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NONDESTRUCTIVE EXAMINATION OF 54 FUEL AND REFLECTOR ELEMENTS FROM FORT ST. VRAIN CORE SEGMENT 2

by

J. J. SAURWEIN

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Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: OCTOBER 1982

GENERAL ATOMIC COMPANY

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA. 22161

NTIS price codes
Printed copy: A10
Microfiche copy: A01

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GA-A--16829

DE83 005992

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ABSTRACT

Fifty-four fuel and reflector elements irradiated in core segment 2 of the Fort St. Vrain high-temperature gas-cooled reactor (HTGR) were nondestructively examined. The time- and volume-averaged graphite irradiation temperatures for the elements ranged from $\sim 350^{\circ}$ to 750°C . The element-averaged fast neutron fluences ranged from ~ 0.2 to $1.6 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}.

The elements, except for two fuel elements in which single localized cracks developed during irradiation, were in excellent condition. No evidence was observed of significant graphite oxidation or mechanical interaction between elements. The cracks in the two elements did not affect their performance or handling. These elements were, otherwise, in excellent condition.

Nearly all elements shrank in both the axial and radial directions, but the dimensional changes were relatively small. The maximum element-average axial and radial strains ($\Delta l/l$) were -0.369% and -0.234% , respectively. The maximum bow was 0.43 mm . Strain calculations were performed with the large HTGR (LHTGR) code SURVEY/STRESS and the results compared with measured strains. The differences between the calculated and measured strains were less than $\pm 0.2\%$, except for elements which had time-averaged irradiation temperatures less than $\sim 600^{\circ}\text{C}$. The relatively large differences (up to $\sim 0.7\%$) in the calculated and measured axial strains for these low-temperature elements can be attributed to the polynomial expression used in HTGR design codes to represent the design data for irradiation-induced dimensional change of H-327 graphite in the axial orientation. At temperatures below $\sim 600^{\circ}\text{C}$, this polynomial significantly overpredicts the axial strain.

All elements were measured for gamma dose rates. At 91.5 cm (3 ft), the gamma dose rates for the fuel elements ranged from ~50 R/h (a control column element which experienced relatively low neutron exposure) to ~500R/h (a standard element which experienced relatively high neutron exposure). The gamma dose rates for the reflector elements ranged from approximately 20 to 400 mR/h. (The gamma dose rate measurements were performed nearly a year after the elements completed irradiation.) Gamma dose rates calculated with the PATH code were compared with the measured dose rates. The dose rates were overpredicted by factors ranging from 1.3 to 2.0.

Selected elements were measured for neutron count rates. Neutron count rates calculated with the MORSE code were compared with the measured values. The count rates were underpredicted by factors ranging from 2.6 to 8.0.

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1. INTRODUCTION

Fifty-four fuel and reflector elements from Fort St. Vrain* (FSV) core segment 2** were nondestructively examined in the hot service facility (HSF) at FSV during April 1982. The elements included all 42 fuel blocks and 2 reflector blocks from region 8, 3 fuel and 3 reflector blocks from region 15, 2 fuel blocks from region 4, a side reflector block from region 25, and fuel test element FTE-1. The elements from regions 15, 4, and 25 were surveillance elements. These elements were extensively characterized prior to irradiation (Ref. 1). The nondestructive examinations included the following:

1. Visual inspections (all elements) for the following:
 - a. Cracks.
 - b. Graphite oxidation.
 - c. Any other structural damage.
 - d. Evidence of mechanical interaction between elements.
 - e. Other features of interest.
2. Dimensional measurements (all elements except two).
 - a. Across-flats dimensions.
 - b. Length.
 - c. Coolant hole diameters.
 - d. Distances between coolant holes.

*The Fort St. Vrain Nuclear Generating Station owned and operated by the Public Service Company of Colorado (PSC).

**Segment 2 completed irradiation on May 13, 1981.

- e. Distances between fiducial holes (surveillance elements and FTE-1 only).
 - f. Bow.
3. Gross gamma activity (all elements) and neutron activity (selected elements only) measurements.

Table 1-1 summarizes the surveillance of FSV core segment 2.

These examinations, except for FTE-1, were performed by General Atomic Company (GA) under the FSV Fuel Surveillance Program sponsored by the Department of Energy (DOE). Previously, 51 fuel and reflector elements from core segment 1 were nondestructively examined at FSV in July 1979 (Ref. 2). Nondestructive examinations of core components from the remaining initial core segments are planned as each is removed from the core. The nondestructive examination of FTE-1 was performed under the DOE-sponsored FSV Fuel Test Element Program and will be the subject of a separate report.

These examinations are intended to accomplish the following objectives:

1. Verify the structural integrity and dimensional stability of the graphite elements.
2. Obtain strain and bow data over ranges of irradiation temperatures and fast neutron fluences representative of those expected in a large high-temperature gas-cooled reactor (LHTGR) for comparison with LHTGR design code strain and bow calculations.
3. Obtain gamma and neutron activity data for comparison with LHTGR shielding code calculations.

TABLE 1-1
SUMMARY OF FSV SEGMENT 2 CORE SURVEILLANCE^(a)

Inspection No.	Element Serial No.	Core Location ^(b)	Element Type	Measurement Sequences ^(c)	Neutron Meas.
1	42-1009	15.05.R.10	Bottom reflector ^(d)	1L,2L,3,4L,5	
2	44-1002	15.01.F.09	Bottom reflector ^(d,e)	1L,2L,3,4L,5	
3	42-1003	15.05.R.03	Top reflector ^(d)	1L,2L,3,4L,5	
4	1-1764	15.06.F.06	Fuel ^(d)	1L,2L,3,4L,5	x
5	1-0553	15.06.F.09	Fuel ^(d)	1L,2L,3,4L,5	
6	2-2769	15.01.F.03	Fuel ^(d,e)	1L,2L,3,4L,5	
7	41-1002	25.12.R.06	Side reflector ^(d)	1L,2L,3,5	
8	8-0085	25.07.F.06	Fuel test element	1L,2L,3,4L,5	x
9	1-2820	04.04.F.06	Fuel ^(d)	1A,2A,3,4L,5	x
10	1-1787	04.04.F.09	Fuel ^(d)	1L,2L,3,4L,5	
11	1-0238	08.06.F.08	Fuel	1A,2A,3,4A	
12	1-1832	08.07.F.08	Fuel	1A,2A,3,4A	
13	2-2501	08.01.F.07	Fuel ^(e)	1A,2A,3,4A	
14	1-4361	08.02.F.08	Fuel	1A,2A,3,4A	
15	1-1421	08.03.F.08	Fuel	1A,2A,3,4A	
16	1-4834	08.04.F.08	Fuel	1A,2A,3,4A	
17	1-1742	08.05.F.08	Fuel	1A,2A,3,4A	
18	1-0172	08.05.F.07	Fuel	1A,2A,3,4A	x
19	1-0250	08.06.F.07	Fuel	1A,3	
20	1-0284	08.07.F.07	Fuel	1A,3	
21	2-1590	08.01.F.06	Fuel ^(e)	1A,2A,3,4A	
22	1-1251	08.03.F.07	Fuel	1A,2A,3	
23	1-0048	08.04.F.07	Fuel	1A,2A,3,4A	
24	1-1305	08.02.F.07	Fuel	1A,2A,3,4A	
25	1-2936	08.06.F.04	Fuel	1A,3	
26	1-1516	08.07.F.04	Fuel	1L,3	
27	2-0962	08.01.F.03	Fuel ^(e)	1A,2A,3,4A	
28	1-2650	08.02.F.04	Fuel	1A,2A,3,4A	
29	1-2423	08.03.F.04	Fuel	1L,3	
30	4-0930	08.04.F.04	Fuel	1A,2A,3	
31	1-0874	08.05.F.04	Fuel	1A,2A,3,4A	x
32	1-0811	08.05.F.09	Fuel	1A,2A,3,4A	x
33	1-0931	08.06.F.09	Fuel	1L,3	
34	1-0033	08.07.F.09	Fuel	1L,3	
35	3-1965	08.01.F.08	Fuel ^(e)	1A,2A,3,4A	
36	1-1057	08.03.F.09	Fuel	1L,3	
37	1-0143	08.04.F.09	Fuel	1A,2A,3	
38	1-1706	08.02.F.09	Fuel	1A,2A,3,4A	
39	17-1366	08.05.R.10	Bottom reflector	None	
40	18-1035	08.01.R.09	Bottom reflector ^(e)	None	
41	2-2693	08.01.F.05	Fuel ^(e)	1A,2A,3	
42	1-2415	08.05.F.06	Fuel	1A,2A,3,4A	x
43	1-0108	08.06.F.06	Fuel	1L,3	
44	1-2038	08.07.F.06	Fuel	1A,2A,3	

TABLE 1-1 (Continued)

Inspection No.	Element Serial No.	Core Location(b)	Element Type	Measurement Sequences(c)	Neutron Meas.
45	2-0518	08.01.F.04	Fuel(e)	1A,2A,3,4A	
46	1-2373	08.02.F.06	Fuel	1A,2A,3,4A	
47	1-1727	08.03.F.06	Fuel	1A,2A,3,4A	
48	1-1913	08.04.F.06	Fuel	1A,2A,3,4A	
49	1-0304	08.04.F.05	Fuel	1A,2A,3,4A	
50	1-0989	08.05.F.05	Fuel	1A,2A,3,4A	x
51	1-0727	08.06.F.05	Fuel	1A,2A,3	
52	1-2155	08.07.F.05	Fuel	1A,2A,3	
53	1-1535	08.02.F.05	Fuel	1A,2A,3	
54	1-2256	08.03.F.05	Fuel	1A,2A,3	

(a) Visual examinations and gross gamma activity measurements were performed for all elements.

(b) The core location is given as region.column.element type (F = fuel block, R = reflector block).core layer.

(c) See Subsection 4.2. A = abbreviated version of measurement sequence; L = full-length version of measurement sequence.

(d) A surveillance element.

(e) Element is a control-rod column element.

2. IRRADIATION CONDITIONS

The time- and volume-averaged graphite irradiation temperatures for the 54 segment 2 fuel and reflector elements examined in the HSF at FSV ranged from approximately 350° to 750°C. The fast neutron fluences ranged from approximately 0.2 to 1.6×10^{25} n/m² ($E > 29$ fJ)_{HTGR}. Table 4-1 gives irradiation temperatures and fast neutron fluences for the elements.

The irradiation conditions for the segment 2 elements were calculated using the following LHTGR design codes:

1. GAUGE (Ref. 3). A two-dimensional, four-group neutron diffusion and core depletion code. GAUGE treats the core as a single layer and calculates nuclide densities as a function of time and radial core location.
2. GATT (Ref. 4). A three-dimensional, four-group neutron diffusion and core depletion code. GATT calculates nuclide densities as a function of time and axial and radial core location.
3. FEVER (Ref. 5). A one-dimensional, multigroup neutron diffusion and depletion program for calculating nuclide densities as a function of axial core location.
4. BUG-2 (Ref. 6). A two-dimensional, multigroup neutron diffusion and depletion program for calculating nuclide densities as a function of axial core location for fuel assemblies influenced by partially inserted control rods.
5. SURVEY (Ref. 7). A computer program for the thermal and fuel performance analysis of high-temperature gas-cooled reactor (HTGR)

fuel elements. The code performs coarse mesh survey analyses for large numbers of spatial positions, calculating a time history of the irradiation conditions and fuel performance for each space point. SURVEY calculations are based on radial power distributions obtained from GAUGE and axial power distributions obtained from FEVER and BUG-2.

The reactor operating power is logged hourly. However, because of the numerous changes in power during cycles 1 and 2, a simulation of the actual reactor operating history would be prohibitively expensive. Consequently, the power history for cycles 1 and 2 was represented by 433 time intervals of approximately uniform power. Cycles 1 and 2 were simulated with the GAUGE code using this detailed power history. A SURVEY analysis of the segment 2 elements was then performed based on the GAUGE results. The number of time intervals was further reduced from 433 to 69 for this analysis. Figure 2-1 shows the reactor power history used for the SURVEY analysis. The time- and volume-averaged graphite irradiation temperatures for the segment 2 elements were obtained from the SURVEY code results.

In addition to the detailed GAUGE analysis, a three-dimensional burnup analysis of cycles 1 and 2 was performed using GATT. This analysis was primarily intended to obtain the fuel accountability data for the segment 1 and 2 fuel elements. Power distributions, neutron fluences, and fuel burnup were also obtained. The fast neutron fluences calculated by GATT are considered to be more accurate than those calculated by SURVEY from the GAUGE and FEVER code results. The fast neutron fluences given for the segment 2 elements in this report were obtained from the GATT code.*

*Actually, the fast fluences obtained from GATT are average fluences for burnup regions which consist of one or more elements. The fast fluences for specific locations, (ϕ_1), were calculated from burnup-region average fluences from the GATT, ($\bar{\phi}_{GATT}$), and SURVEY ($\bar{\phi}_{SURVEY}$) codes using the following equation:

$$\phi_1 = \frac{(\phi_1)_{SURVEY}}{\bar{\phi}_{SURVEY}} \times \bar{\phi}_{GATT} \quad .$$

Fig. 2-1. Fort St. Vrain reactor power history: SURVEY analysis of cycles 1 and 2

Based on the results of nuclear and thermal design verification studies performed with data from the Peach Bottom HTGR (Ref. 8), the uncertainty in the power (and fast neutron fluence) calculated for a given core location is $\sim \pm 10\%$ (1 σ). Also, the temperature uncertainty is primarily due to the uncertainty in the power. The uncertainty for a given temperature is therefore approximately 10% of the difference between the calculated temperature and the gas inlet temperature (336°C, time averaged).

3. VISUAL EXAMINATIONS

3.1. AT FORT ST. VRAIN

The 54 segment 2 fuel and reflector elements were visually examined in the hot service facility (HSF) using four remotely controlled television cameras equipped with pan-tilt units and zoom lenses. All surfaces of each element were thoroughly inspected and recorded on videotape. The sides and top of each element were photographed through the HSF window with a 35-mm camera and telephoto lens. Two photographs (top and bottom) were taken of each side face and put together to give a composite picture of the surface. Polaroid photographs were taken of the top and bottom surfaces and other features of interest on the elements. These pictures were taken off the television monitors.

The inspected elements were in good condition. Although two elements had single localized cracks, their performance and handling were not affected. Little evidence was observed of graphite oxidation or erosion. Most blemishes observed on the elements were stains, scratches, scrapes, rub marks, and flow marks. Similar blemishes were observed during the visual examinations of segment 1 fuel and reflector elements in July 1979 (Ref. 2) and during the inspection of core region 35 in March 1979 (Ref. 9).

The following subsections discuss the results of the visual examinations in more detail.

3.1.1. Cracks

Two fuel elements each had a single localized crack. The more prominent crack, observed in element 1-2415, was located in the center of the face adjacent to the single large dowel (face B or 4) and extended the

length of the element (Fig. 3-1), running parallel to and into the adjacent coolant hole (Fig. 3-2). The crack did not appear to extend further into the block but this could not be determined with certainty (see Section 3.2). The crack appeared to be widest at the bottom of the block. Element 1-2415 was irradiated in region 8, column 5, core layer 6 (the third layer of fuel elements from the top of the core). Figure 3-3 shows the core location.

The second crack was observed in fuel element 1-0172, which was located directly beneath element 1-2415 in the core. This crack was also located in the center of the face adjacent to the single large dowel and ran vertically down the element. It could not be determined whether the crack extended all the way to the bottom of the block or if it ran into the adjacent coolant hole.*

The pre-irradiation inspection reports indicate that neither element was cracked prior to insertion into the core, and there is no record of any damage having been done during handling. Therefore, these cracks are assumed to have developed during irradiation. Both cracks appear to have originated at the interface between the top and bottom surfaces of the two elements.

To better characterize the cracks and determine why they occurred, the two elements with the cracked webs and three other elements of potential interest were returned to GA for further examination. To date, visual inspections have been completed for each element. Subsection 3.2 discusses these inspections.

During the inspections of the segment 2 elements, faint markings, which had the appearance of hairline cracks, were observed on the top surfaces of many elements. These markings ran between holes (generally a coolant and a

*The crack was not identified as such during the visual inspection at FSV, but was later concluded to be a crack during a review of the videotapes and photographs for the segment 2 surveillance. For this reason, efforts were not made during the visual inspection to better characterize the crack.

Fig. 3-1. Crack in face B of fuel element 1-2415 (08.05.F.06)

Fig. 3-2. Crack at top surface of fuel element 1-2415. Crack in face B can be seen running from the edge of the block to the adjacent coolant hole.

*FUEL ELEMENT 1-2415
REGION 8, COLUMN 5, CORE LAYER 6 (ACTIVE CORE LAYER 3)

Fig. 3-3. Core location of fuel element 1-2415

fuel hole) or between a hole (coolant or fuel) and the edge of the block. To determine if these markings were cracks, fuel element 1-2373, which had several of these markings, was squirted with alcohol and observed as the alcohol dried. The alcohol test is a widely used procedure for detecting small cracks in graphite. The alcohol seeps into a crack and evaporates more slowly than the liquid on the surface. Consequently, the appearance of the crack is enhanced as the alcohol on the surface evaporates. In this instance, the appearance of the markings was not noticeably enhanced. It is therefore concluded that the markings on element 1-2373 were not cracks. Since the markings on other elements were similar in appearance to the markings observed on element 1-2373, it is also concluded that these markings were not cracks. Due to time limitations, an alcohol test could not be performed on all elements which had these markings.

3.1.2. Stains

Dark stains were observed on many side faces of the elements. Some stains were very prominent (Fig. 3-4); others were barely visible. The path of a stain could generally be traced from element to element down a column, but some stains began or ended abruptly. In many instances, the path of a stain was horizontally displaced at the top or bottom edge of the element or at the interface of the stained element and the top edge of the adjacent element which apparently leaned against it (Fig. 3-5).

