.53
AC-09-4486	"	"	"	32.30	32.62	32.42	"	549.2	A1-1	"	"	"	2.60	5.70
AC-09-4487	"	"	"	32.39	32.64	32.47	"	548.4	A1-1	"	"	"	2.60	4.43
AC-09-4488	"	"	"	32.32	32.63	32.49	"	549.6	A1-1	"	"	"	2.61	5.48
AC-09-4489	"	"	"	32.33	32.60	32.44	"	548.6	A1-1	"	"	"	2.60	4.81
AC-02-04065	"	"	"	33.66	34.0	33.8	"	464.9	A1-1	"	0.0141	"	2.40	5.80
AC-02-04353	"	"	"	33.23	33.57	33.36	"	463.5	A1-1	"	0.0141	"	2.34	5.86
AC-02-04126	"	"	"	34.06	34.26	34.14	"	464.7	A1-1	"	0.0141	"	2.45	5.88
AC-02-04180	"	"	"	33.87	34.16	33.98	"	465.4	A1-1	"	0.0141	"	2.43	4.92
AC-69-3164	"	F	"	29.82	30.27	29.95	52.0024	594.5	A1-1	"	0.0140	0.10	2.41	8.63
AC-69-3169	"	"	"	30.37	30.83	30.49	52.0023	595.5	A1-1	"	0.0140	"	2.50	8.70
AC-69-3155	"	"	"	29.77	30.24	29.87	52.0021	595.0	A1-1	"	0.0140	"	2.41	9.04
AC-69-3153	"	"	"	29.89	30.42	29.99	52.0014	593.0	A1-1	"	0.0140	"	2.43	10.20
AC-69-3158	"	"	"	29.71	30.23	29.85	52.0017	592.8	A1-1	"	0.0140	"	2.40	10.01
AC-69-3163	C	"	"	29.94	30.53	30.06	52.0057	625.02	A1-1	"	0.0140	"	2.56	11.33
AC-69-3160	"	"	"	29.75	30.29	29.91	52.0052	625.53	A1-1	"	0.0140	"	2.53	9.99
AC-69-3159	"	"	"	29.70	30.31	29.85	52.0044	624.823	A1-1	"	0.0140	"	2.52	11.80
AC-69-3161	"	"	"	29.72	30.33	29.85	52.0056	624.623	A1-1	"	0.0140	"	2.52	11.75
AC-69-3156	"	"	"	29.66	30.36	29.80	52.0053	622.523	A1-1	"	0.0140	"	2.50	13.55

TABLE I (continued)
10.2.1 DYNAMIC MODULUS TESTS

ELEMENT SERIAL NO.	MANF. AND DESIGNATION			FREQUENCY			LENGTH	WEIGHT	TYPE OF TEST	TEST TEMP.	Element Moment of Inertia	GENERATOR INPUT	Dynamic YOUNG'S MODULUS	BLUNTNESS (b)
				1/2 Ampl.		f _n								
	coating	fuel	Manf.	cps	cps	cps	inches	grams		°F	(inches) ⁴	amperes	psi x 10 ⁶	x 10 ⁻³
V1-2045	UC	UF	O.R.	29.69	30.16	29.80	52.00	571.75	A 1-1	Room, 76°F	0.014	0.150	2.29	9.1
V1-0011	"	"	"	30.46	30.93	30.59	"	573.5	"	"	"	"	2.42	8.9
V1-1914	"	"	"	29.90	30.39	30.05	"	572.1	"	"	"	"	2.33	9.3
V1-1366	"	"	"	29.77	30.20	29.87	"	572.55	"	"	"	"	2.31	8.3
V1-1388	"	"	"	29.69	30.13	29.80	"	572.15	"	"	"	"	2.29	8.5
V1-1212	"	"	"	30.49	30.94	30.59	"	572.4	"	"	"	"	2.42	8.5
V1-2348	"	"	"	30.46	30.97	30.59	"	570.5	"	"	"	"	2.41	9.6
V1-1106	"	"	"	29.45	30.03	29.64	"	561.75	"	"	"	"	2.23	11.3
V1-2278	"	"	"	29.79	30.27	29.94	"	569.8	"	"	"	"	2.31	9.2
V1-2294	"	"	"	30.27	30.76	30.39	"	569.25	"	"	"	"	2.37	9.3

TABLE II
10.2.2 DYNAMIC MODULUS TESTS

ELEMENT SERIAL NO.	MANF. AND DESIGNATION			FREQUENCY			LENGTH	WEIGHT	TYPE OF TEST	TEST TEMP.	Element Moment of Inertia	GENERATOR INPUT	Dynamic YOUNG'S MODULUS	BLUNTNESS (b)
	coating	fuel	Manf.	1/2 Ampl. cps	f_n cps	f_n cps								
							inches	grams		°F	(inches) ⁴	amperes	psi x 10 ⁶	x 10 ⁻³
AC-09-4474	UC	UF	Ches.	1151.2	1161.6	1156.4	52.00	550.9	A1-2	Ambient, 76°	0.014	0.01	2.45	5.175
AC-09-4984	"	"	"	1148.6	1160.6	1154.7	"	549.7	A1-2	"	"	"	2.43	5.875
AC-09-4486	"	"	"	1146.3	1157.6	1151.7	"	549.2	A1-2	"	"	"	2.42	5.65
AC-09-4487	"	"	"	1151.1	1162.2	1160.0	"	548.4	A1-2	"	"	"	2.45	5.53
AC-09-4488	"	"	"	1147.5	1157.2	1152.5	"	549.6	A1-2	"	"	"	2.43	4.85
AC-09-4489	"	"	"	1147.1	1157.1	1152.0	"	548.6	A1-2	"	"	"	2.42	5.00
AC-09-4509	"	"	"	1145.2	1156.7	1151.0	"	546.8	A1-2	"	"	"	2.40	5.74
AC-02-04180	"	"	"	1106.6	1122.5	1114.2	"	465.4	A1-2	"	0.0141	"	2.26	8.24
AC-02-04126	"	"	"	1106.6	1127.4	1117.5	"	464.7	A1-2	"	"	"	2.26	10.70
AC-02-04353	"	"	"	1080.5	1098.9	1090.3	"	463.5	A1-2	"	"	"	2.15	9.71
AC-02-04065	"	"	"	1097.6	1115.7	1106.4	"	464.9	A1-2	"	"	"	2.22	9.40
AC-02-04104	"	"	"	1100.4	1116.1	1107.9	"	464.2	A1-2	"	"	"	2.22	8.19
AC-02-04104	"	"	"	1146.2	1165.2	1152.6	"	582.5	A1-2	"	"	"	3.02	9.46
AC-02-04065	"	"	"			1149.5	"	583.2	A1-2	"	"	"	3.00	16.45
AC-02-04353	"	"	"	1119.7	1152.1	1135.4	"	581.8	A1-2	"	"	"	2.92	16.40
AC-02-04126	"	"	"			1155.6	"	581.0	A1-2	"	"	"	3.03	
AC-02-04180	"	"	"	1143.7	1175.2	1155.4	"	583.7	A1-2	"	"	"	3.05	15.68
AC-02-04180	"	"	"		1152.0	1052.0	"	682.4	A1-2	"	"	0.05	2.95	
AC-02-04126	"	"	"	845.0	1158.0	967.0	"	681.7	A1-2	"	"	0.15	2.48	18.61
AC-02-04180	"	"	"	742.0	1136.0	1004.0	52.0026	493.4	A1-2	"	"	0.15	1.94	22.6
AC-02-04180	"	"	"	759.0	1163.0	899.0	52.0026	681.7	A1-2	"	"	0.15	2.15	25.9
AC-02-04353	"	"	"	756.4	1140.5	898.1	52.00	680.5	A1-2	"	"	0.15	2.14	25.45

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TABLE II (continued)
10.2.2 DYNAMIC MODULUS TESTS