Similar stains were observed on the fuel and reflector elements during the inspection of region 35 (Ref. 11). Samples of the staining material were collected by scraping the elements and subjected to gamma spectroscopic analysis. A high concentration of iron and silicon and lesser amounts of aluminum, copper, and silver were detected. The presence of iron is not surprising considering the water ingresses into the prestressed concrete reactor vessel (PCRVR) that have occurred. The silicon and aluminum are believed to have come from the Kaowool insulation used in the core. The copper apparently came from alloys used for reactor or water system components. This material was apparently carried down the elements by water,

Fig. 3-4. Face B of element 2-2693: examples of the stains observed on the sides of FSV core components

Fig. 3-5. Face B of element 2-1590: examples of horizontal displacement of stains at, or adjacent to, the top/bottom interface of two adjacent blocks

which had leaked into the core, and was left behind as a residue when the water evaporated.

3.1.3. Oxidation

Dark areas, which may have been localized graphite oxidation, were observed on the side faces of several elements (Figs. 3-6 through 3-8). Some of the more conspicuous of these areas were in close proximity to stains (Fig. 3-7). This suggests that oxidation (if that was what these dark areas were) occurred due to contamination by iron which seeped into the graphite. Iron is a catalyst for graphite oxidation.

3.1.4. Scratches

Numerous scratches were observed on the surfaces of the elements. Most scratches were insignificant, but some are notable in that they resembled, and could have been mistaken for, cracks. Side face C (or 5) of several elements, including 21 of the examined elements from core segment 1 (Ref. 2), had a straight, vertical scratch of some depth down its middle. The scratch extended nearly the entire length of the element (Fig. 3-9). Since these scratches were nearly identical in appearance and appeared only on face C, they are believed to have been made during handling, possibly from contact between the elements and a storage rack in the fuel handling machine.

Markings, such as those shown in Fig. 3-10, were common to the upper-left side of face D (or 6) of several elements. These markings looked like stains, but are thought to have been handling-induced scratches because of their similar appearance. They were not cracks.

3.1.5. Rub Marks

Light vertical bands or columns of short, horizontal markings were observed near the right and/or left edges of some side faces of several

Fig. 3-6. Possible oxidation on face C of element 2-2501

POSSIBLE
OXIDATION

Fig. 3-7. Possible oxidation on face B of element 2-2501

Fig. 3-8. Possible oxidation on face D of element 1-1913

3-13

ELEMENT 18-1035

ELEMENT 1-0172

Fig. 3-9. Reflector element 18-1035 and fuel element 1-0172: examples of scratches observed on face C of several FSV core components

Fig. 3-10. Fuel element 1-0172: example of scratches observed near the left edge of face D on several segment 2 elements

elements (Fig. 3-11). These markings are thought to be indicative of surface burnishing which resulted from the rubbing together of adjacent elements in the core.

3.1.6. Flow Marks

Dark horizontal bands, approximately 45 mm wide, were observed on nearly all faces of the control-rod elements (Fig. 3-12) and on face E (or 1) of the regular fuel elements (Fig. 3-13). Face E of the regular elements always faced the column of control-rod elements. In the FSV core, the control-rod columns are vertically offset from the surrounding columns of regular fuel elements by one-quarter of a block length. The dark bands appeared at the axial locations corresponding to the top and bottom chamfers of the adjacent fuel elements. Two chamfers are 45 mm wide, the same width as one of the dark bands.

The dark appearance of these areas is indicative of surface roughening due to graphite erosion caused by particulates in the coolant flowing through the flow paths formed by the sides of elements and the top and bottom chamfers of the adjacent elements. The horizontal displacement of stains (Subsection 3.1.2) at these block interfaces suggests that substantial coolant flowed through these flow paths. On several blocks, there were dark areas above or below the dark bands (Fig. 3-12). These are thought to have been soot deposits formed by the graphite abraded from the elements.

Other flow-related marks were observed in addition to those discussed above. Widespread soot deposits were observed (Figs. 3-14 and 3-15) on the top surfaces of the replaceable reflector blocks in columns 1 and 5 of region 8. This suggests that there were gaps between the top surfaces of these elements and the bottom surfaces of the elements above them. The resultant discontinuities in the coolant channels permitted coolant and dust transported by the coolant to leak onto the element surfaces. Smaller soot deposits were observed (Fig. 3-16) on the top surface of element 1-0811 (region 8, column 5, core layer 9).

ELEMENT 44-1002

ELEMENT 1-2423

Fig. 3-11. Machine marks or rub marks on face C of fuel element 1-2423 and face A of reflector element 44-1002

SOOT
DEPOSITS

Fig. 3-12. Flow marks and apparent soot deposits on faces E and F of control-rod fuel element 2-2769

ELEMENT 18-1035

ELEMENT 1-1421

Fig. 3-13. Flow marks on face E of fuel element 1-1421 and reflector element 18-1035

Fig. 3-14. Soot deposits on the top surface of bottom reflector element 17-1366 (08.05.R.10)

Fig. 3-15. Soot deposits on the top surface of bottom reflector element
18-1035 (08.01.R.09)

Fig. 3-16. Soot deposits on the top surface of fuel element 1-0811
(08.05.F.09)

A partial mirror image of the identification engraved into an adjacent element could be seen on a few elements (Fig. 3-17). This is also believed to be a flow-related phenomenon.

3.2. AT GENERAL ATOMIC COMPANY

As discussed in Subsection 3.1.1, the examinations of the segment 2 fuel and reflector elements in the HSF at FSV showed that two fuel elements each had a single localized crack. Although the television and still cameras used for these examinations provided good coverage and picture quality, the system had limitations (primarily inadequate lighting), which prevented full characterization of the cracks in these elements. To better characterize the observed cracks, determine why they developed, and determine if there are additional, undetected cracks in the elements, the two elements with the cracked webs and three other elements were returned to GA for further examination in the hot cell.

An element can be viewed in far more detail in the hot cell than in the HSF at FSV since it can be positioned for optimum viewing and lights can be positioned with hot cell manipulators for optimum illumination. Two Kollmorgen periscopes are available for viewing and photographing the elements at up to 10x magnification.

The three additional elements returned to GA were 1-0108 (08.06.F.06), 2-2693 (08.01.F.05), and 5-0801 (25.03.F.07). Element 1-0108 was selected for further examination because it was next to element 1-2415 in the core and had similar irradiation conditions; element 2-2693, because it was a control-rod element and had similar irradiation conditions to element 1-2415; and element 5-0801, because it was suspected to have had higher than average stresses. Only element 5-0801 was not examined at FSV.

The visual inspection of element 1-2415 revealed that the crack in face B ran to the dowel at the top of the block and into the coolant hole inside the dowel socket at the bottom of the block (Fig. 3-18). The visual

Fig. 3-17. Face E of element 1-0048 with a mirror image of the serial number engraved on the adjacent fuel element

(a)

Fig. 3-18. Top and bottom surface views of the crack in fuel element 1-2415: (a) at top surface running from side face B to the dowel (sheet 1 of 2)

(b)

(c)

Fig. 3-18. Top and bottom surface views of the crack in fuel element 1-2415: (b) at bottom surface running from face B to the dowel socket, (c) inside the dowel socket (sheet 2 of 2)

inspection of element 1-0172 revealed that the crack in face B (Fig. 3-19) extended the length of the element and also ran to the dowel at the top of the block.* At the bottom of the block, the crack ran from the edge of the surface to the adjacent coolant hole, but not to the coolant hole inside the dowel socket. No other cracks were observed in these or the other three elements, although all were thoroughly inspected. The hairline markings observed on the top surfaces of the elements during the inspections in the HSF at FSV (see Subsection 3.1.1) could not be seen during the hot cell inspections. It is concluded that these markings were irregularities in the graphite surfaces which had the appearance of hairline cracks under the particular lighting conditions in the HSF. This conclusion is consistent with the observation that the markings usually disappeared when the elements being examined were rotated, causing the surfaces on which these markings were observed to be at different angles to the cameras and the spotlights.

The locations of the cracks in elements 1-2415 and 1-0172 suggested that the cracks may have been caused by stresses resulting from an improper fit between the large dowel in element 1-0172 and the corresponding dowel socket in element 1-2415. However, a stacking test was performed, and element 1-2415 was placed on top of element 1-0172 without difficulty (Fig. 3-20). While the elements were in this stacked configuration, the clearance between the dowel and dowel socket was determined by moving element 1-2415 as far as it would go to the left, then the right, and observing the change in position of the crack in this element relative to the stationary crack in element 1-0172. A double exposure photograph recorded the relative movement (Fig. 3-21). This test indicates that the clearance was approximately 1 mm, which is about what it should be.

*The crack could be seen through the Kollmorgen, but it was so fine in this area that it cannot be clearly seen in any of the photographs that were taken.

Fig. 3-19. Crack in face B of fuel element 1-0172. The crack is widest at the top of the element and virtually disappears as it runs down the face of the element.

Fig. 3-20. Element 1-2415 stacked on top of element 1-0172. The elements fit together easily with no indication of poor fitting between the dowels and dowel sockets.

Fig. 3-21. Double exposure showing the amount of clearance between the large dowel on element 1-0172 and the corresponding dowel socket in element 1-2415. A clearance of 0.8 to 1.0 mm is indicated, which is about what it should be.

4. DIMENSIONAL MEASUREMENTS

Dimensional measurements on the segment 2 fuel and reflector elements were performed in the HSF at FSV with the GA metrology robot. The strain and bow data obtained from these measurements were compared with LHTGR design code strain and bow predictions.

4.1. DESCRIPTION OF METROLOGY ROBOT

The metrology robot (Fig. 4-1) consists of a structural frame, turntable, probe, and instrumentation. The fuel handling machine places irradiated core components on the turntable of the robot. Rotation of the turntable permits all points on the top and sides of a component to be positioned within the operating range of the probe. The probe (Fig. 4-2) moves in the $\pm x$, $\pm y$, and $\pm z$ directions (Fig. 4-3). Upon contact with the test object, the probe head undergoes a displacement which activates a microswitch and terminates probe movement. The probe head has a primary and backup microswitch for each direction of displacement ($\pm x$, $\pm y$, $\pm z$).

Programmable stepping motors power the four drive systems of the robot. Each full motor step is equivalent to 0.025-mm (0.001-in.) movement in the x and y directions, 0.032 mm (0.00125 in.) in the z direction, and 0.03-deg rotation. The coordinates of a point on the surface of an element are determined by running the probe into the element and recording the position data of the robot. Magnetic encoders (Sony Magnescales) and rotary potentiometers (backup) measure the position of the probe. Linear potentiometers and linear variable differential transformers (backup) measure the displacement of the probe head. A resolver measures the position of the turntable. A second resolver serves as a backup. Resistivity thermometers (RTD's) monitor the temperatures of robot components. An infrared thermometer measures the surface temperature of the core component.

Fig. 4-1. Metrology robot in HSF at FSV

Fig. 4-2. Side view of the metrology robot probe; the probe leg is inserted into a fiducial hole in the corner of a surveillance fuel element.

Fig. 4-3. Metrology robot coordinate system

A data logger collects the raw data from the readout devices of the robot and sends these data to the computer. The computer controls the robot and the data logger and processes the data. The robot is operated in a fully automated, closed-loop mode. The computer monitors robot operation for potential problems. When a problem is detected, the computer either corrects the problem itself or asks the operator for assistance. Reference 10 discusses the data acquisition and analysis software for the metrology robot.

4.2. MEASUREMENT SEQUENCES

The dimensional examination of an irradiated fuel or reflector element may consist of up to five types of measurements:

1. Across flats. Measure the across-flats dimensions at the top of the block only (Fig. 4-4).
2. Side face. Map the side faces of the block at up to 55 points per face (Fig. 4-5). Side face bow and across-flats dimensions along the length of the block are determined from the coordinates established for these points.
3. Top surface. Map the top surface of the block at up to 54 points (Fig. 4-6). Block lengths are determined from the z coordinates for these points and for the corresponding points on the robot's turntable.
4. Coolant hole. Measure the diameters of coolant holes at the top of the block. These measurements also locate the coordinates of the centers of the holes from which the distances between coolant holes can be determined (Fig. 4-7).
5. Fiducial hole. Locate the fiducial holes drilled in the corners of surveillance elements and test elements. The distances between

MEASUREMENTS (POINTS) 1 THROUGH 6
REPEATED WITH EACH CORNER
OF THE ELEMENT FACING THE PROBE.

FULL-LENGTH INSPECTION

MEASUREMENTS (POINTS) 1 THROUGH 4
REPEATED WITH EACH CORNER OF
THE ELEMENT FACING THE PROBE.

(ALL DIMENSIONS IN INCHES)

ABBREVIATED INSPECTION

Fig. 4-4. Across-flats measurements of FSV core components

Fig. 4-6. Top surface measurements of FSV core components (sheet 1 of 2)

(b) CONTROL-ROD FUEL ELEMENT; FULL-LENGTH
AND ABBREVIATED INSPECTIONS

Fig. 4-6. Top surface measurements of FSV core components (sheet 2 of 2)

FULL LENGTH INSPECTION – REGULAR FUEL ELEMENT

NOTE: COOLANT HOLES 66, 81, 103, 112, 144, 145, 180, 181, 213, 222, 244, AND 259 OMITTED FOR ABBREVIATED INSPECTION OF REGULAR FUEL ELEMENT. COOLANT HOLES 312, 270, 219, 181, 199, 235, 180, 216, 264, 303, 319, 295, 267, 13, 106, 144, 145, 109, AND 22 MEASURED FOR CONTROL-ROD ELEMENTS.

Fig. 4-7. Coolant hole measurements of FSV core components

fiducial holes are determined from the z coordinates of these holes (Fig. 4-8).

As shown in Figs. 4-4 through 4-8, the measurement sequences may vary for different types of elements. Also, the top-surface, side-face, and coolant-hole measurements have both full-length and abbreviated versions. The full-length versions are used for elements which have been extensively characterized prior to irradiation (i.e., surveillance and test elements). The abbreviated versions are generally used for all other elements. A full-length inspection of a surveillance fuel element requires approximately 4-1/2 h. An abbreviated inspection of a regular fuel element requires approximately 3 h.

Measurement sequences 2 and/or 4 were not performed for several segment 2 elements to save time. This deviation from normal procedure was necessary because the surveillance task had to be completed earlier than originally scheduled so that a test of a reserve shutdown system unit required by the Nuclear Regulatory Commission (NRC) could begin in the HSF. Table 1-1 identifies the measurement sequences performed for each segment 2 element.

4.3. METROLOGY ROBOT CALIBRATION

The metrology robot was calibrated in accordance with Ref. 11 and accepted by Quality Assurance for shipment to FSV (Ref. 12). Appendix A discusses the metrology robot calibration and presents the detailed calibration data.

4.4. MEASURED STRAIN AND BOW

The axial and radial dimensions of nearly all of the 47 examined H-327 graphite fuel elements shrank as a result of irradiation. Two elements expanded slightly in the radial direction (i.e., across flats). The maximum element-average decreases in length and across-flats dimensions measured for segment 2 fuel elements were 2.92 mm (0.115 in.) and 0.94 mm (0.037 in.), respectively. The maximum observed bow (see Fig. 4-9) was 0.43 mm (0.017

Fig. 4-8. Fiducial hole measurements of FSV core components

Fig. 4-9. Bow of FSV core components. Bow is defined as the displacement of the side face relative to a straight line connecting the top and bottom (below and above the chamfers) of the side face

in.). The examined reflector elements underwent very little dimensional change (less than ± 0.15 mm). Tables 4-1 and 4-2 list the element-averaged axial and radial strains and the maximum bow measured for each segment 2 element.

The surveillance of each initial core segment is intended to include the inspection of a complete core region. For segment 2, region 8 was examined since it was identified as having had a large power tilt and, consequently, greater-than-average stresses. Figure 4-10 shows the axial strain and bow distributions measured for region 8 fuel elements. The intra-element and intra-region temperature and fluence gradients shown in Fig. 4-10 are the result of control rods which were fully inserted in region 19 and partially or fully inserted in region 20 during cycle 1 and fully inserted in region 8 during cycle 2. The axial strain follows the same pattern as the fast neutron fluences. The bow in the elements corresponds to the axial strain. The sides with lower (less negative) axial strains were convex, and the opposite sides were concave. For a given element, faces A and D, B and E, and C and F were bowed approximately the same amount, but in opposite directions. Figure 4-11 shows the radial strain distribution in region 8. Figures 4-12 and 4-13 show the axial strain, radial strain, and bow distributions in the remaining segment 2 fuel elements.

The fast neutron doses received by the segment 2 elements [$<1.6 \times 10^{25}$ n/m² (E < 29 fJ)_{HTGR}] were far less than the lifetime doses that would be received by most fuel elements in an LHTGR. At these low fluences, the strains were relatively small. Figures 4-14 and 4-15 provide some perspective as to how the segment 2 (and segment 1) strain data compare to the range of potential strains in LHTGR fuel elements.*

*Some liberty has been taken in plotting the measured strains ($\Delta l/l$) on the design curves for irradiation-induced dimensional change in Figs. 4-14 and 4-15. The measured strains include the creep strain and elastic strain as well as the irradiation-induced strain. However, the creep strain and elastic strain for these elements were small, so the measured strain is approximately equal to the irradiation-induced strain (at room temperature).