ELEMENT SERIAL NO.	MANF. AND DESIGNATION			FREQUENCY			LENGTH	WEIGHT	TYPE OF TEST	TEST TEMP.	Element Moment of Inertia (inches) ⁴	GENERATOR INPUT amperes	Dynamic YOUNG'S MODULUS psi x 10 ⁶	BLUNTNESS (b) x 10 ⁻³
	coating	fuel	Manf.	1/2 Ampl. cps	cps	f _n cps								
AC-69-3164	UC	F	Ches.	1079.5	1089.1	1084.1	52.0024	594.5	A1-2	Ambient, 76°	0.0140	0.10	2.39	5.09
AC-69-3169	"	"	"	1094.7	1108.7	1100.2	52.0023	595.5	A1-2	"	"	"	2.46	7.35
AC-69-3155	"	"	"	1075.4	1088.9	1080.8	52.0021	595.0	A1-2	"	"	"	2.38	7.18
AC-69-3153	"	"	"	1079.1	1088.7	1083.2	52.0014	593.0	A1-2	"	"	"	2.38	5.11
AC-69-3158	"	"	"	1073.1	1087.0	1078.4	52.0017	592.8	A1-2	"	"	"	2.36	7.41
AC-69-3163	C	"	"	1083.7	1095.0	1087.4	52.0057	625.02	A1-2	"	"	"	2.53	6.00
AC -69-3160	"	"	"	1074.4	1090.0	1080.6	52.0052	625.53	A1-2	"	"	"	2.50	8.30
AC-69-3159	"	"	"	1074.1	1089.6	1079.4	52.0044	624.823	A1-2	"	"	"	2.49	8.30
AC-69-3161	"	"	"	1076.2	1091.7	1082.0	52.0056	624.623	A1-2	"	"	"	2.50	8.23
AC-69-3156	"	"	"	1076.1	1092.7	1081.8	52.0053	622.523	A1-2	"	"	"	2.49	8.85

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TABLE II (continued)
10.2.2 DYNAMIC MODULUS TESTS

ELEMENT SERIAL NO.	MANF. AND DESIGNATION			FREQUENCY			LENGTH	WEIGHT	TYPE OF TEST	TEST TEMP.	Element Moment of Inertia ⁴	GENERATOR INPUT	Dynamic YOUNG'S MODULUS ⁵	BLUNTNESS (b)
				1/2 Ampl.		f _n								
	coating	fuel	Manf.	cps	cps	cps	inches	grams		°F	(inches) ⁴	amperes	psi x 10 ⁶	x 10 ⁻³
V1-1715	UC	UF	O.R.	1096.1	1110.1	1102.6	52.00	576.5	A 1-2	Ambient, 76°	0.014	0.15	2.40	7.32
V1-1773	"	"	"	1075.3	1089.0	1080.7	"	573.8	"	"	"	"	2.29	7.31
V1-2002	"	"	"	1068.0	1078.0	1073.4	"	569.2	"	"	"	"	2.24	5.37
V1-2006	"	"	"	1067.0	1082.1	1073.4	"	573.7	"	"	"	"	2.26	8.10
V1-2111	"	"	"	1070.2	1084.1	1075.7	"	569.2	"	"	"	"	2.25	7.45

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TABLE III
10.2.3 TENSION AND COMPRESSION TESTS

SPECIMEN NUMBER	ELEMENT TYPE				TYPE TEST	DIMENSIONS		FRACTURE LOAD	FRACTURE STRESS	YOUNG'S MODULUS *	POISSON'S RATIO **
	No. Holes	Fuel	Coating	Manf.		Area	Length				
						In. ²	In.	lbs.	psi	psi	
AC-09-4490A	19	UF	UC	Ches.	Comp.	.35	2.0	4650	13,200		
AC-09-4490B	19	"	"	"	"	"	"	4440	12,600		
AC-09-4490C	19	"	"	"	"	"	"	4715	13,400		
AC-09-4490D	19	"	"	"	"	"	"	4150	11,800		
AC-09-4490E	19	"	"	"	"	"	"	4765	14,100		
AC-09-4517A	19	"	"	"	"	"	"	3760	10,700		
AC-09-4517B	19	"	"	"	"	"	"	4805	13,700		
AC-09-4517C	19	"	"	"	"	"	"	4605	13,100		
AC-09-4517D	19	"	"	"	"	"	"	4775	13,600		
AC-09-4517E	19	"	"	"	"	"	"	4855	13,800		
AC-09-4567A	19	"	"	"	"	"	"	4735	13,500		
AC-09-4567B	19	"	"	"	"	"	"	4500	12,800		
AC-09-4567C	19	"	"	"	"	"	"	4560	13,000		
AC-09-4567D	19	"	"	"	"	"	"	4615	13,100		
AC-09-4567E	19	"	"	"	"	"	"	3825	10,900		
AC-09-1173A	1	"	"	"	"	.39	"	4350	11,150		.066
AC-09-1173B	1	"	"	"	"	"	"	4810	12,300		.137
AC-09-1173C	1	"	"	"	"	"	"	2995	***	-----	----
AC-09-1173D	1	"	"	"	"	"	"	4665	11,950		.139
AC-09-1173E	1	"	"	"	"	"	"	4800	12,300		.091

- * Initial and final values as determined from strain gage reading $\left(\mu = \frac{\epsilon_{\text{transverse}}}{\epsilon_{\text{axial}}}\right)$ were averaged.
 ** Strain gage readings taken at each loading condition were averaged.
 *** Specimens were not supported over the entire face (effective cross-sectional area was less than area indicated).

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TABLE III (continued)
 10.2.3 TENSION AND COMPRESSION TESTS

SPECIMEN NUMBER	ELEMENT TYPE				TYPE TEST	DIMENSIONS		FRACTURE LOAD	FRACTURE STRESS	YOUNG'S MODULUS *	POISSON'S RATIO **
	No.Hole	Fuel	Coating	Manf.		Area	Length				
						In. ²	In.				
VI 2111A	19	UF	UC	O. R.	Comp.	.35	2.0	*** 3060	8,600	1.26 x 10 ⁶	
VI 2111B	19	"	"	"	"	"	"	4060	11,600	1.24 x 10 ⁶	
VI 2111C	19	"	"	"	"	"	"	4165	11,900	1.19 x 10 ⁶	
VI 2111D	19	"	"	"	"	"	"	*** 3000	8,000	-----	
VI 2111E	19	"	"	"	"	"	"	3925	11,200	-----	
VI 2348A	19	"	"	"	"	"	"	3930	11,200	-----	
VI 2348B	19	"	"	"	"	"	"	3855	11,000	-----	
VI 2348C	19	"	"	"	"	"	"	3775	10,800	1.40 x 10 ⁶	
VI 2348D	19	"	"	"	"	"	"	3985	11,400	1.27 x 10 ⁶	
VI 2348E	19	"	"	"	"	"	"	4000	11,400	1.29 x 10 ⁶	
-----	19	"	"	Ches.	"	"	"	3965	11,300	1.47 x 10 ⁶	
-----	19	"	"	Ches.	"	"	"	4715	13,500	1.63 x 10 ⁶	
-----	19	"	"	Ches.	"	"	"	3840	11,000	-----	
VI 2226A	19	"	"	O. R.	"	"	"	3950	11,300	1.1 x 10 ⁶	
VI 2226B	19	"	"	O. R.	"	"	"	4250	12,000	.93 x 10 ⁶	

* Initial and final values as determined from strain gage reading $\left(\mu = \frac{\epsilon_{\text{transverse}}}{\epsilon_{\text{axial}}} \right)$ were averaged.