TABLE 4-1
RESULTS OF DIMENSIONAL INSPECTIONS OF FSV SEGMENT 2 CORE COMPONENTS, AXIAL STRAIN AND BOW

Element Serial No.	Core Location	Irradiation Conditions ^(a)		Axial Strain ^(b) (%)				Bow (mm)		Calculated Stresses ^(c)	
		Temperature (°C)	Fast Fluence ($\times 10^{25}$ n/m ²)	Measured		Calculated ^(d) (E_z) _c	Difference (E_z) _c - (E_z) _m	Measured	Calculated ^(e)	Max Stress (MPa)	Max Stress- Mean Strength Ratio
				(E_z) _m	$\pm 1\sigma$						
2-0962	08.01.F.03	428	0.79	-0.152	0.010	-0.786	-0.634	0.18	0.01	3.33	0.12
1-2650	08.02.F.04	422	0.76	-0.161	0.014	-0.845	-0.684	0.15	0.41	3.08	0.10
1-2423	08.03.F.04	424	0.78	-0.150	0.006	-0.850	-0.700	NM ^(f)	0.37	3.30	0.12
4-0930	08.04.F.04	444	0.87	-0.193	0.014	-0.851	-0.658	0.30	0.36	3.22	0.12
1-0874	08.05.F.04	460	0.94	-0.230	0.010	-0.831	-0.601	0.36	0.21	2.52	0.09
1-2936	08.06.F.04	457	0.86	-0.204	0.010	-0.847	-0.643	NM	0.33	3.01	0.11
1-1516	08.07.F.04	432	0.78	-0.168	0.006	-0.854	-0.686	NM	0.45	2.78	0.10
2-0518	08.01.F.04	495	1.07	-0.220	0.010	-0.612	-0.392	0.23	0.17	3.19	0.12
1-1535	08.02.F.05	489	1.17	-0.278	0.014	-0.697	-0.419	0.23	0.44	2.85	0.10
1-2256	08.03.F.05	494	1.19	-0.276	0.018	-0.680	-0.404	0.20	0.40	3.39	0.12
1-0304	08.04.F.05	529	1.33	-0.336	0.010	-0.591	-0.255	0.38	0.28	3.32	0.12
1-0989	08.05.F.05	560	1.45	-0.369	0.010	-0.503	-0.134	0.40	0.22	2.42	0.09
1-0727	08.06.F.05	536	1.32	-0.336	0.010	-0.572	-0.236	0.38	0.33	3.15	0.11
1-2155	08.07.F.05	506	1.21	-0.309	0.010	-0.656	-0.347	0.30	0.38	2.83	0.10
2-2693	08.01.F.05	559	1.07	-0.191	0.014	-0.387	-0.196	0.18	0.21	2.41	0.12
1-2373	08.02.F.06	552	1.24	-0.242	0.010	-0.452	-0.210	0.20	0.39	2.67	0.10
1-1727	08.03.F.06	558	1.25	-0.252	0.010	-0.426	-0.174	0.15	0.36	3.08	0.11
1-1913	08.04.F.06	608	1.41	-0.238	0.027	-0.322	-0.084	0.25	0.25	2.80	0.10
1-2415	08.05.F.06	653	1.55	-0.337	0.027	-0.247	0.090	0.43	0.18	2.31	0.09
1-0108	08.06.F.06	619	1.43	-0.327	0.027	-0.305	0.022	NM	0.29	2.83	0.11
1-2038	08.07.F.06	576	1.32	-0.264	0.003	-0.398	-0.134	0.28	0.30	2.55	0.09
2-1590	08.01.F.06	587	0.85	-0.098	0.010	-0.246	-0.148	0.05	0.17	1.91	0.10
1-1305	08.02.F.07	583	1.02	-0.150	0.010	-0.277	-0.127	0.08	0.28	2.10	0.08
1-1251	08.03.F.07	591	1.03	-0.114	0.010	-0.255	-0.141	0.10	0.26	2.35	0.09
1-0048	08.04.F.07	649	1.18	-0.166	0.006	-0.176	-0.010	0.23	0.17	1.91	0.07
1-0172	08.05.F.07	700	1.28	-0.163	0.010	-0.133	0.030	0.28	0.08	1.90	0.08
1-0250	08.06.F.07	660	1.20	-0.155	0.010	-0.166	-0.011	NM	0.19	2.44	0.09

TABLE 4-1 (Continued)

Element Serial No.	Core Location	Irradiation Conditions(a)		Axial Strain(b)(%)				Bow (mm)		Calculated Stresses(c)	
		Temperature (°C)	Fast Fluence (x 10 ²⁵ n/m ²)	Measured		Calculated(d) (E _z) _c	Difference (E _z) _c - (E _z) _m	Measured	Calculated(e)	Max Stress (MPa)	Max Stress- Mean Strength Ratio
				(E _z) _m	±1σ						
1-0284	08.07.F.07	609	1.10	-0.146	0.010	-0.263	-0.117	NM	0.19	1.99	0.08
2-2501	08.01.F.07	613	0.62	-0.042	0.010	-0.162	-0.120	0.05	0.12	1.71	0.10
1-4361	08.02.F.08	612	0.75	-0.056	0.010	-0.172	-0.116	0.05	0.20	1.81	0.07
1-1421	08.03.F.08	621	0.76	-0.063	0.014	-0.154	-0.091	0.05	0.18	1.79	0.07
1-4834	08.04.F.08	685	0.89	-0.080	0.010	-0.099	-0.019	0.18	0.10	1.76	0.07
1-1742	08.05.F.08	743	0.97	-0.097	0.006	-0.084	0.013	0.20	0.01	2.20	0.09
1-0238	08.06.F.08	698	0.91	-0.081	0.010	-0.095	-0.014	0.18	0.10	2.36	0.10
1-1832	08.07.F.08	641	0.83	-0.054	0.006	-0.139	-0.085	0.13	0.12	1.99	0.08
3-1965	08.01.F.08	627	0.35	0.002	0.014	-0.103	-0.105	0.03	0.08	1.54	0.09
1-1706	08.02.F.09	627	0.44	-0.018	0.006	-0.103	-0.085	0.08	0.12	1.72	0.07
1-1057	08.03.F.09	636	0.45	-0.006	0.010	-0.090	-0.084	NM	0.11	1.64	0.08
1-0143	08.04.F.09	704	0.53	-0.023	0.006	-0.054	-0.031	0.08	0.06	2.27	0.10
1-0811	08.05.F.09	765	0.57	-0.047	0.018	-0.048	-0.001	0.08	0.01	2.20	0.09
1-0931	08.06.F.09	716	0.53	-0.037	0.010	-0.054	-0.017	NM	0.06	2.87	0.13
1-0033	08.07.F.09	658	0.49	-0.020	0.010	-0.080	-0.060	NM	0.07	1.79	0.07
1-0553	15.06.F.09	660	0.54	-0.034	0.010	-0.085	-0.051	0.08	0.07	1.62	0.06
1-1764	15.06.F.06	569	1.40	-0.279	0.010	-0.412	-0.133	0.25	0.06	2.66	0.10
1-2820	04.04.F.06	585	1.53	-0.357	0.010	-0.426	-0.069	0.30	0.57	2.41	0.09
1-1787	04.04.F.09	669	0.61	-0.019	0.010	-0.082	-0.063	0.05	0.18	1.00	0.04
2-2769	15.01.F.03	411	0.70	-0.136	0.010	-0.783	-0.647	0.05	0.03	3.35	0.11
42-1009	15.05.R.10	NC(g)	NC	0.028	0.011	NC	--	0.03	NC	NC	NC
44-1002	15.01.R.09	NC	NC	0.019	0.019	NC	--	0.03	NC	NC	NC
42-1003	15.05.R.03	NC	NC	-0.013	0.019	NC	--	0.05	NC	NC	NC
41-1002	25.12.R.06	NC	NC	-0.003	0.010	NC	--	0.13	NC	NC	NC

(a) Temperatures were obtained from SURVEY code calculations based on the GAUGE code depletion analysis of FSV cycles 1 and 2. Fast neutron fluences were obtained from the GATT code depletion analysis of cycles 1 and 2. Temperatures are time and volume averaged. The temperature uncertainty (1σ) is estimated by 10% of the difference between the temperature and the gas-inlet temperature (~335°C, time averaged). The fast neutron fluences (E > 29 fJ)HTGR are volume averaged. The uncertainty in the fast fluence is ±10% (1σ).

(b) Axial strains are element averages.

(c) Calculated stresses and stress-to-strength ratios were obtained from SURVEY/STRESS.

(d) The axial strains were obtained by subtracting the thermal strain at 177°C (350°F) (0.027 x 10⁻² mm/mm) from the end-of-life shutdown strain calculated by SURVEY/STRESS for axial point 3, the element midplane.

(e) Bow calculated at the element midplane by SURVEY/STRESS.

(f) NM = not measured.

(g) NC = not calculated.

TABLE 4-2
RESULTS OF DIMENSIONAL INSPECTIONS OF FSV SEGMENT 2 CORE COMPONENTS, RADIAL STRAIN

Element Serial No.	Core Location	Irradiation Conditions ^(a)		Radial Strain ^(b) (%)			
		Temperature (°C)	Fast Fluence ($\times 10^{25}$ n/m ²)	Measured		Calculated ^(c) (E_x) _c	Difference (E_x) _c - (E_x) _m
				(E_x) _m	$\pm \sigma$		
2-0962	08.01.F.03	405	0.50	-0.049	0.022	0.032	0.081
1-2650	08.02.F.04	404	0.39	-0.045	0.027	0.028	0.073
1-2423	08.03.F.04	402	0.39	-0.049	NC ^(d)	0.029	0.078
4-0930	08.04.F.04	416	0.44	-0.061	0.019	0.027	0.088
1-0874	08.05.F.04	429	0.46	-0.039	0.017	0.025	0.064
1-2936	08.06.F.04	421	0.43	-0.065	NC	0.027	0.092
1-1516	08.07.F.04	413	0.40	-0.070	NC	0.028	0.098
2-0518	08.01.F.04	459	0.98	-0.160	0.029	-0.006	0.154
1-1535	08.02.F.05	452	1.04	-0.182	0.019	-0.001	0.181
1-2256	08.03.F.05	456	1.06	-0.171	0.031	-0.005	0.166
1-0304	08.04.F.05	483	1.18	-0.191	0.012	-0.033	0.158
1-0989	08.05.F.05	505	1.28	-0.234	0.017	-0.054	0.180
1-0727	08.06.F.05	488	1.17	-0.216	0.022	-0.036	0.180
1-2155	08.07.F.05	466	1.07	-0.171	0.022	-0.014	0.157
2-2693	08.01.F.05	528	1.10	-0.152	0.019	-0.057	0.095
1-2373	08.02.F.06	517	1.25	-0.186	0.019	-0.055	0.131
1-1727	08.03.F.06	526	1.27	-0.220	0.022	-0.060	0.160
1-1913	08.04.F.06	569	1.43	-0.233	0.024	-0.104	0.129
1-2415	08.05.F.06	607	1.56	-0.257	0.027	-0.139	0.118
1-0108	08.06.F.06	578	1.44	-0.233	NC	-0.107	0.126
1-2038	08.07.F.06	542	1.32	-0.230	0.024	-0.075	0.155
2-1590	08.01.F.06	568	0.95	-0.067	0.017	-0.065	0.002
1-1305	08.02.F.07	562	1.16	-0.128	0.019	-0.066	0.062
1-1251	08.03.F.07	569	1.16	-0.122	NC	-0.072	0.050
1-0048	08.04.F.07	622	1.33	-0.140	0.018	-0.118	0.022
1-0172	08.05.F.07	668	1.45	-0.089	0.019	-0.156	-0.067
1-0250	08.06.F.07	633	1.36	-0.112	NC	-0.121	-0.009
1-0284	08.07.F.07	586	1.25	-0.134	NC	-0.086	0.048
2-2501	08.01.F.07	603	0.72	-0.028	0.031	-0.061	-0.033
1-4361	08.02.F.08	601	0.86	-0.040	0.022	-0.062	-0.022
1-1421	08.03.F.08	609	0.87	-0.025	0.027	-0.067	-0.042

TABLE 4-2 (Continued)

Element Serial No.	Core Location	Irradiation Conditions ^(a)		Radial Strain ^(b) (%)			
		Temperature (°C)	Fast Fluence ($\times 10^{25}$ n/m ²)	Measured (E_x) _m	$\pm 1\sigma$	Calculated ^(c) (E_x) _c	Difference (E_x) _c - (E_x) _m
1-4834	08.04.F.08	671	1.02	-0.035	0.014	-0.109	-0.074
1-1742	08.05.F.08	727	1.11	-0.025	0.024	-0.145	-0.120
1-0238	08.06.F.08	683	1.05	-0.038	0.019	-0.112	-0.074
1-1832	08.07.F.08	629	0.95	-0.036	0.021	-0.079	-0.043
3-1965	08.01.F.08	620	0.48	-0.015	0.025	-0.047	-0.032
1-1706	08.02.F.09	620	0.61	-0.016	0.018	-0.051	-0.035
1-1057	08.03.F.09	630	0.60	-0.002	NC	-0.055	-0.053
1-0143	08.04.F.09	696	0.71	-0.023	0.040	-0.089	-0.066
1-0811	08.05.F.09	756	0.76	-0.002	0.027	-0.119	-0.117
1-0931	08.06.F.09	708	0.71	-0.033	NC	-0.091	-0.058
1-0033	08.07.F.09	651	0.66	-0.007	NC	-0.064	-0.057
1-0553	15.06.F.09	652	0.72	0.003	0.022	-0.071	-0.074
1-1764	15.06.F.06	533	1.40	-0.245	0.012	-0.068	0.177
1-2820	04.04.F.06	548	1.53	-0.264	0.027	-0.109	0.155
1-1787	04.04.F.09	663	0.81	-0.046	0.030	-0.082	-0.036
2-2769	15.01.F.03	394	0.47	-0.040	0.043	0.035	0.075
42-1009	15.05.R.10	NC	NC	0.028	0.024	NC	--
44-1002	15.01.R.09	NC	NC	0.003	0.025	NC	--
42-1003	15.05.R.03	NC	NC	-0.010	0.024	NC	--
41-1002	25.12.R.06	NC	NC	0.011	0.019	NC	--

(a) Temperatures were obtained from SURVEY code calculations based on the GAUGE code depletion analysis of FSV cycles 1 and 2. They are time- and volume-averaged temperatures for axial point 1, the top of the block. The temperature uncertainty (1σ) is estimated by 10% of the difference between the temperature and the gas-inlet temperature ($\sim 335^\circ\text{C}$, time averaged). Fast neutron fluences ($E > 29$ fJ)_{HTGR} were obtained from the GATT code depletion analysis of cycles 1 and 2 and are element-averaged fluences at the top of the blocks. The uncertainty in the fast fluence is $\pm 10\%$ (1σ).

(b) Radial strains are element-averaged strains at the tops of the elements.

(c) The radial strains were obtained by subtracting the thermal strain at 177°C (350°F) (0.056×10^{-2} mm/mm) from the end-of-life shutdown strain calculated by SURVEY/STRESS for axial point 1, the top of the element.

(d) NC = not calculated.

Fig. 4-10. Axial strain distribution and side face bow in FSV core region 8
(sheet 1 of 6)

(b) CORE LAYER 5 (ACTIVE CORE LAYER 2)

Fig. 4-10. Axial strain distribution and side face bow in FSV core region 8 (sheet 2 of 6)

(c) CORE LAYER 6 (ACTIVE CORE LAYER 3)

Fig. 4-10. Axial strain distribution and side face bow in FSV core region 8 (sheet 3 of 6)

(d) CORE LAYER 7 (ACTIVE CORE LAYER 4)

Fig. 4-10. Axial strain distribution and side face bow in FSV core region 8 (sheet 4 of 6)

(e) CORE LAYER 8 (ACTIVE CORE LAYER 5)

Fig. 4-10. Axial strain distribution and side face bow in FSV core region 8 (sheet 5 of 6)

COLUMN						
1	2	3	4	5	6	7
405 0.50 -0.049	404 0.39 -0.045	402 0.39 -0.049	416 0.44 -0.061	429 0.46 -0.039	421 0.43 -0.065	413 0.40 -0.070
428 0.79 -0.095	422 0.76 -0.106	N.M.*	444 0.87 -0.145	460 0.94 -0.145	N.M.	N.M.
459 0.98 -0.112	452 1.04 -0.135	N.M.	483 1.18 -0.175	505 1.28 -0.177	N.M.	N.M.
459 0.98 -0.160	489 1.17 -0.212	494 1.19 -0.196	529 1.33 -0.225	560 1.45 -0.260	536 1.32 -0.250	506 1.21 -0.207
495 1.07 -0.152	517 1.25 -0.177	526 1.27 -0.160	569 1.43 -0.173	607 1.56 -0.185	578 1.44 -0.182	542 1.32 -0.168
528 1.10 -0.099	517 1.25 -0.186	526 1.27 -0.220	569 1.43 -0.233	607 1.56 -0.257	578 1.44 -0.233	542 1.32 -0.230
528 1.10 -0.152	552 1.24 -0.130	558 1.25 -0.167	608 1.41 -0.148	653 1.55 -0.204	N.M.	576 1.32 -0.178
559 1.07 -0.095	583 1.16 -0.031	590 1.16 -0.074	648 1.33 -0.051	700 1.45 -0.109	N.M.	610 1.25 -0.081
590 0.95 -0.028	562 1.16 -0.128	569 1.16 -0.122	622 1.33 -0.140	668 1.45 -0.089	633 1.36 -0.112	586 1.25 -0.134
568 0.95 -0.067	583 1.02 -0.075	591 1.03 -0.058	649 1.18 -0.089	700 1.28 -0.056	N.M.	N.M.
587 0.85 -0.028	601 0.86 -0.020	609 0.87 -0.010	671 1.02 -0.039	727 1.11 -0.032	N.M.	N.M.
603 0.72 0.004	601 0.86 -0.040	609 0.87 -0.025	671 1.02 -0.035	727 1.11 -0.025	683 1.05 -0.038	629 0.95 -0.036
603 0.72 -0.028	612 0.75 -0.019	621 0.76 -0.008	685 0.89 -0.025	743 0.97 -0.012	698 0.91 -0.045	641 0.83 -0.021
613 0.62 -0.023	620 0.61 -0.003	630 0.60 0.011	696 0.71 -0.001	756 0.76 0.009	708 0.71 -0.041	651 0.66 -0.001
620 0.48 -0.030	620 0.61 -0.016	630 0.60 -0.002	696 0.71 -0.023	756 0.76 -0.002	708 0.71 -0.033	651 0.66 -0.007
620 0.48 -0.015	627 0.44 -0.017	N.M.	704 0.53 -0.005	765 0.57 0.029	N.M.	N.M.
627 0.35 0.015	637 0.23 0.007	N.M.	717 0.27 0.012	779 0.29 0.062	N.M.	N.M.
639 0.19 0.046	*NOT MEASURED					

NOTE: TIME-AVERAGED TEMPERATURES ($^{\circ}\text{C}$), FAST NEUTRON FLUENCES ($\times 10^{25} \text{ N/M}^2$, $E > 29 \text{ kJ/TGR}$), AND RADIAL STRAINS (%) ARE GIVEN AT THE TOP, MIDDLE, AND BOTTOM OF EACH ELEMENT. THE RADIAL STRAINS ARE THE AVERAGE STRAINS ACROSS FLATS.