** Strain gage readings taken at each loading condition were averaged.

*** Specimens were not supported over the entire face (effective cross-sectional area was less than .35)

TABLE IV
10.2.4 FATIGUE TESTS

ELEMENT NUMBER	ELEMENT TYPE				TEST TEMP.	LOAD	STRAIN	NOMINAL TEST FREQ.	TOTAL CYCLES	MOMENT	STRESS (2)	ELASTIC MODULUS	TYPE OF TEST (1)
	no. hole	fuel	coating	Manf.	°F	lbs	µin./in.	cps		in.-lb	psi	psi x 10 ⁶	
AC-09-4510 A	19	UF	UC	Ches.	Ambient, 76°	24.0	3,066	23.7	0.25	216.0	5,800	1.89	A 1-7
AC-09-4510 B	"	"	"	"	"	12.2	1,420	"	*1.09 x 10 ⁶	109.8	2,872	2.02	"
AC-09-4510 C	"	"	"	"	"	10.3	2,160	"	6,920.0	146.7	3,946	1.83	"
AC-09-4510 D	"	"	"	"	"	21.15	2,440	"	*0.25	190.0	5,120	2.1	"
AC-09-4510 E	"	"	"	"	"	16.25	2,600	"	27.0	146.0	3,930	1.5	"
AC-09-4510 E	"	"	"	"	"	25.6	3,420	"	0.75	229.4	6,200	1.82	"
AC-09-4511 A	"	"	"	"	"	23.0	2,900	"	0.25	207.0	5,570	1.92	"
AC-09-4511 B	"	"	"	"	"	11.4	1,280	"	**2.0 x 10 ⁶	102.6	2,759	2.16	"
AC-09-4511 D	"	"	"	"	"	21.15	2,400	"	*0.25	190.0	5,120	2.13	"
AC-09-4511 D	"	"	"	"	"	14.6	2,720	"	192.0	131.5	3,530	1.3	"
AC-09-4511 E	"	"	"	"	"	21.1	2,740	"	7.25	189.9	5,110	1.87	"
AC-09-4518 A	"	"	"	"	"	21.5	2,635	"	0.25	193.5	5,200	1.97	"
AC-09-4518 B	"	"	"	"	"	13.4	1,600	"	**2.0 x 10 ⁶	120.6	3,244	2.03	"
AC-09-4518 C	"	"	"	"	"	17.1	2,120	"	2,070.0	153.9	4,139	1.95	"
AC-09-4518 D	"	"	"	"	"	20.3	2,440	"	*0.25	183.0	4,840	1.98	"
AC-09-4518 D	"	"	"	"	"	14.6	2,810	"	99.0	131.4	3,530	1.26	"
AC-09-4518 E	"	"	"	"	"	24.3	2,960	"	1.75	218.7	5,880	1.99	"
AC-09-4645 A	"	"	"	"	"	27.0	3,292	"	0.25	243.0	6,530	1.98	"
AC-09-4645 B	"	"	"	"	"	12.2	1,600	"	0.25	109.8	2,953	1.85	"
AC-09-4645 D	"	"	"	"	"	22.75	2,340	"	*0.25	205.0	5,510	2.36	"

(1) A 1-6, 4 pt bending; A 1-7, 3 pt bending (cantilever).

(2) Stress was calculated from $\sigma = \frac{Mc}{I}$.

* Static Tests.

** Specimen did not fail.

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TABLE IV (continued)

10.2.4 FATIGUE TEST

ELEMENT NUMBER	ELEMENT TYPE				TEST TEMP.	LOAD	STRAIN	NOMINAL TEST FREQ.	TOTAL CYCLES	MOMENT	STRESS (2)	ELASTIC MODULUS	TYPE OF TEST (1)
	no. hole	fuel	coating	Manf.	°F	lbs	μin./in.	cps		in.-lb	psi	psi x 10 ⁶	
AC-09-4561-1	19	UF	UC	Ches.	Ambient, 76°	20.0	1,856	30	1	225.0	6,050	3.26	A 1-7
AC-09-4561-2	"	"	"	"	"	15.0	2,450	"	15	156.0	4,180	1.71	"
AC-09-4561-3	"	"	"	"	"	15.0	2,528	"	2,500	154.0	4,130	1.63	"
AC-09-4561-4	"	"	"	"	"	12.0	1,873	"	1.328 x 10 ⁶	135.0	3,630	1.94 **	"
AC-09-4514-1	"	"	"	"	"	14.0	2,176	"	9	157.5	4,240	1.90	"
AC-09-4514-2	"	"	"	"	"	13.0	2,032	"	45	135.0	3,640	1.79	"
AC-09-4514-3	"	"	"	"	"	13.0	2,000	"	500	130.0	3,500	1.75	"
AC-09-4514-4	"	"	"	"	"	12.5	1,920	"	86	144.0	3,890	2.01 **	"
AC-09-4516-1	"	"	"	"	"	12.5	1,680	"	5	141.0	3,790	2.26	"
AC-09-4516-2	"	"	"	"	"	12.0	1,808	"	885	135.0	3,636	2.05	"
AC-09-4516-3	"	"	"	"	"	12.0	1,880	"	48	135.0	3,640	1.93	"
AC-09-4516-4	"	"	"	"	"	12.0	1,905	"	1.707 x 10 ⁶	135.0	3,630	1.91 **	"
AC-09-4515-1	"	"	"	"	"	12.25	1,920	"	3,000	139.0	3,750	1.95	"
AC-09-4515-2	"	"	"	"	"	12.25	1,848	"	1.903 x 10 ⁶	138.0	3,710	2.02 **	"
AC-09-4515-3	"	"	"	"	"	12.35	1,920	"	2,505	140.5	3,775	1.97	"
AC-09-4515-4	"	"	"	"	"	12.35	1,920	"	2.62 x 10 ⁶	136.0	3,660	1.91 **	"
AC-09-4554-1	"	"	"	"	"	12.40	1,780	"	2.856 x 10 ⁶	124.0	3,340	1.88	"
AC-09-4554-4	"	"	"	"	"	12.40	1,840	"	6,000	137.5	3,720	2.02	"
AC-09-4554-3	"	"	"	"	"	12.40	1,825	"	9.727 x 10 ⁶	136.0	3,670	2.07 **	"
AC-09-4554-2	"	"	"	"	"	12.50	2,250	"	5	137.0	3,700	1.64	"