Fig. 4-11. Radial strain distribution in FSV core region 8

Fig. 4-12. Axial strain distribution and side face bow for FSV segment 2 surveillance fuel elements

Fig. 4-13. Radial strain distribution for FSV segment 2 surveillance fuel elements

Fig. 4-14. Envelope of axial strains observed in FSV segment 1 and segment 2 fuel elements

Fig. 4-15. Envelope of radial strains observed in FSV segment 1 and segment 2 fuel elements

4.5. COMPARISONS OF MEASURED AND CALCULATED STRAINS AND BOW

Tables 4-1 and 4-2 compare the strain and bow predictions obtained using the SURVEY/STRESS (Ref. 13) code with the corresponding measurements. SURVEY/STRESS calculates stresses, strains, and bow in an LHTGR fuel block using viscoelastic beam theory. This code is one of three computer codes currently employed by GA to calculate stresses in LHTGR fuel blocks. It is the simplest and most efficient of the three and is used to survey the entire core to identify potentially critical elements. Once identified, these elements are subjected to more refined analyses using the GBEAM (Ref. 14) and TWOD (Ref. 15) codes. Since SURVEY/STRESS accounts for all important physical effects and structural interactions, the results obtained from the code should correlate reasonably well with results from the more refined analyses.

Figures 4-16 and 4-17 show the differences between calculated and measured element-average strains for the segment 2 elements versus fast neutron fluence. The figures also show the differences between calculated and measured strains for the segment 1 elements (Ref. 2). The results of these strain comparisons are given below:

1. Axial strain.
 - a. For the fuel elements having time- and volume-averaged irradiation temperatures greater than $\sim 600^{\circ}\text{C}$, the calculated and measured strains were within ± 0.001 mm/mm. The agreement between calculated and measured strains for these elements did not appear to be dependent on temperature or fluence.
 - b. The calculated strains were consistently high for fuel elements having time- and volume-averaged irradiation temperatures less than $\sim 600^{\circ}\text{C}$. Within a given range of irradiation temperatures, the disagreement between the calculated and measured strains for these elements increased

Fig. 4-16. Differences in calculated and measured axial strains for FSV segment 1 and segment 2 fuel elements

Fig. 4-17. Differences in calculated and measured radial strains for FSV segment 1 and segment 2 fuel elements

as the fast neutron exposure increased. For a given fast neutron fluence, the disagreement increased as the irradiation temperature decreased.

2. Radial strain.

- a. The agreement between calculated and measured strains was within ± 0.002 mm/mm for all elements.
- b. The calculated strains were generally underpredicted for fuel elements having time- and volume-averaged irradiation temperatures less than 600°C and overpredicted for elements with temperatures greater than 600°C .
- c. The agreement between the calculated and measured strains varied little with fast neutron fluence.

The dimensional changes in fuel elements 1-2415 (08.05.F.06) and 1-0172 (08.05.F.07) are of particular interest since both elements had cracked webs (see Section 3). Table 4-3 compares the measured and calculated strain distributions for these elements. The axial and radial strain gradients calculated by SURVEY/STRESS were smaller than the measured gradients and were, for the most part, in the opposite direction. The resultant error in the calculated stresses was not evaluated.

As discussed previously in Ref. 2, the relatively large differences (up to $\sim 0.7\%$) in the calculated and measured axial strains in elements with time-averaged temperatures less than $\sim 600^{\circ}\text{C}$ can be attributed to the polynomial expression used in HTGR design codes to represent the design data for irradiation-induced dimensional change of H-327 graphite in the axial orientation. At irradiation temperatures below $\sim 650^{\circ}\text{C}$, this polynomial exaggerates the rate at which the graphite shrinks with fast neutron exposure. As the irradiation temperature decreases from 650° to 400°C , the rate of shrinkage is increasingly exaggerated. As a result, SURVEY/STRESS

TABLE 4-3
DETAILED COMPARISONS OF CALCULATED AND MEASURED STRAINS FOR
FSV SEGMENT 2 FUEL ELEMENTS 1-2415 (08.05.F.06) AND 1-0172 (08.05.F.07)

Parameter	Fuel Element 1-2415 (08.05.F.06)				Fuel Element 1-0172 (08.05.F.07)			
	Strain (%)		Irradiation Temperature (°C)	Fast Fluence (x 10 ²⁵ n/m ²)	Strain (%)		Irradiation Temperature (°C)	Fast Fluence (x 10 ²⁵ n/m ²)
	Calculated	Measured			Calculated	Measured		
Element-averaged axial strain	-0.247	-0.337	653	1.55	-0.133	-0.163	700	1.28
Axial strain distribution								
Local point 1	-0.229	-0.334	657	1.56	-0.117	-0.156	707	1.26
Local point 2	-0.304	-0.267	599	1.26	-0.170	-0.112	641	1.02
Local point 3	-0.312	-0.269	596	1.26	-0.177	-0.106	637	1.02
Local point 4	-0.272	-0.351	647	1.65	-0.142	-0.176	695	1.33
Local point 5	-0.260	-0.411	690	1.89	-0.157	-0.230	744	1.52
Local point 6	-0.236	-0.399	707	1.86	-0.153	-0.214	765	1.50
Local point 7	-0.240	-0.334	662	1.62	-0.126	-0.154	713	1.31
Across-block strain differences								
Face A - Face D ^(a)	0.006	-0.157	ΔT = 37	ΔF = 0.31	-0.007	-0.088	ΔT = 43	ΔF = 0.24
Face B - Face E ^(b)	0.060	-0.177	ΔT = 102	ΔF = 0.59	0.018	-0.143	ΔT = 116	ΔF = 0.46
Face C - Face F ^(c)	0.054	-0.079	ΔT = 63	ΔF = 0.27	0.019	-0.054	ΔT = 73	ΔF = 0.21
Element-averaged radial strain	-0.159	-0.190	653	1.55	-0.149	-0.058	700	1.28
Radial strain distribution								
Top of block	-0.139	-0.257	607	1.55	-0.155	-0.089	668	1.45
Middle of block	-0.162	-0.204	653	1.57	-0.149	-0.056	703	1.27
Bottom of block	-0.170	-0.109	700	1.46	-0.146	-0.032	727	1.16
Top-to-bottom strain difference								
Bottom - Top	-0.031	0.148	ΔT = 93	ΔF = -0.09	0.009	0.057	ΔT = 59	ΔF = -0.29
Bow	0.18mm (d)	0.43mm (e)	--	--	0.08mm (d)	0.28mm (e)	--	--

- (a) Calculated: Face A = average of local points 4 and 5.
Face D = average of local points 2 and 7.
Measured: average of five measurement points adjacent to faces A and D.
(b) Calculated: Face B = average of local points 5 and 6.
Face E = average of local points 2 and 3.
Measured: average of five measurement points adjacent to faces B and E.
(c) Calculated: Face C = average of local points 6 and 7.
Face F = average of local points 3 and 4.
Measured: average of five measurement points adjacent to faces C and F.
(d) Calculated bow from coupled block calculations for SURVEY/STRESS axial point 3.
(e) Maximum measured bow.

overpredicts the axial strains and strain gradients in low-temperature elements. This explains why the stresses calculated with SURVEY/STRESS for the segment 2 elements (see Table 4-1) were highest for the top two layers of fuel elements. These stresses are not believed to be representative of the actual stresses in these elements.

5. GAMMA AND NEUTRON ACTIVITY MEASUREMENTS

5.1. GAMMA DOSE RATES

Gamma dose rates at 91.5 cm (3 ft) were measured for each of the segment 2 elements with a Reuter-Stokes, Model RS-C4-1606-203, gamma ionization chamber. The ionization chamber has a sensitivity of 1.2×10^{-10} A/R/h and linearity of output current over a gamma flux range of 10^{-2} to 10^4 R/h. Figure 5-1 shows the geometry for the gamma dose rate measurements. Table 5-1 lists the measured dose rates.

Gamma dose rates at 91.5 cm (3 ft) from the elements were calculated using the PATH code (Ref. 16) and compared with the measured dose rates (Table 5-2). The calculated dose rates were consistently higher by a factor of 1.3 to 2.0 than the measured dose rates. Appendix B describes the calculations.

5.2. NEUTRON COUNT RATES

Neutron count rates for selected segment 2 fuel elements were measured using a SNOOPY-type detector system equipped with a Reuter-Stokes, Model RS-P6-0805-134, fission counter. The fission counter was used instead of a BF_3 detector because of the high gamma activity of the elements. The fission counter is much less sensitive to gamma radiation than a BF_3 detector. This is the same detector system as was previously used to measure neutron dose rates for Peach Bottom fuel test element FTE-6 (Ref. 17). Figure 5-2 shows the geometry for the neutron count rate measurements.

Neutron count rate calculations were performed with the Monte Carlo code MORSE (Ref. 18). Table 5-3 compares the results with the measured count rates. The calculated count rates were lower than the measured count

Fig. 5-1. Geometry for gamma dose rate measurements

TABLE 5-1
GAMMA DOSE RATE MEASUREMENTS FOR FSV SEGMENT 2 CORE COMPONENTS^(a)

Element Serial No.	Core Location	Gross γ Activity (R/h) at 91.5 cm (3 ft)						Average
		Face E ^(b)	Face F	Face A	Face B	Face C	Face D	
42-1009	15.05.R.10	0.022	NM ^(c)	NM	NM	NM	NM	--
44-1002 ^(d)	15.01.R.09	2.7	6.0	9.3	12.2	8.7	5.7	7.4
42-1003	15.05.R.03	0.075	NM	NM	NM	NM	NM	--
01-1764	15.06.F.06	500	NM	NM	NM	NM	NM	--
01-0553	15.06.F.09	NM	NM	196	NM	188	NM	--
02-2769	15.01.F.03	150	150	NM	NM	NM	NM	--
41-1002	25.12.R.06	0.375	NM	NM	NM	NM	NM	--
01-2820	04.04.F.06	NM	541	517	517	NM	NM	--
01-1787	04.04.F.09	217	213	205	200	200	210	208
01-0238	08.06.F.08	NM	275	NM	300	NM	NM	--
01-1832	08.07.F.08	221	232	246	247	238	227	235
02-2501	08.01.F.07	93	98	112	125	112	100	107
01-4361	08.02.F.08	212	217	221	219	217	212	216
01-1421	08.03.F.08	211	212	221	228	228	219	220
01-4834	08.04.F.08	250	250	250	250	267	250	253
01-1742	08.05.F.08	267	267	292	308	292	267	282
01-0172	08.05.F.07	350	375	400	417	392	375	385
01-0250	08.06.F.07	300	333	358	358	NM	317	~333
01-0284	08.07.F.07	283	283	292	292	292	275	286
02-1590	08.01.F.06	133	142	158	178	158	142	152
01-1251	08.03.F.07	283	283	300	308	308	300	297
01-0048	08.04.F.07	333	333	354	379	383	354	356
01-1305	08.02.F.07	296	300	304	300	300	296	299
01-2936	08.06.F.04	217	229	238	238	225	217	227
01-1516	08.07.F.04	200	200	213	215	208	200	206
02-0962	08.01.F.03	110	117	130	145	131	117	125
01-2650	08.02.F.04	191	192	192	192	192	192	192
01-2423	08.03.F.04	182	183	185	185	187	185	185
04-0930	08.04.F.04	208	206	217	231	236	225	220
01-0874	08.05.F.04	233	247	267	275	267	250	256
01-0811	08.05.F.09	164	169	183	192	188	173	178
01-0931	08.06.F.09	148	160	172	173	163	151	161
01-0033	08.07.F.09	129	133	142	140	135	129	135
03-1965	08.01.F.08	41	42	48	53	48	42	46
01-1057	08.03.F.09	117	119	129	133	132	125	126
01-0143	08.04.F.09	142	142	151	167	167	152	154
01-1706	08.02.F.09	127	129	133	133	132	129	130
17-1366	08.05.R.10	0.014	0.014	0.014	0.014	0.013	0.013	0.014
18-1035	08.01.R.09	0.018	0.020	0.021	0.020	0.019	0.018	0.019

TABLE 5-1 (Continued)

Element Serial No.	Core Location	Gross γ Activity (R/h) at 91.5 cm (3 ft)						
		Face E ^(b)	Face F	Face A	Face B	Face C	Face D	Average
02-2693	08.01.F.05	170	180	202	222	203	181	193
01-2415	08.05.F.06	425	438	471	488	479	446	458
01-0108	08.06.F.06	375	400	433	425	400	375	401
01-2038	08.07.F.06	333	342	365	367	354	333	349
02-0518	08.01.F.04	150	152	NM	200	179	158	~170
01-2373	08.02.F.06	325	333	338	338	333	329	333
01-1727	08.03.F.06	325	325	333	342	342	333	333
01-1913	08.04.F.06	375	371	400	429	433	404	402
01-0304	08.04.F.05	342	342	358	383	387	375	364
01-0989	08.05.F.05	383	396	421	433	425	400	410
01-0727	08.06.F.05	333	358	379	379	354	338	357
01-2155	08.07.F.05	300	312	325	325	317	304	314
01-1535	08.02.F.05	300	304	308	308	304	300	304
01-2256	08.03.F.05	300	302	302	308	308	NM	~304

(a) All measurements were performed in April 1982. The elements completed irradiation on May 13, 1981.

(b) Side of element facing the detector (see Fig. 5-1).

(c) NM = not measured.

(d) Element 44-1002 contained four neutron-absorber rods. These rods consisted of boronated graphite pellets encased in capped Hastelloy X tubes. The Hastelloy tubes were responsible for the high gamma dose rates measured for this bottom reflector element. Neutron-absorber rods are located in the permanent bottom reflector blocks and provide the thermal neutron barrier for the bottom of the core. Four of these rods are being irradiated in each of three replaceable bottom reflector blocks to accelerate the neutron exposure and permit the effects of high boron burnup on the structural integrity of the graphite matrix to be studied.

TABLE 5-2
COMPARISONS OF CALCULATED AND MEASURED GAMMA DOSE RATES
FOR FSV SEGMENT 2 FUEL ELEMENTS

Element Serial No.	Core Location	Gamma Dose (R/h)		Calculated/Measured
		Calculated ^(a)	Measured	
1-0048	08.04.F.07	558	356	1.6
1-0172	08.05.F.07	556	385	1.4
1-0250	08.06.F.07	512	333	1.5
1-0284	08.07.F.07	512	286	1.8
1-0874	08.05.F.04	459	256	1.8
1-1251	08.03.F.07	445	297	1.5
1-1305	08.02.F.07	443	299	1.5
1-1421	08.03.F.08	323	220	1.5
1-1516	08.07.F.04	415	206	2.0
1-1742	08.05.F.08	413	282	1.5
1-1787	04.04.F.09	311	208	1.5
1-1832	08.07.F.08	382	235	1.6
1-2423	08.03.F.04	375	185	2.0
1-2650	08.02.F.04	380	192	2.0
1-2936	08.06.F.04	413	227	1.8
1-4361	08.02.F.08	326	216	1.5
1-4834	08.04.F.08	418	253	1.7
2-0962	08.01.F.03	247	125	2.0
2-1590	08.01.F.06	236	152	1.6
2-2501	08.01.F.07	136	107	1.3
4-0930	08.04.F.04	454	220	2.0
1-0033	08.07.F.09	240	135	1.8
1-0108	08.06.F.06	645	401	1.6
1-0143	08.04.F.09	264	154	1.7
1-0304	08.04.F.05	651	364	1.8
1-0727	08.06.F.05	589	357	1.6
1-0931	08.06.F.09	242	161	1.5
1-0989	08.05.F.05	647	410	1.6
1-1057	08.03.F.09	208	126	1.7
1-1535	08.02.F.05	538	304	1.8
1-1706	08.02.F.09	207	130	1.6
1-1727	08.03.F.06	567	333	1.7
1-2038	08.07.F.06	645	349	1.8
1-2155	08.07.F.05	590	314	1.9
1-2256	08.03.F.05	538	304	1.8
1-2373	08.02.F.06	561	333	1.7
1-2415	08.05.F.06	697	458	1.5
2-0518	08.01.F.04	314	170	1.8
2-2693	08.01.F.05	315	193	1.6
3-1965	08.01.F.08	78	46	1.7
Av				1.65

(a) Calculations were performed with the PATH code. See Appendix B for details.

THE NEUTRON DETECTOR
WAS APPROXIMATELY $\perp$
TO THE FACE OF THE
ELEMENT

THE NEUTRON DETECTOR WAS
ALIGNED WITH THE MIDPOINT
OF THE FUEL ELEMENT.

Fig. 5-2. Geometry for neutron count rate measurements

TABLE 5-3
COMPARISONS OF CALCULATED AND MEASURED NEUTRON COUNT
RATES FOR FSV SEGMENT 2 FUEL ELEMENTS

Element Serial No.	Core Location	FIMA (%)	Counts per Second			
			$\pm 1\sigma$ (a)		Calculated (b)	Meas./Calc
			Measured	(%)		
1-0172	08.05.F.07	8.3	0.00753	13	0.0027	2.80
1-0811	08.05.F.09	4.8	0.00280	22	0.00035	8.00
1-0874	08.05.F.04	6.1	0.00277	22	0.00098	2.85
1-0989	08.05.F.05	7.8	0.01023	11	0.0027	3.80
1-1764	15.06.F.06	7.8	0.00761	12	0.0026	2.90
1-2415	08.05.F.06	8.4	0.01235	8	0.0035	3.50
1-2820	04.04.F.06	8.9	0.01087	12	0.0042	2.60

(a) 1σ error approximated by $\sqrt{1/\text{counts}}$.

(b) Calculations were performed with the MORSE code. See Appendix B for details.

rates by factors ranging from 2.6 to 8.0. If the worst case of 8.0 is omitted, the average ratio of measured versus calculated count rates is approximately 3. In an earlier comparison of measured and calculated neutron dose rates for Peach Bottom test element FTE-6 (Ref. 17), this ratio was approximately 2. Appendix B describes the neutron dose calculations.

6. SUMMARY AND CONCLUSIONS

Fifty-four fuel and reflector elements from FSV core segment 2 were nondestructively examined in the HSF at FSV during April 1982. These examinations were performed by GA as part of the DOE-sponsored surveillance program for FSV. The time- and volume-averaged graphite irradiation temperatures and volume-averaged fast neutron fluences for the elements ranged from approximately 350° to 750°C and from 0.2 to 1.6×10^{25} n/m², respectively. The examinations were intended to verify the structural integrity and dimensional stability of the elements and to obtain dimensional change data and gamma and neutron dose rates to verify HTGR design code calculations.

During the examinations at FSV, a single localized crack was observed in each of two fuel elements. These elements and three others were returned to GA for further examination to better characterize the cracks and determine why they developed. To date, all five elements have been visually examined.

The results and conclusions of the nondestructive examinations are summarized below.

6.1. CORE COMPONENT PERFORMANCE

The inspected elements were in good condition. Two elements had single localized cracks, but the cracks did not affect their performance. No other cracks were observed. There was little evidence of graphite oxidation or mechanical interaction between elements.

Fuel elements 1-2415 (08.05.F.06) and 1-0172 (08.05.F.07) each had a crack running down the center of the side face adjacent to the single large dowel. (See Subsections 3.1.1 and 3.2 for a detailed description of the

cracks.) It must be assumed that these cracks developed during irradiation since the pre-irradiation inspection reports verify that the elements were not cracked prior to insertion into the core and no record exists of unusual occurrences during handling. The crack in element 1-2415, which was located directly above element 1-0172 in the core, appeared to have originated at the bottom of the block (where the crack was the widest). The crack in element 1-0172 clearly originated at the top of the block. Because of their apparent origins and because the crack in element 1-0172 ran to the single large dowel and the crack in element 1-2415 ran into the corresponding dowel socket, it was speculated that the cracks may have been caused by stresses resulting from an improper fit between this dowel and dowel socket. However, the clearance between the dowel and dowel socket was checked and found to be adequate, and a stacking test demonstrated that element 1-2415 could be stacked on top of element 1-0172 without difficulty.

Of all the examined elements, element 1-2415 had the highest fast neutron exposure and the most bow. It also had close to the highest element-averaged axial and radial strains and intra-block strain gradients. However, several elements had fast neutron fluences, strains, strain gradients, and bow that were similar to those in element 1-2415 and substantially higher than those in element 1-0172. Also, elements 1-2415 and 1-0172 were apparently not weak blocks. The tensile strengths of samples from the graphite logs from which the elements were machined were higher than the average tensile strength for all such samples from the logs from which all the inspected elements were machined.

It is not currently known why these cracks developed.

The axial and radial dimensions of nearly all the inspected H-327 graphite fuel elements shrank as a result of irradiation, but the dimensional changes were relatively small. The maximum element-average axial and radial strains ($\Delta l/l$) were -0.369% and -0.234%, respectively. The maximum bow was 0.43 mm. The reflector elements underwent very little dimensional change (less than ± 0.15 mm). The dimensional changes and bow measured in

the segment 2 elements were reasonably close to, or less than, the calculated dimensional changes and bow.

6.2. CODE VERIFICATION

Strain calculations were performed with the LHTGR design code SURVEY/STRESS and the results compared with measured strains. The differences between the calculated and measured strains were less than $\pm 0.2\%$, except for elements which had time-averaged irradiation temperatures less than approximately 600°C . The relatively large differences (up to $\sim 0.7\%$) in the calculated and measured axial strains for these elements can be attributed to the polynomial expression used in HTGR design codes to represent the design data for irradiation-induced dimensional change of H-327 graphite in the axial orientation. At irradiation temperatures below $\sim 650^{\circ}\text{C}$, this polynomial exaggerates the rate at which the graphite shrinks with fast neutron exposure. As the irradiation temperature decreases from 650° to 400°C , the rate of shrinkage is increasingly exaggerated. As a result, SURVEY/STRESS overpredicts the axial strains, strain gradients, and bow (and consequently the stresses) in low-temperature elements.

In elements such as 1-2415 and 1-0172 (the two elements with cracked webs) in which local time-averaged temperatures were both below and above 650°C , SURVEY/STRESS underpredicted, and generally reversed, the axial strain gradients and bow. This can again be attributed to the polynomial expression identified in the above paragraph. If this polynomial is corrected or a better method of representing the design data is developed, stresses in the FSV elements can be more accurately calculated.

Gamma dose rates were calculated with the gamma shielding code PATH and compared with measured dose rates. At 91.5 cm (3 ft), the gamma dose rates for the fuel elements ranged from ~ 50 R/h (a control column element which experienced relatively low neutron exposure) to 500 R/h (a standard element

which experienced relatively high neutron exposure).^{*} The dose rates calculated with the PATH code were 1.3 to 2.0 times greater than the measured dose rates. These results are considered to be quite good for gamma dose rate calculations. Gamma dose rates were also measured for the inspected reflector elements. At 91.5 cm (3 ft), these varied from 20 to 400 mR/h.^{*} No attempt was made to calculate the dose rates for these elements.

Neutron count rates were calculated with the neutron Monte Carlo transport code MORSE and compared with measured count rates. The count rates were underpredicted by factors ranging from 2.6 to 8.0. If the worst case of 8.0 is omitted, these factors average about 3.0. The poor agreement can be attributed to one or more of the following:

1. Uncertainty in the source term. The source term could be significantly in error due to uncertainties in the epithermal flux and source conversion factors.
2. Measurement uncertainties. The estimated measurement uncertainties range from 8% to 22%.
3. Statistical uncertainty of the MORSE calculations. Due to the high thermal absorption cross section of the attenuator, relatively few of the neutrons thermalized in the SNOOPY moderator end up in the fission counter. Consequently, the statistical uncertainty is high ($1\sigma \approx 50\%$).

The uncertainty in the source term is apparently the only uncertainty which could account for the large discrepancies between the calculated and measured neutron count rates. Therefore, an analysis should be performed to determine the sensitivity of the source term to changes in the epithermal flux.

^{*}All gamma dose rate measurements were performed in April 1982. The elements completed irradiation on May 13, 1981.

7. ACKNOWLEDGMENTS

The author wishes to acknowledge the following individuals who contributed to this project:

Preparation and Pre-irradiation Characterization of Surveillance Elements:

W. W. Hudritsch, W. J. Scheffel, and O. M. Stansfield

Metrology Robot Development:

C. F. Wallroth, T. L. Smith, N. I. Marsh, J. P. Smith, and R. Acotte
(Simpact Associates)

Examination of Core Components at FSV:

N. I. Marsh, F. McCord, C. M. Miller, F. C. Montgomery, W. J. Scheffel, J. P. Smith, and T. L. Smith. Also, the following employees of PSC: L. Bishard, T. Schuyler, and crews (fuel handling); C. Fuller, F. Novachek, and J. Eggebroten (technical services); and W. Woodard and staff (health physics).

Data Reduction:

F. McCord

Nuclear, Thermal, and Strain Calculations:

S. C. Bachelor and F. McCord

Gamma and Neutron Dose Rate Calculations:

M. Y. Wan

Calibration of Instruments for Gamma and Neutron Dose Rate Measurements:

R. G. Bamford and J. R. Shoptaugh, Jr.

Visual Examinations in the GA Hot Cell:

J. Ketterer, W. J. Scheffel, and H. O. Johnson and staff

Interpretation of Photographs:

L. A. Beaven

Quality Assurance:

G. P. Connors

Editing:

E. R. Bolen

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APPENDIX A
METROLOGY ROBOT CALIBRATION

Eight full-length inspections of calibration element 8-0182* were performed prior to shipping the metrology robot to FSV for the surveillance of core segment 2. The accuracies of the robot measurements were determined and found to satisfy the accuracy requirements specified in Ref. 11 (Table A-1). The results were reviewed and approved by Quality Assurance (QA). Quality Assurance approval of these results constituted QA acceptance of the metrology robot for shipment to FSV.

Three more inspections of calibration element 8-0182 were performed at FSV prior to the inspection of the first irradiated element. The results for these inspections (Table A-1) demonstrated that the quality of the robot measurements had not deteriorated after shipping and established the measurement biases to be used in processing the robot measurement data into fuel or reflector block dimensions. The robot calibration procedure (Ref. 11) specifies that a final inspection of calibration element 8-0182 be performed after the last irradiated element of a surveillance campaign has been examined, but this inspection had to be forgone when the HSF had to be vacated earlier than originally scheduled. However, during each inspection of an irradiated element, repeated measurements were made on a precisely machined 25.4-mm (1.000-in.) cube mounted on the robot to check the repeatability of robot measurements. The results (Table A-2) indicate that the quality of the robot measurements remained acceptable throughout the element examinations.

*Element 8-0182 is a fully-machined graphite fuel element on which quality control measurements, corresponding to those performed on irradiated core components by the metrology robot, have been performed using calibrated measurement equipment traceable to the National Bureau of Standards. Quality Assurance has certified element 8-0182 as a special calibration standard for the metrology robot.

TABLE A-1
SUMMARY OF METROLOGY ROBOT MEASUREMENT ACCURACY, CALIBRATION FOR FSV SEGMENT 2 SURVEILLANCE (IN.)^(a)

Type of Measurement	Required Accuracy $\pm \sigma$	Calibration Inspections at GA ^(b)												Calibration Inspections at FSV ^(b)					
		Sony Magnescales and Linear Potentiometers ^(c)						Rotary Potentiometers and Linear Variable Differential Transformers ^(c)						Rotary Potentiometers and Linear Variable Differential Transformers ^(c)					
		Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual	Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual	Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual	Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual	Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual	Run No.	Accuracy $\pm \sigma$	Bias Meas. - Actual
Across-flats dimensions	0.003	9	0.003	-0.004	4	0.003	-0.004	3	0.002	-0.004	7	0.002	-0.003	FSV1	0.002	-0.005	FSV2	0.002	-0.010
		10	0.003	-0.003	5	0.003	-0.001	6	0.002	-0.003	8	0.002	-0.005	FSV3	0.003	-0.003	--	--	--
		Av	0.003	-0.004	Av	0.003	-0.002	Av	0.002	-0.003	Av	0.002	-0.004	Av	0.003	-0.004	Av	0.002	-0.010
Side-face bow	0.001	9	0.001	0	4	0.001	0	3	0.001	0	7	0.001	0	FSV1	0.001	0	FSV2	0.001	0
		10	0	0	5	0.001	0	6	0.001	0	8	0.001	0	FSV3	--	--	--	--	--
		Av	0.001	0	Av	0.001	0	Av	0.001	0	Av	0.001	0	Av	0.001	0	Av	0.001	0
Element lengths	0.005	9	0.003	-0.005	4	0.003	-0.004	3	0.005	0.001	7	0.006	-0.001	FSV1	0.003	-0.009	FSV2	0.003	-0.010
		10	0.002	-0.003	5	0.004	-0.004	6	0.006	-0.003	8	0.006	-0.001	FSV3	0.003	-0.009	--	--	--
		Av	0.002	-0.004	Av	0.003	-0.004	Av	0.006	-0.001	Av	0.006	-0.001	Av	0.003	-0.009	Av	0.003	-0.010
Distances between coolant holes	0.004	9	0.004	-0.004	4	0.004	-0.004	3	0.002	-0.006	7	0.004	-0.008	FSV1	0.002	-0.006	FSV2	0.005	-0.012
		10	0.004	-0.003	5	0.006	-0.001	6	0.003	-0.008	8	0.004	-0.008	FSV3	0.001	-0.004	--	--	--
		Av	0.004	-0.004	Av	0.005	-0.003	Av	0.003	-0.007	Av	0.004	-0.008	Av	0.002	-0.005	Av	0.005	-0.012
Coolant hole diameters	0.002	9	0.001	0.004	4	0.001	0.003	3	0.002	0.007	7	0.002	0.007	FSV1	0.001	0.006	FSV2	0.001	0.010
		10	0.001	0.002	5	0.001	0.001	6	0.002	0.008	7	0.002	0.007	FSV3	0.001	0.004	--	--	--
		Av	0.001	0.003	Av	0.002	0.002	Av	0.002	0.007	Av	0.002	0.007	Av	0.001	0.005	Av	0.001	0.010
Distances between fiducial holes	±0.005	9	0.004	-0.001	4	0.003	-0.001	3	0.003	-0.001	7	0.005	0	FSV1	0.003	-0.002	FSV2	0.003	-0.001
		10	0.005	-0.001	5	0.004	0.001	6	0.004	-0.002	8	0.004	0	FSV3	0.004	-0.001	--	--	--
		Av	0.004	-0.001	Av	0.004	0	Av	0.003	-0.001	Av	0.004	0	Av	0.004	-0.002	Av	0.003	-0.001

(a) All values listed in this table are in inches (1 in. = 25.4 mm).

(b) Inspections performed on calibration element 8-0182.

(c) Instrumentation used to record the position and head displacement of the probe:

	Probe position	Probe-head displacement
Primary	Sony Magnescales	Linear potentiometers
Backup	Rotary potentiometers	Linear variable differential transformers

(d) Measurement biases used in processing robot measurement data for the segment 2 core components into fuel or reflector block dimensions.

TABLE A-2
ON-LINE CALIBRATION DATA DEMONSTRATING THE REPEATABILITY
OF METROLOGY ROBOT MEASUREMENTS FOR FSV SEGMENT 2 SURVEILLANCE

Inspection No.	Measurement of Calibration Cube Dimensions						Measurement of Calibration Cube Coordinates(a) $\pm 1\sigma$ (10^{-3} in.)				
	Δx with z probe leg			Δy with z probe leg			x/z	y/z	z/z	y/y	z/y
	$\Delta x(b)$ (in.)	$\pm 1\sigma$ (10^{-3} in.)	$\Delta x - \Delta x_c(c)$ (10^{-3} in.)	$\Delta y(b)$ (in.)	$\pm 1\sigma$ (10^{-3} in.)	$\Delta y - \Delta y_c(c)$ (10^{-3} in.)					
Calibration(d)	0.996	2	--	0.991	1	--	1	1	2	1	1
1	0.993	1	-3	0.989	1	-2	1	1	1	0	1
2	0.993	1	-3	0.989	0	-2	1	1	2	1	1
3	0.993	1	-3	0.989	1	-2	1	0	2	1	2
4	0.993	1	-3	0.990	1	-1	1	1	2	1	1
5	0.994	2	-2	0.990	1	-1	1	1	2	0	1
6	0.992	1	-4	0.989	1	-2	1	1	2	1	1
7	0.996	2	0	0.990	1	-1	2	1	2	0	1
8	0.993	1	-3	0.988	0	-3	5	5	2	5	2
9	0.996	2	0	0.990	1	-1	1	1	2	1	2
10	0.994	1	-2	0.991	1	0	1	1	2	1	1
11	0.995	2	-1	0.990	1	-1	1	1	2	1	1
12	0.994	1	-2	0.991	0	0	0	1	1	1	1
13	0.995	1	-1	0.990	1	-1	1	1	2	0	1
14	0.994	2	-2	0.990	1	-1	1	1	2	1	1
15	0.996	2	0	0.990	0	-1	1	1	3	1	1
16	0.996	1	0	0.989	0	-2	1	1	2	1	2
17	0.991	3	-5	0.989	1	-2	2	0	1	1	1
18	0.993	2	-3	0.990	1	-1	1	1	2	1	1
19	0.992	4	-4	0.991	1	0	3	0	2	0	1
20	0.994	1	-2	0.989	1	-2	1	1	2	1	1
21	0.995	1	-1	0.990	1	-1	1	1	2	1	1
22	0.995	1	-1	0.990	1	-1	1	1	2	0	2
23	0.994	1	-2	0.989	1	-2	1	1	1	1	1
24	0.996	2	0	0.990	0	-1	1	1	2	0	0
25	0.996	1	0	0.989	0	-2	2	0	2	0	2
26	0.994	1	-2	0.989	1	-2	1	0	1	1	1
27	0.994	2	-2	0.990	1	-1	1	1	2	1	1

TABLE A-2 (Continued)

Inspection No.	Measurement of Calibration Cube Dimensions						Measurement of Calibration Cube Coordinates ^(a) ±1σ (10 ⁻³ in.)				
	Δx with z probe leg			Δy with z probe leg			x/z	x/z	z/z	y/y	z/y
	Δx(b) (in.)	±1σ (10 ⁻³ in.)	Δx - Δx _c (c) (10 ⁻³ in.)	Δy(b) (in.)	±1σ (10 ⁻³ in.)	Δy - Δy _c (c) (10 ⁻³ in.)					
28	0.994	2	-2	0.991	1	0	1	1	3	0	2
29	0.994	1	-2	0.991	1	0	1	0	1	0	2
30	0.995	2	-1	0.989	1	-2	1	1	3	0	0
31	0.995	1	-1	0.990	1	-1	1	0	2	1	1
32	0.995	2	-1	0.989	1	-2	1	1	4	0	1
33	0.994	1	-2	0.991	0	0	0	0	2	0	1
34	0.995	0	-1	0.990	0	-1	0	1	2	1	0
35	0.996	1	0	0.990	1	0	1	1	3	0	0
36	0.996	1	0	0.991	1	0	1	0	2	0	2
37	0.996	1	0	0.991	1	0	1	1	1	1	2
38	0.996	1	0	0.992	0	1	1	1	1	0	1
41 ^(d)	0.995	1	-1	0.991	0	0	1	0	3	1	2
42	0.996	2	0	0.991	1	0	1	0	2	0	2
43	0.996	1	0	0.991	0	0	0	1	2	1	2
44	0.996	1	0	0.991	1	0	1	1	0	1	1
45	0.996	2	0	0.991	0	0	1	1	2	1	1
46	0.996	1	0	0.991	1	0	1	0	2	0	1
47	0.996	2	0	0.991	0	0	1	1	2	1	1
48	0.995	1	-1	0.991	1	0	1	1	2	0	0
49	0.996	1	0	0.991	1	0	1	1	2	1	2
50	0.999	1	3	0.992	0	1	1	0	2	1	2
51	0.998	2	2	0.992	1	1	1	1	2	1	1
52	0.998	1	2	0.991	0	0	1	0	2	0	1
53	0.997	2	1	0.991	0	0	1	1	3	0	1
54	0.997	1	1	0.991	1	0	1	1	4	1	1
Av			-1			-1					
1σ			±2			±1					

(a) Coordinate/probe leg. For example, x/z = x coordinate of cube with z probe leg.