(1) A 1-6, 4 pt bending; A 1-7, 3 pt bending (cantilever).
 (2) Stress was calculated from $\sigma = \frac{Mc}{I}$.
 * Static tests.
 ** Specimen did not fail.

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TABLE IV (continued)
10.2.4 FATIGUE TESTS

ELEMENT NUMBER	ELEMENT TYPE				TEST TEMP.	LOAD	STRAIN	NOMINAL TEST FREQ.	TOTAL CYCLES	MOMENT	STRESS (2)	ELASTIC MODULUS	TYPE OF TEST (1)
	no. hole	fuel	coating	Manf.	°F	lbs	μin./in.	cps		in.-lb	psi	psi x 10 ⁶	
AC-09-4645 D	19	UF	UC	Ches.	Ambient, 76°	16.25	2,760	23.7	185.0	146.0	3,930	1.42	A 1-7
AC-09-4645 E	"	"	"	"	"	24.3	2,816	"	4.5	218.7	5,880	2.09	"
AC-09-4646 A	"	"	"	"	"	19.0	2,068	"	0.25	171.0	4,600	2.23	"
AC-09-4646 B	"	"	"	"	"	13.0	1,320	"	**1.9 x 10 ⁶	117.0	3,147	2.39	"
AC-09-4646 E	"	"	"	"	"	26.0	2,960	"	3.75	234.0	6,270	2.12	"
AC-09-4552 A	"	"	"	"	"	21.0	2,685	"	0.25	189.0	5,080	1.89	"
AC-09-4552 B	"	"	"	"	"	13.0	1,520	"	82,800.0	117.0	3,147	2.07	"
AC-09-4552 C	"	"	"	"	"	16.3	2,040	"	250.0	146.7	3,946	1.94	"
AC-09-4552 D	"	"	"	"	"	18.7	2,440	"	0.75	168.0	4,520	1.86	"
AC-09-4565-1	"	"	"	"	"	15.4	1,840	3	1.0	141.5	4,000	2.17	"
AC-09-4565-2	"	"	"	"	"	16.5	1,856	"	3,552	148.5	4,000	2.155	"
AC-09-4565-3	"	"	"	"	"	20.5	2,400	"	290	172.0	4,640	1.935	"
AC-09-4565-4	"	"	"	"	"	20.25	2,400	"	240	182.0	4,920	2.05	"
AC-09-4476-1	"	"	"	"	"	17.6	1,905	"	2,662	156.0	4,200	2.20	"
AC-09-4476-2	"	"	"	"	"	14.0	1,480	"	239,745	126.0	3,390	2.29	"
AC-09-4476-3	"	"	"	"	"	15.9	1,616	"	945,832	145.0	3,900	2.42	"
AC-09-4476-4	"	"	"	"	"	16.5	1,800	"	2,357	149.5	4,020	2.23	"
AC-09-4553-4	"	"	"	"	"	16.8	1,950	"	148	151.0	4,070	2.09	"
AC-09-4553-3	"	"	"	"	"	15.6	1,640	"	87	140.0	3,780	2.30	"

(1) A 1-6, 4 pt bending, A 1-7, 3 pt bending (cantilever).
 (2) Stress was calculated from $\sigma = \frac{Mc}{I}$.
 * Static tests.
 ** Specimen did not fail.