(b) The calibration cube dimensions for each inspection have been corrected for differences in the probe deflection data used in the inspection and the probe deflection data used for the calibration inspections.

(c) The calibration cube measurements for each inspection are compared with the cube measurements for the calibration inspections to ascertain the validity of measurement biases determined from the calibration inspections and used in the data reduction of all inspections.

(d) Average for z inspections.

Tables A-3 through A-67 give detailed results for the inspections of calibration element 8-0182.

TABLE A-3
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Rotary potentiometers
 Probe displacement: Linear potentiometers
 Recalibration run: Run 3, 3/11/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.171	14.171	14.172		
	Robot - QC	-0.004	-0.005	-0.003	-0.004	±0.001
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.172	14.170	14.172		
	Robot - QC	-0.004	-0.006	-0.004	-0.005	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.171	14.172	14.174		
	Robot - QC	-0.004	-0.002	0	-0.002	±0.002
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.170	14.172	14.171		
	Robot - QC	-0.004	-0.002	-0.003	-0.003	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.169	14.173	14.173		
	Robot - QC	-0.007	-0.003	-0.003	-0.004	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.172	14.173	14.170		
	Robot - QC	-0.004	-0.003	-0.006	-0.004	±0.002
Robot - QC						
Mean		-0.004	-0.004	-0.003	-0.004	
SD		±0.001	±0.002	±0.002	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-4
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:

Rotary potentiometers

Probe displacement:

Linear potentiometers

Recalibration run:

Run 3, 3/11/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	-0.001	-0.001	0.001	-0.001	0	0	0	±0.001
3	-0.001	-0.001	0	0	-0.001	0	-0.001	±0.001
4	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	0
5	-0.001	-0.001	-0.001	0	-0.001	0	-0.001	±0.001
6	-0.001	-0.001	0	0	-0.001	0	-0.001	±0.001
7	0	-0.001	0	-0.001	-0.001	0	-0.001	±0.001
8	0	0	0	0	-0.001	0	0	0
9	0.001	0	0	0	0	0	0	0
10	0	0	0	0.001	0	0.001	0	±0.001
Mean	0	-0.001	0	0	-0.001	0	0	--
SD	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-5
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0812 (IN.)

Instrumentation			
Probe table position:		Rotary potentiometers	
Probe displacement:		Linear potentiometers	
Recalibration run:		Run 3, 3/11/82	
Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.004
2	321-322	31.223	-0.002
3	S-319	31.223	0
4	316-317	31.223	0.004
5	C-314	31.223	0.003
6	275-289	31.223	0.008
7	293-294	31.222	0.009
8	296-297	31.222	0.003
9	288-301	31.223	-0.003
10	S-259	31.222	-0.006
11	257-272	31.222	0.001
12	237-254	31.223	-0.004
13	251-252	31.222	0.004
14	233-249	31.222	0.008
15	246-262	31.222	0.011
16	S-244	31.222	0.005
17	190-209	31.223	0.004
18	192-211	31.222	0.009
19	195-214	31.222	0.006
20	203-221	31.222	-0.001
21	206-224	31.222	-0.001
22	208-226	31.222	-0.008
23	C-171	31.223	-0.007
24	165-166	31.222	-0.001
25	HH-163	31.222	0.005
26	HH-200	31.222	-0.001
27	HH-198	31.222	0.004
28	HH-127	31.222	-0.003
29	HH-125	31.222	0
30	HH-162	31.222	0
31	159-160	31.222	0.001
32	C-154	31.223	0.003
33	99-117	31.223	0.006
34	101-119	31.222	0.005
35	104-122	31.222	0.001
36	111-130	31.222	-0.002
37	114-133	31.222	-0.006
38	116-135	31.223	-0.003
39	S-81	31.222	0.001

TABLE A-5 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	0.004
41	76-92	31.222	0.006
42	73-74	31.222	0.005
43	71-88	31.222	0.009
44	53-68	31.222	0.006
45	S-66	31.223	0.005
46	24-37	31.223	0.004
47	28-29	31.222	-0.002
48	31-32	31.222	-0.004
49	36-50	31.222	-0.008
50	C-11	31.222	-0.003
51	8-9	31.222	-0.007
52	5-6	31.222	-0.001
53	3-4	31.222	0.001
54	C-1	31.222	0.003
Mean			0.001
SD(b)			±0.005

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-6
DISTANCES BETWEEN COOLANT HOLES OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear potentiometers

Recalibration run: Run 3, 3/11/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.588	-0.007
270 to 219	1.594	1.588	-0.006
219 to 106	3.814	NM(b)	--
106 to 55	1.594	1.586	-0.008
55 to 13	1.593	1.586	-0.007
312 to 13	12.693	NM	--
319 to 295	0.656	0.649	-0.007
295 to 267	0.657	0.652	-0.005
267 to 235	0.656	0.651	-0.005
235 to 90	4.500	NM	--
90 to 58	0.656	0.648	-0.008
58 to 30	0.655	0.646	-0.009
30 to 6	0.655	0.647	-0.008
319 to 6	12.189	NM	--
303 to 264	1.595	1.590	-0.005
264 to 216	1.594	1.586	-0.008
216 to 109	3.814	NM	--
109 to 61	1.593	1.586	-0.007
61 to 22	1.593	1.587	-0.006
303 to 22	12.693	NM	--
170 to 167	1.594	1.589	-0.005
167 to 164	1.595	1.583	-0.012
164 to 161	3.815	NM	--
161 to 158	1.594	1.585	-0.009
158 to 155	1.594	1.591	-0.003
170 to 155	12.695	NM	--
13 to 22	6.034	6.032	-0.002
22 to 170	6.033	6.027	-0.006
170 to 312	6.033	NM	--
312 to 303	6.034	6.033	-0.001
303 to 155	6.034	6.028	-0.006
155 to 13	6.033	NM	--
Mean			-0.006
SD(c)			±0.002

(a)QC = Quality Control.

(b)NM = not measured.

(c)SD = standard deviation.

TABLE A-7
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear potentiometers

Recalibration run: Run 3, 3/11/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.634	0.007
13	0.627	0.636	0.009
22	0.627	0.631	0.004
30	0.627	0.635	0.008
55	0.626	0.633	0.007
58	0.627	0.636	0.009
61	0.627	0.634	0.007
66	0.626	0.635	0.009
81	0.626	0.637	0.011
90	0.626	0.632	0.006
103	0.626	0.632	0.006
106	0.626	0.633	0.007
109	0.626	0.632	0.006
112	0.626	0.631	0.005
126	0.498	0.505	0.007
144	0.498	0.504	0.006
145	0.498	0.505	0.007
155	0.626	0.631	0.005
158	0.626	0.632	0.006
161	0.625	0.632	0.007
164	0.626	0.631	0.005
167	0.626	0.635	0.009
170	0.626	0.633	0.007
180	0.498	0.503	0.005
181	0.498	0.504	0.006
199	0.498	0.505	0.007
213	0.625	0.631	0.006
216	0.626	0.632	0.006
219	0.626	0.631	0.005
222	0.626	0.632	0.006
235	0.626	0.632	0.006
244	0.626	0.634	0.008
259	0.626	0.634	0.008
264	0.626	0.634	0.008
267	0.626	0.631	0.005
270	0.625	0.633	0.008

TABLE A-7 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.632	0.006
303	0.626	0.630	0.004
312	0.626	0.634	0.008
319	0.626	0.632	0.006
Mean			0.007
SD(b)			±0.002

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-8
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation					
Probe table position:			Rotary potentiometers		
Probe displacement:			Linear potentiometers		
Recalibration run:			Run 3, 3/11/82		
Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.005	8.998	9.004	27.008
	Robot - QC	0.002	-0.004	0.004	0.003
2	QC	9.003	9.001	9.000	27.004
	Robot	8.999	8.998	9.000	26.998
	Robot - QC	-0.004	-0.003	0	-0.006
3	QC	9.003	9.001	9.001	27.005
	Robot	9.000	8.999	9.003	27.003
	Robot - QC	-0.003	-0.002	0.002	-0.002
4	QC	9.004	9.001	9.001	27.007
	Robot	9.001	9.004	8.996	27.002
	Robot - QC	-0.003	0.003	-0.005	-0.005
5	QC	9.004	9.002	9.001	27.006
	Robot	9.001	9.006	8.999	27.007
	Robot - QC	-0.003	0.004	-0.002	0.001
6	QC	9.002	9.002	9.001	27.005
	Robot	8.997	9.003	9.004	27.005
	Robot - QC	-0.005	0.001	0.003	0
Robot - QC(b)					
Mean		-0.003	0	0	-0.002
SD(c)		±0.002	±0.003	±0.003	±0.004

(a)QC = Quality Control.

(b)All robot - QC mean = -0.001, standard deviation = ±0.003.

(c)SD = standard deviation.

TABLE A-9
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run 4, 3/27/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.172	14.165	14.173		
	Robot - QC	-0.003	-0.011	-0.002	-0.005	±0.005
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.172		
	Robot - QC	-0.003	-0.003	-0.004	-0.003	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.173	14.173	14.173		
	Robot - QC	-0.002	-0.001	-0.001	-0.001	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.172	14.174	14.172		
	Robot - QC	-0.002	0	-0.002	-0.001	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.168	14.171	14.173		
	Robot - QC	-0.008	-0.005	-0.003	-0.005	±0.003
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.167		
	Robot - QC	-0.003	-0.003	-0.009	-0.005	±0.003
Robot - QC						
Mean		-0.004	-0.004	-0.004	-0.004	
SD		±0.002	±0.004	±0.003	±0.003	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-10
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear variable differential transformers
Recalibration run: Run 4, 3/27/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	0	0	0	0	0	0	0	0
3	0.001	0.001	0	0.001	0.001	0.001	0.001	0
4	0	0	0	0.001	0.001	0.001	0.001	±0.001
5	0	0.001	0.001	0.002	0.001	0.003	0.001	±0.001
6	0.001	0.001	0	0.001	0	0.002	0.001	±0.001
7	-0.001	0	0	0.001	-0.001	0.001	0	±0.001
8	-0.001	0	-0.001	0.001	0	0	0	±0.001
9	-0.001	0	-0.001	0	0	0	0	±0.001
10	0	0.001	0	0.001	0.001	0	0.001	±0.001
Mean	0	0	0	0.001	0	0.001	0	--
SD	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-11
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0812 (IN.)

Instrumentation

Probe table position: Sony Magnescales
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run 4, 3/27/82

Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.006
2	321-322	31.223	-0.005
3	S-319	31.223	-0.006
4	316-317	31.223	-0.004
5	C-314	31.223	-0.007
6	275-289	31.223	-0.003
7	293-294	31.222	-0.001
8	296-297	31.222	-0.002
9	288-301	31.223	-0.007
10	S-259	31.222	-0.005
11	257-272	31.222	-0.004
12	237-254	31.223	-0.004
13	251-252	31.222	-0.003
14	233-249	31.222	0.002
15	246-262	31.222	-0.001
16	S-244	31.222	-0.005
17	190-209	31.223	-0.010
18	192-211	31.222	-0.010
19	195-214	31.222	-0.002
20	203-221	31.222	-0.004
21	206-224	31.222	-0.004
22	208-226	31.222	-0.007
23	C-171	31.223	-0.004
24	165-166	31.222	-0.009
25	HH-163	31.222	-0.003
26	HH-200	31.222	-0.004
27	HH-198	31.222	0.001
28	HH-127	31.222	-0.006
29	HH-125	31.222	-0.008
30	HH-162	31.222	-0.005
31	159-160	31.222	-0.010
32	C-154	31.223	-0.007
33	99-117	31.223	-0.004
34	101-119	31.222	-0.002
35	104-122	31.222	-0.003
36	111-130	31.222	-0.003
37	114-133	31.222	-0.004
38	116-135	31.223	0
39	S-81	31.222	-0.007

TABLE A-11 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	0.001
41	76-92	31.222	0.007
42	73-74	31.222	0.004
43	71-88	31.222	0.007
44	53-68	31.222	0.006
45	S-66	31.223	0.004
46	24-37	31.223	0.003
47	28-29	31.222	-0.008
48	31-32	31.222	-0.004
49	36-50	31.222	-0.004
50	C-11	31.222	-0.004
51	8-9	31.222	-0.004
52	5-6	31.222	-0.001
53	3-4	31.222	0.004
54	C-1	31.222	<u>0.001</u>
Mean			-0.004
SD(b)			± 0.003

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-12
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable differential transformers

Recalibration run: Run 4, 3/27/82

Hole to Hole	QC ^(a)	Robot	Robot - QC
312 to 270	1.595	1.590	-0.005
270 to 219	1.594	1.591	-0.003
219 to 106	3.814	3.812(b)	-0.002(b)
106 to 55	1.594	1.588	-0.006
55 to 13	1.593	1.588	-0.005
312 to 13	12.693	12.680(b)	-0.013(b)
319 to 295	0.656	0.651	-0.005
295 to 267	0.657	0.652	-0.005
267 to 235	0.656	0.652	-0.004
235 to 90	4.500	4.495(b)	-0.005(b)
90 to 58	0.656	0.652	-0.004
58 to 30	0.655	0.652	-0.003
30 to 6	0.655	0.649	-0.006
319 to 6	12.189	12.176(b)	-0.013(b)
303 to 264	1.595	1.592	-0.003
264 to 216	1.594	1.589	-0.005
216 to 109	3.814	3.812(b)	-0.002(b)
109 to 61	1.593	1.591	-0.002
61 to 22	1.593	1.588	-0.005
303 to 22	12.693	12.688(b)	-0.005(b)
170 to 167	1.594	1.589	-0.005
167 to 164	1.595	1.594	-0.001
164 to 161	3.815	3.818(b)	0.003(b)
161 to 158	1.594	1.593	-0.001
158 to 155	1.594	1.591	-0.003
170 to 155	12.695	12.698(b)	0.003(b)
13 to 22	6.034	6.030	-0.004
22 to 170	6.033	6.031	-0.002
170 to 312	6.033	6.024(b)	-0.009(b)
312 to 303	6.034	6.025	-0.009
303 to 155	6.034	6.027	-0.007
155 to 13	6.033	6.038(b)	0.005(b)
Mean			-0.004(d)
SD(c)			±0.004

(a)QC = Quality Control.

(b)Rotational position of block different for measurements on the two holes.

(c)SD = standard deviation.

(d)Without (b)'s $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.006}$.

TABLE A-13
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable
differential
transformers

Recalibration run: Run 4, 3/27/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.633	0.006
13	0.627	0.632	0.005
22	0.627	0.632	0.005
30	0.627	0.630	0.003
55	0.626	0.629	0.003
58	0.627	0.630	0.003
61	0.627	0.630	0.003
66	0.626	0.630	0.004
81	0.626	0.631	0.005
90	0.626	0.628	0.002
103	0.626	0.629	0.003
106	0.626	0.628	0.002
109	0.626	0.629	0.003
112	0.626	0.630	0.004
126	0.498	0.502	0.004
144	0.498	0.501	0.003
145	0.498	0.502	0.004
155	0.626	0.629	0.003
158	0.626	0.629	0.003
161	0.625	0.628	0.003
164	0.626	0.628	0.002
167	0.626	0.629	0.003
170	0.626	0.631	0.005
180	0.498	0.499	0.001
181	0.498	0.501	0.003
199	0.498	0.502	0.004
213	0.625	0.629	0.004
216	0.626	0.629	0.003
219	0.626	0.628	0.002
222	0.626	0.629	0.003
235	0.626	0.629	0.003
244	0.626	0.630	0.004
259	0.626	0.628	0.002
264	0.626	0.630	0.004
267	0.626	0.629	0.003
270	0.625	0.628	0.003

TABLE A-13 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.629	0.003
303	0.626	0.630	0.004
312	0.626	0.629	0.003
319	0.626	0.630	0.004
Mean			0.003
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-14
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear variable differential transformers
Recalibration run: Run 4, 3/27/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.002	9.001	9.001	27.003
	Robot - QC	-0.001	-0.001	0.001	-0.002
2	QC	9.003	9.001	9.000	27.004
	Robot	9.001	9.001	9.004	27.005
	Robot - QC	-0.002	0	0.004	0.001
3	QC	9.003	9.001	9.001	27.005
	Robot	9.003	8.997	8.997	26.996
	Robot - QC	0	-0.004	-0.004	-0.009
4	QC	9.004	9.001	9.001	27.007
	Robot	9.008	9.002	9.001	27.010
	Robot - QC	0.004	0.001	0	0.003
5	QC	9.004	9.002	9.001	27.006
	Robot	9.005	8.996	9.004	27.004
	Robot - QC	0.001	-0.006	0.003	-0.002
6	QC	9.002	9.002	9.001	27.005
	Robot	9.002	9.003	9.001	27.005
	Robot - QC	0	0.001	0	0
Robot - QC(b)					
Mean		0	-0.002	0.001	-0.002
SD(c)		±0.002	±0.003	±0.003	±0.004

(a)QC = Quality Control.

(b)All robot - QC mean = -0.001, standard deviation = ±0.003.

(c)SD = standard deviation.

TABLE A-15
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run 5B, 3/22/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.176	14.169	14.178		
	Robot - QC	0.001	-0.007	0.003	-0.001	±0.005
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.175	14.176	14.174		
	Robot - QC	-0.001	0	-0.002	-0.001	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.176	14.175	14.176		
	Robot - QC	0.001	0.001	0.002	0.001	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.175	14.176	14.174		
	Robot - QC	0.001	0.002	0	0.001	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.171	14.176	14.176		
	Robot - QC	-0.005	0	0	-0.002	±0.003
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.176	14.177	14.169		
	Robot - QC	0	0.001	-0.007	-0.002	±0.004
Robot - QC						
Mean		-0.001	-0.001	-0.001	-0.001	
SD		±0.002	±0.003	±0.004	±0.003	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-16
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable differential transformers

Recalibration run: Run 5A, 3/21/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	-0.001	-0.001	0	0	0	0	0	±0.001
3	-0.001	0	0	-0.001	0	0	0	±0.001
4	-0.001	0	0	0	-0.001	0	0	±0.001
5	-0.001	0.001	0	-0.001	-0.001	0.001	0	±0.001
6	-0.001	0	0.001	0	0	0	0	±0.001
7	0	0	0	-0.001	-0.001	0.001	0	±0.001
8	0	0	0	0	0	0.001	0	0
9	-0.001	0	0	0	-0.001	0.001	0	±0.001
10	-0.001	0.001	0	-0.001	0	0.001	0	±0.001
Mean	-0.001	0	0	0	0	0.001	0	--
SD	0	±0.001	0	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-17
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0812 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable differential
transformers

Recalibration run: Run 5A, 3/21/82

Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.004
2	321-322	31.223	-0.008
3	S-319	31.223	-0.004
4	316-317	31.223	-0.004
5	C-314	31.223	-0.009
6	275-289	31.223	-0.004
7	293-294	31.222	-0.001
8	296-297	31.222	-0.001
9	288-301	31.223	-0.002
10	S-259	31.222	-0.004
11	257-272	31.222	-0.005
12	237-254	31.223	0
13	251-252	31.222	-0.001
14	233-249	31.222	0
15	246-262	31.222	0.001
16	S-244	31.222	-0.017
17	190-209	31.223	-0.002
18	192-211	31.222	-0.003
19	195-214	31.222	0.003
20	203-221	31.222	-0.005
21	206-224	31.222	-0.005
22	208-226	31.222	-0.005
23	C-171	31.223	-0.007
24	165-166	31.222	-0.005
25	HH-163	31.222	-0.003
26	HH-200	31.222	-0.002
27	HH-198	31.222	-0.001
28	HH-127	31.222	-0.007
29	HH-125	31.222	-0.009
30	HH-162	31.222	-0.005
31	159-160	31.222	-0.006
32	C-154	31.223	-0.007
33	99-117	31.223	-0.003
34	101-119	31.222	-0.003
35	104-122	31.222	-0.004
36	111-130	31.222	-0.003
37	114-133	31.222	-0.006
38	116-135	31.223	-0.001
39	S-81	31.222	-0.005

TABLE A-17 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	-0.002
41	76-92	31.222	-0.001
42	73-74	31.222	0
43	71-88	31.222	-0.018
44	53-68	31.222	-0.003
45	S-66	31.223	-0.005
46	24-37	31.223	-0.004
47	28-29	31.222	-0.001
48	31-32	31.222	-0.005
49	36-50	31.222	-0.006
50	C-11	31.222	-0.007
51	8-9	31.222	-0.005
52	5-6	31.222	0.001
53	3-4	31.222	-0.003
54	C-1	31.222	-0.002
Mean			-0.004
SD(b)			± 0.004

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-18
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation			
Probe table position:		Sony Magnescales	
Probe displacement:		Linear variable differential transformers	
Recalibration run:		Run 5B, 3/22/82	
Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.592	-0.003
270 to 219	1.594	1.592	-0.002
219 to 106	3.814	3.816(b)	0.002(b)
106 to 55	1.594	1.590	-0.004
55 to 13	1.593	1.589	-0.004
312 to 13	12.693	12.683(b)	-0.010(b)
319 to 295	0.656	0.654	-0.002
295 to 267	0.657	0.655	-0.002
267 to 235	0.656	0.655	-0.001
235 to 90	4.500	4.498(b)	-0.002(b)
90 to 58	0.656	0.655	-0.001
58 to 30	0.655	0.653	-0.002
30 to 6	0.655	0.651	-0.004
319 to 6	12.189	12.179(b)	-0.010(b)
303 to 264	1.595	1.595	0
264 to 216	1.594	1.592	-0.002
216 to 109	3.814	3.817(b)	0.003(b)
109 to 61	1.593	1.591	-0.002
61 to 22	1.593	1.590	-0.003
303 to 22	12.693	12.691(b)	-0.002(b)
170 to 167	1.594	1.595	0.001
167 to 164	1.595	1.595	0
164 to 161	3.815	3.819(b)	0.004(b)
161 to 158	1.594	1.595	0.001
158 to 155	1.594	1.595	0.001
170 to 155	12.695	12.702(b)	0.007(b)
13 to 22	6.034	6.035	0.001
22 to 170	6.033	6.031	-0.002
170 to 312	6.033	6.051(b)	0.018(b)
312 to 303	6.034	6.028	-0.006
303 to 155	6.034	6.031	-0.003
155 to 13	6.033	6.017(b)	-0.016(b)
Mean			-0.001(d)
SD(c)			±0.006

(a)QC = Quality Control.

(b)Rotational position of block different for measurements on the two holes.

(c)SD = standard deviation.

(d)Without (b)'s $\frac{\text{Mean}}{-0.002}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.002}$ $\frac{\text{SD}}{\pm 0.010}$.

TABLE A-19
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable
differential
transformers

Recalibration run: Run 5B, 3/22/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.631	0.004
13	0.627	0.631	0.004
22	0.627	0.629	0.002
30	0.627	0.628	0.001
55	0.626	0.628	0.002
58	0.627	0.628	0.001
61	0.627	0.629	0.002
66	0.626	0.629	0.003
81	0.626	0.628	0.002
90	0.626	0.626	0
103	0.626	0.626	0
106	0.626	0.626	0
109	0.626	0.625	-0.001
112	0.626	0.626	0
126	0.498	0.499	0.001
144	0.498	0.500	0.002
145	0.498	0.500	0.002
155	0.626	0.626	0
158	0.626	0.626	0
161	0.625	0.626	0.001
164	0.626	0.625	-0.001
167	0.626	0.627	0.001
170	0.626	0.626	0
180	0.498	0.499	0.001
181	0.498	0.498	0
199	0.498	0.499	0.001
213	0.625	0.626	0.001
216	0.626	0.626	0
219	0.626	0.624	-0.002
222	0.626	0.627	0.001
235	0.626	0.625	-0.001
244	0.626	0.627	0.001
259	0.626	0.627	0.001
264	0.626	0.627	0.001
267	0.626	0.627	0.001
270	0.625	0.626	0.001

TABLE A-19 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.625	-0.001
303	0.626	0.626	0
312	0.626	0.628	0.002
319	0.626	0.630	0.004
Mean			0.001
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-20
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear variable differential transformers

Recalibration run: Run 5A, 3/21/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.005	8.997	9.009	27.012
	Robot - QC	0.002	-0.005	0.009	0.007
2	QC	9.003	9.001	9.000	27.004
	Robot	9.006	8.999	9.004	27.010
	Robot - QC	0.003	-0.002	0.004	0.006
3	QC	9.003	9.001	9.001	27.005
	Robot	8.998	9.001	9.007	27.007
	Robot - QC	-0.005	0	0.006	0.002
4	QC	9.004	9.001	9.001	27.007
	Robot	9.006	8.999	9.001	27.007
	Robot - QC	0.002	-0.002	0	0
5	QC	9.004	9.002	9.001	27.006
	Robot	8.998	9.003	9.002	27.004
	Robot - QC	-0.006	0.001	0.001	-0.002
6	QC	9.002	9.002	9.001	27.005
	Robot	9.004	8.995	9.009	27.009
	Robot - QC	0.002	-0.007	0.008	0.004
Robot - QC(b)					
Mean		0	-0.002	0.005	0.003
SD(c)		±0.004	±0.003	±0.004	±0.003

(a)QC = Quality Control.

(b)All robot - QC mean = -0.001, standard deviation = ±0.004.

(c)SD = standard deviation.

TABLE A-21
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Rotary potentiometers
 Probe displacement: Linear potentiometers
 Recalibration run: Run 6, 3/25/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.172	14.170	14.171		
	Robot - QC	-0.003	-0.006	-0.004	-0.004	±0.002
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.174	14.174	14.172		
	Robot - QC	-0.002	-0.002	-0.004	-0.003	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.172	14.173	14.173		
	Robot - QC	-0.003	-0.001	-0.001	-0.002	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.173	14.173	14.173		
	Robot - QC	-0.001	-0.001	-0.001	-0.001	0
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.167	14.172	14.174		
	Robot - QC	-0.009	-0.004	-0.002	-0.005	±0.004
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.175	14.174	14.171		
	Robot - QC	-0.005	-0.002	-0.005	-0.004	±0.002
Robot - QC						
Mean		-0.004	-0.003	-0.003	-0.003	
SD		±0.003	±0.002	±0.002	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-22
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear potentiometers

Recalibration run: Run 6, 3/25/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	0	-0.001	0.001	0	0	-0.001	0	±0.001
3	0	-0.001	0	0	0	0	0	0
4	0	-0.001	0	-0.001	-0.001	0	0	±0.001
5	0	-0.001	0	0	0	0.001	0	±0.001
6	0	0	0	0	0	0.001	0	0
7	-0.001	-0.001	-0.001	0	-0.001	0.001	0	±0.001
8	-0.001	0	0	0	0	0.001	0	±0.001
9	-0.001	0.001	0	-0.001	0	0.001	0	±0.001
10	0	0.001	0	0	0.001	0	0	±0.001
Mean	0	0	0	0	0	0	0	--
SD	0	±0.001	0	0	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-23
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0812 (IN.)

Instrumentation			
Probe table position:		Rotary potentiometers	
Probe displacement:		Linear potentiometers	
Recalibration run:		Run 6, 3/25/82	
Measurement	Location	QC ^(a)	Robot - QC
1	C-324	31.223	-0.008
2	321-322	31.223	-0.005
3	S-319	31.223	-0.004
4	316-317	31.223	0
5	C-314	31.223	-0.001
6	275-289	31.223	0.009
7	293-294	31.222	0.006
8	296-297	31.222	-0.003
9	288-301	31.223	-0.009
10	S-259	31.222	-0.014
11	257-272	31.222	-0.009
12	237-254	31.223	-0.005
13	251-252	31.222	0
14	233-249	31.222	0.003
15	246-262	31.222	0.005
16	S-244	31.222	0.002
17	190-209	31.223	0.006
18	192-211	31.222	0.006
19	195-214	31.222	0.002
20	203-221	31.222	-0.006
21	206-224	31.222	-0.010
22	208-226	31.222	-0.009
23	C-171	31.223	-0.011
24	165-166	31.222	-0.009
25	HH-163	31.222	-0.005
26	HH-200	31.222	-0.001
27	HH-198	31.222	0.001
28	HH-127	31.222	-0.009
29	HH-125	31.222	-0.007
30	HH-162	31.222	-0.006
31	159-160	31.222	0
32	C-154	31.223	-0.002
33	99-117	31.223	0.008
34	101-119	31.222	0
35	104-122	31.222	-0.002
36	111-130	31.222	-0.010
37	114-133	31.222	-0.011
38	116-135	31.223	-0.008
39	S-81	31.222	-0.002

TABLE A-23 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	0.001
41	76-92	31.222	0.002
42	73-74	31.222	0.002
43	71-88	31.222	-0.012
44	53-68	31.222	0.009
45	S-66	31.223	0.009
46	24-37	31.223	0.002
47	28-29	31.222	-0.003
48	31-32	31.222	-0.012
49	36-50	31.222	-0.012
50	C-11	31.222	-0.012
51	8-9	31.222	-0.018
52	5-6	31.222	-0.005
53	3-4	31.222	-0.003
54	C-1	31.222	-0.002
Mean			-0.003
SD(b)			±0.006

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-24
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers
Probe displacement: Linear potentiometers
Recalibration run: Run 6, 3/25/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.584	-0.011
270 to 219	1.594	1.586	-0.008
219 to 106	3.814	3.805	-0.009(b)
106 to 55	1.594	1.585	-0.009
55 to 13	1.593	1.586	-0.007
312 to 13	12.693	12.678	-0.015(b)
319 to 295	0.656	0.649	-0.007
295 to 267	0.657	0.649	-0.008
267 to 235	0.656	0.648	-0.008
235 to 90	4.500	4.487	-0.013(b)
90 to 58	0.656	0.650	-0.006
58 to 30	0.655	0.646	-0.009
30 to 6	0.655	0.646	-0.009
319 to 6	12.189	12.175	-0.014(b)
303 to 264	1.595	1.587	-0.008
264 to 216	1.594	1.585	-0.009
216 to 109	3.814	3.805	-0.009(b)
109 to 61	1.593	1.585	-0.008
61 to 22	1.593	1.586	-0.007
303 to 22	12.693	12.687	-0.006(b)
170 to 167	1.594	1.588	-0.006
167 to 164	1.595	1.582	-0.013
164 to 161	3.815	3.818	0.003(b)
161 to 158	1.594	1.583	-0.011
158 to 155	1.594	1.590	-0.004
170 to 155	12.695	12.689	-0.006(b)
13 to 22	6.034	6.028	-0.006
22 to 170	6.033	6.025	-0.008
170 to 312	6.033	6.021	-0.012(b)
312 to 303	6.034	6.029	-0.005
303 to 155	6.034	6.024	-0.010
155 to 13	6.033	6.028	-0.0005(b)
Mean			-0.008(d)
SD(c)			±0.003

(a)QC = Quality Control.

(b)Rotational position of block different for measurements on the two holes.

(c)SD = standard deviation.

(d)Without (b)'s $\frac{\text{Mean}}{-0.008}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.009}$ $\frac{\text{SD}}{\pm 0.005}$.

TABLE A-25
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers
Probe displacement: Linear potentiometers
Recalibration run: Run 6, 3/25/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.635	0.008
13	0.627	0.635	0.008
22	0.627	0.632	0.005
30	0.627	0.636	0.009
55	0.626	0.635	0.009
58	0.627	0.635	0.008
61	0.627	0.636	0.009
66	0.626	0.636	0.010
81	0.626	0.636	0.010
90	0.626	0.631	0.005
103	0.626	0.633	0.007
106	0.626	0.632	0.006
109	0.626	0.634	0.008
112	0.626	0.634	0.008
126	0.498	0.507	0.009
144	0.498	0.508	0.010
145	0.498	0.506	0.008
155	0.626	0.632	0.006
158	0.626	0.633	0.007
161	0.625	0.631	0.006
164	0.626	0.632	0.006
167	0.626	0.634	0.008
170	0.626	0.635	0.009
180	0.498	0.505	0.007
181	0.498	0.507	0.009
199	0.498	0.505	0.007
213	0.625	0.631	0.006
216	0.626	0.634	0.008
219	0.626	0.631	0.005
222	0.626	0.632	0.006
235	0.626	0.634	0.008
244	0.626	0.635	0.009
259	0.626	0.634	0.008
264	0.626	0.635	0.009
267	0.626	0.634	0.008
270	0.625	0.635	0.010

TABLE A-25 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.632	0.006
303	0.626	0.629	0.003
312	0.626	0.634	0.008
319	0.626	0.634	0.008
Mean			0.008
SD(b)			±0.002

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-26
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:	Rotary potentiometers
Probe displacement:	Linear potentiometers
Recalibration run:	Run 6, 3/25/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.001	8.996	8.999	26.997
	Robot - QC	-0.002	-0.006	-0.001	-0.008
2	QC	9.003	9.001	9.000	27.004
	Robot	9.000	8.995	9.003	26.999
	Robot - QC	-0.003	-0.006	0.003	-0.005
3	QC	9.003	9.001	9.001	27.005
	Robot	9.004	9.001	8.996	27.002
	Robot - QC	0.001	0	-0.005	-0.003
4	QC	9.004	9.001	9.001	27.007
	Robot	9.005	9.002	9.001	27.009
	Robot - QC	0.001	0.001	0	0.002
5	QC	9.004	9.002	9.001	27.006
	Robot	9.003	8.993	9.006	27.003
	Robot - QC	-0.001	-0.009	0.005	-0.003
6	QC	9.002	9.002	9.001	27.005
	Robot	9.003	9.005	8.997	27.006
	Robot - QC	0.001	0.003	-0.004	0.001
Robot - QC(b)					
Mean		-0.001	-0.003	0	-0.003
SD(c)		±0.002	±0.005	±0.004	±0.004

(a)QC = Quality Control.

(b)All robot - QC mean = -0.002, standard deviation = ±0.004.

(c)SD = standard deviation.

TABLE A-27
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:	Rotary potentiometers
Probe displacement:	Linear variable differential transformers
Recalibration run:	Run 7, 3/25/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.172	14.170	14.172		
	Robot - QC	-0.003	-0.006	-0.003	-0.004	±0.002
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.172		
	Robot - QC	-0.003	-0.003	-0.004	-0.003	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.170	14.172	14.173		
	Robot - QC	-0.005	-0.002	-0.001	-0.003	±0.002
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.174	14.175	14.172		
	Robot - QC	0	0.001	-0.002	0	±0.002
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.168	14.172	14.171		
	Robot - QC	-0.008	-0.004	-0.005	-0.006	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.170		
	Robot - QC	-0.003	-0.003	-0.006	-0.004	±0.002
Robot - QC						
Mean		-0.004	-0.003	-0.004	-0.003	
SD		±0.003	±0.002	±0.002	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-28
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential transformers

Recalibration run: Run 7, 3/25/82

Axial Level(b)	Face A(c)	Face B(c)	Face C(c)	Face D(c)	Face E(c)	Face F(c)	Mean	SD(d)
2	-0.001	0	0	-0.001	0	0	0	±0.001
3	0	0	0	0.001	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0
6	0	-0.001	0.001	0	0.001	0.001	0	±0.001
7	0	-0.002	0	0	0.001	0.001	0	±0.001
8	-0.001	-0.002	0	0	0	0	-0.001	±0.001
9	0	-0.002	0	0	0	0	0	±0.001
10	0	0.001	0	0	0	0.001	0	±0.001
Mean	0	-0.001	0	0	0	0	0	--
SD	±0.001	±0.001	0	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-29
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential
transformers

Recalibration run: Run 7, 3/25/82

Measurement	Location	QC ^(a)	Robot - QC
1	C-324	31.223	-0.007
2	321-322	31.223	-0.008
3	S-319	31.223	-0.002
4	316-317	31.223	0.002
5	C-314	31.223	0.002
6	275-289	31.223	0.006
7	293-294	31.222	0.005
8	296-297	31.222	0.002
9	288-301	31.223	-0.005
10	S-259	31.222	-0.008
11	257-272	31.222	-0.006
12	237-254	31.223	0
13	251-252	31.222	0.005
14	233-249	31.222	0.003
15	246-262	31.222	0.004
16	S-244	31.222	--
17	190-209	31.223	0.004
18	192-211	31.222	0.008
19	195-214	31.222	0.009
20	203-221	31.222	-0.003
21	206-224	31.222	-0.008
22	208-226	31.222	-0.011
23	C-171	31.223	-0.019
24	165-166	31.222	-0.005
25	HH-163	31.222	0
26	HH-200	31.222	-0.001
27	HH-198	31.222	0
28	HH-127	31.222	-0.007
29	HH-125	31.222	-0.009
30	HH-162	31.222	-0.002
31	159-160	31.222	-0.002
32	C-154	31.223	-0.001
33	99-117	31.223	0.009
34	101-119	31.222	0
35	104-122	31.222	0
36	111-130	31.222	-0.004
37	114-133	31.222	-0.009
38	116-135	31.223	-0.007
39	S-81	31.222	0.001

TABLE A-29 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	0.002
41	76-92	31.222	0.003
42	73-74	31.222	0.004
43	71-88	31.222	-0.005
44	53-68	31.222	0.009
45	S-66	31.223	0.009
46	24-37	31.223	0.005
47	28-29	31.222	-0.004
48	31-32	31.222	-0.008
49	36-50	31.222	-0.010
50	C-11	31.222	-0.012
51	8-9	31.222	-0.005
52	5-6	31.222	0.002
53	3-4	31.222	0.002
54	C-1	31.222	0.004
Mean			-0.001
SD(b)			±0.006

(a)QC = Quality Control.

(b)SD = standard deviation.

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.589	-0.006
270 to 219	1.594	1.586	-0.008
219 to 106	3.814	3.808(b)	-0.006(b)
106 to 55	1.594	1.585	-0.009
55 to 13	1.593	1.584	-0.009
312 to 13	12.693	12.679(b)	-0.014(b)
319 to 295	0.656	0.649	-0.007
295 to 267	0.657	0.649	-0.008
267 to 235	0.656	0.650	-0.006
235 to 90	4.500	4.486	-0.014(b)
90 to 58	0.656	0.648	-0.008
58 to 30	0.655	0.648	-0.007
30 to 6	0.655	0.648	-0.007
319 to 6	12.189	12.175(b)	-0.014(b)
303 to 264	1.595	1.588	-0.007
264 to 216	1.594	1.587	-0.007
216 to 109	3.814	3.807(b)	-0.007(b)
109 to 61	1.593	1.585	-0.008
61 to 22	1.593	1.582	-0.011
303 to 22	12.693	12.683(b)	-0.010(b)
170 to 167	1.594	1.589	-0.005
167 to 164	1.595	1.584	-0.011
164 to 161	3.815	3.817(b)	0.002(b)
161 to 158	1.594	1.583	-0.011
158 to 155	1.594	1.590	-0.004
170 to 155	12.695	12.692(b)	-0.003(b)
13 to 22	6.034	6.030	-0.004
22 to 170	6.033	6.023	-0.010
170 to 312	6.033	6.017(b)	-0.016(b)
312 to 303	6.034	6.023	-0.011
303 to 155	6.034	6.025	-0.009
155 to 13	6.033	6.036(b)	-0.003(b)
Mean			-0.008(d)
SD(c)			±0.004

(b) Rotational position of block different for measurements the two holes.

on the two holes.

	<u>Mean</u>	<u>SD</u>		<u>Mean</u>	<u>SD</u>
(d) Without (b)'s	-0.008	±0.002;	(b)'s only	-0.008	±0.006

TABLE A-31
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable
differential
transformers

Recalibration run: Run 7, 3/25/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.635	0.008
13	0.627	0.636	0.009
22	0.627	0.633	0.006
30	0.627	0.634	0.007
55	0.626	0.635	0.009
58	0.627	0.634	0.007
61	0.627	0.637	0.010
66	0.626	0.636	0.010
81	0.626	0.636	0.010
90	0.626	0.633	0.007
103	0.626	0.634	0.008
106	0.626	0.632	0.006
109	0.626	0.633	0.007
112	0.626	0.633	0.007
126	0.498	0.506	0.008
144	0.498	0.506	0.008
145	0.498	0.506	0.008
155	0.626	0.631	0.005
158	0.626	0.634	0.008
161	0.625	0.632	0.007
164	0.626	0.632	0.006
167	0.626	0.633	0.007
170	0.626	0.635	0.009
180	0.498	0.504	0.006
181	0.498	0.503	0.005
199	0.498	0.504	0.006
213	0.625	0.629	0.004
216	0.626	0.633	0.007
219	0.626	0.629	0.003
222	0.626	0.631	0.005
235	0.626	0.633	0.007
244	0.626	0.634	0.008
259	0.626	0.633	0.007
264	0.626	0.633	0.007
267	0.626	0.633	0.007
270	0.625	0.632	0.007

TABLE A-31 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.633	0.007
303	0.626	0.631	0.005
312	0.626	0.633	0.007
319	0.626	0.634	0.008
Mean			0.007
SD(b)			±0.002

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-32
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:

Rotary potentiometers

Probe displacement:

Linear variable differential transformers

Recalibration run:

Run 7, 3/25/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.002	8.998	9.006	27.007
	Robot - QC	-0.001	-0.004	0.006	0.002
2	QC	9.003	9.001	9.000	27.004
	Robot	9.004	9.003	9.002	27.010
	Robot - QC	0.001	0.002	0.002	0.006
3	QC	9.003	9.001	9.001	27.005
	Robot	9.000	9.001	8.995	26.997
	Robot - QC	-0.003	0	-0.006	-0.008
4	QC	9.004	9.001	9.001	27.007
	Robot	9.002	8.995	9.002	27.000
	Robot - QC	-0.002	-0.006	0.001	-0.007
5	QC	9.004	9.002	9.001	27.006
	Robot	9.009	8.996	9.005	27.011
	Robot - QC	0.005	-0.006	0.004	0.005
6	QC	9.002	9.002	9.001	27.005
	Robot	9.007	8.996	9.009	27.013
	Robot - QC	0.005	-0.006	0.008	0.008
Robot - QC(b)					
Mean		0.001	-0.003	0.002	0.001
SD(c)		±0.003	±0.004	±0.005	±0.007

(a) QC = Quality Control.

(b) All robot - QC mean = 0, standard deviation = ±0.005.

(c) SD = standard deviation.

TABLE A-33
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Rotary potentiometers
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run 8, 3/25/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC ^(b)	14.175	14.176	14.175		
	Robot	14.173	14.165	14.172		
	Robot - QC	-0.002	-0.011	-0.003	-0.005	±0.005
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.170	14.172	14.173		
	Robot - QC	-0.006	-0.004	-0.003	-0.004	±0.002
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.170	14.170	14.170		
	Robot - QC	-0.005	-0.004	-0.004	-0.004	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.170	14.171	14.171		
	Robot - QC	-0.004	-0.003	-0.003	-0.003	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.166	14.172	14.172		
	Robot - QC	-0.010	-0.004	-0.004	-0.006	±0.003
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.173	14.172	14.168		
	Robot - QC	-0.003	-0.004	-0.008	-0.005	±0.003
Robot - QC						
Mean		-0.005	-0.005	-0.004	-0.005	
SD		±0.003	±0.003	±0.002	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-34
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential transformers

Recalibration run: Run 8, 3/25/82

Axial Level ^(b)	Face A(c)	Face B(c)	Face C(c)	Face D(c)	Face E(c)	Face F(c)	Mean	SD(d)
2	-0.001	0	0	0	0.001	0.001	0	±0.001
3	0	0.001	0.002	0	0.001	0	0.001	±0.001
4	0	0	0	0	0	0.001	0	0
5	0	0.001	0.001	0	0	0.001	0.001	±0.001
6	0	0	0.001	0	0	0	0	0
7	0	0	0	0	0	0.001	0	0
8	0	0	0	0	0	0.001	0	0
9	0	0.001	0	0.001	0	0.001	0.001	±0.001
10	0.001	0.001	0.001	0	0	0	0.001	±0.001
Mean	0	0	0.001	0	0	0.001	0	--
SD	±0.001	±0.001	±0.001	0	0	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-35
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential
transformers

Recalibration run: Run 8, 3/25/82

Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.008
2	321-322	31.223	-0.004
3	S-319	31.223	-0.001
4	316-317	31.223	0.002
5	C-314	31.223	0.002
6	275-289	31.223	0.006
7	293-294	31.222	0.004
8	296-297	31.222	0.002
9	288-301	31.223	-0.011
10	S-259	31.222	-0.009
11	257-272	31.222	-0.006
12	237-254	31.223	0.001
13	251-252	31.222	0.004
14	233-249	31.222	0.002
15	246-262	31.222	0.008
16	S-244	31.222	0.009
17	190-209	31.223	0.005
18	192-211	31.222	0.007
19	195-214	31.222	0.008
20	203-221	31.222	-0.002
21	206-224	31.222	-0.007
22	208-226	31.222	-0.012
23	C-171	31.223	-0.013
24	165-166	31.222	-0.005
25	HH-163	31.222	0.001
26	HH-200	31.222	0
27	HH-198	31.222	0
28	HH-127	31.222	-0.007
29	HH-125	31.222	-0.004
30	HH-162	31.222	-0.005
31	159-160	31.222	-0.006
32	C-154	31.223	-0.001
33	99-117	31.223	0.006
34	101-119	31.222	0.004
35	104-122	31.222	-0.004
36	111-130	31.222	-0.009
37	114-133	31.222	-0.009
38	116-135	31.223	-0.006
39	S-81	31.222	0

TABLE A-35 (Continued)

Measurement	Location	QC ^(a)	Robot - QC
40	63-79	31.222	0.003
41	76-92	31.222	0.005
42	73-74	31.222	0.007
43	71-88	31.222	0.009
44	53-68	31.222	0.006
45	S-66	31.223	-0.002
46	24-37	31.223	0.005
47	28-29	31.222	-0.004
48	31-32	31.222	-0.008
49	36-50	31.222	-0.013
50	C-11	31.222	-0.014
51	8-9	31.222	-0.005
52	5-6	31.222	0.002
53	3-4	31.222	0
54	C-1	31.222	0.003
Mean			-0.001
SD ^(b)			±0.006

(a) QC = Quality Control.

(b) SD = standard deviation.

TABLE A-36
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation			
Probe table position:		Rotary potentiometers	
Probe displacement:		Linear variable differential transformers	
Recalibration run:		Run 8, 3/25/82	
Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.589	-0.006
270 to 219	1.594	1.587	-0.007
219 to 106	3.814	3.808(b)	-0.006(b)
106 to 55	1.594	1.585	-0.009
55 to 13	1.593	1.585	-0.008
312 to 13	12.693	12.677	-0.016(b)
319 to 295	0.656	0.649	-0.007
295 to 267	0.657	0.650	-0.007
267 to 235	0.656	0.649	-0.007
235 to 90	4.500	4.486(b)	-0.014(b)
90 to 58	0.656	0.647	-0.009
58 to 30	0.655	0.649	-0.006
30 to 6	0.655	0.647	-0.008
319 to 6	12.189	12.173(b)	-0.016(b)
303 to 264	1.595	1.588	-0.007
264 to 216	1.594	1.587	-0.007
216 to 109	3.814	3.805(b)	-0.009(b)
109 to 61	1.593	1.584	-0.009
61 to 22	1.593	1.586	-0.007
303 to 22	12.693	12.684(b)	-0.009(b)
170 to 167	1.594	1.587	-0.007
167 to 164	1.595	1.582	-0.013
164 to 161	3.815	3.817(b)	0.002(b)
161 to 158	1.594	1.583	-0.011
158 to 155	1.594	1.591	-0.003
170 to 155	12.695	12.691(b)	-0.004(b)
13 to 22	6.034	6.032	-0.002
22 to 170	6.033	6.025	-0.008
170 to 312	6.033	6.015(b)	-0.018(b)
312 to 303	6.034	6.020	-0.014
303 to 155	6.034	6.024	-0.010
155 to 13	6.033	6.034(b)	0.001(b)
Mean			-0.008(d)
SD(c)			±0.004

(a) QC = Quality Control.

(b) Rotational position of block different for measurements on the two holes.

(c) SD = standard deviation.

(d) Without (b)'s $\frac{\text{Mean}}{-0.008}$ $\frac{\text{SD}}{\pm 0.003}$; (b)'s only $\frac{\text{Mean}}{-0.009}$ $\frac{\text{SD}}{\pm 0.007}$.

TABLE A-37
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable
differential
transformers

Recalibration run: Run 8, 3/25/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.635	0.008
13	0.627	0.638	0.011
22	0.627	0.634	0.007
30	0.627	0.634	0.007
55	0.626	0.634	0.008
58	0.627	0.635	0.008
61	0.627	0.636	0.009
66	0.626	0.636	0.010
81	0.626	0.637	0.011
90	0.626	0.633	0.007
103	0.626	0.635	0.009
106	0.626	0.631	0.005
109	0.626	0.634	0.008
112	0.626	0.634	0.008
126	0.498	0.506	0.008
144	0.498	0.507	0.009
145	0.498	0.506	0.008
155	0.626	0.633	0.007
158	0.626	0.633	0.007
161	0.625	0.632	0.007
164	0.626	0.633	0.007
167	0.626	0.635	0.009
170	0.626	0.634	0.008
180	0.498	0.505	0.007
181	0.498	0.504	0.006
199	0.498	0.503	0.005
213	0.625	0.632	0.007
216	0.626	0.632	0.006
219	0.626	0.629	0.003
222	0.626	0.631	0.005
235	0.626	0.632	0.006
244	0.626	0.635	0.009
259	0.626	0.632	0.006
264	0.626	0.634	0.008
267	0.626	0.631	0.005
270	0.625	0.631	0.006

TABLE A-37 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.632	0.006
303	0.626	0.633	0.007
312	0.626	0.633	0.007
319	0.626	0.633	0.007
Mean			0.007
SD(b)			±0.002

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-38
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential
transformers

Recalibration run: Run 8, 3/25/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.005	8.998	9.000	27.004
	Robot - QC	0.002	-0.004	0	-0.001
2	QC	9.003	9.001	9.000	27.004
	Robot	9.004	8.998	9.002	27.005
	Robot - QC	0.001	-0.003	0.002	0.001
3	QC	9.003	9.001	9.001	27.005
	Robot	8.998	9.006	9.001	27.006
	Robot - QC	-0.005	0.005	0	0.001
4	QC	9.004	9.001	9.001	27.007
	Robot	9.001	9.003	9.004	27.009
	Robot - QC	-0.003	0.002	0.003	0.002
5	QC	9.004	9.002	9.001	27.006
	Robot	9.002	8.995	9.007	27.005
	Robot - QC	-0.002	-0.007	0.006	-0.001
6	QC	9.002	9.002	9.001	27.005
	Robot	9.007	8.994	9.005	27.007
	Robot - QC	0.005	-0.008	0.004	0.002
Robot - QC(b)					
Mean		0	-0.002	0.002	0.001
SD(c)		±0.004	±0.005	±0.002	±0.001

(a)QC = Quality Control.

(b)All robot - QC mean = 0, standard deviation = ±0.004.

(c)SD = standard deviation.

TABLE A-39
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run 3, 3/11/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.172	14.163	14.172		
	Robot - QC	-0.003	-0.013	-0.003	-0.006	±0.006
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.172	14.171	14.171		
	Robot - QC	-0.004	-0.005	-0.005	-0.005	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.173	14.174	14.173		
	Robot - QC	-0.002	0	-0.001	-0.001	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.172	14.172	14.170		
	Robot - QC	-0.002	-0.002	-0.004	-0.003	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.171	14.172	14.171		
	Robot - QC	-0.005	-0.004	-0.005	-0.005	±0.001
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.172	14.171	14.168		
	Robot - QC	-0.004	-0.005	-0.008	-0.006	±0.002
Robot - QC						
Mean		-0.003	-0.005	-0.004	-0.004	
SD		±0.001	±0.004	±0.002	±0.003	

(a)SD = standard deviation.
(b)QC = Quality Control.

TABLE A-40
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:

Sony Magnescales

Probe displacement:

Linear potentiometers

Recalibration run:

Run 9, 3/26/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	0	0	0	0.001	0	0	0	0
3	0	0.001	-0.001	0.001	0	0	0	±0.001
4	-0.001	0	-0.001	0	-0.001	-0.001	-0.001	±0.001
5	0	0	0	0	0	0	0	0
6	-0.001	-0.001	0	0	0	0	0	±0.001
7	-0.001	0	0	0	0	0	0	0
8	-0.001	0	0	0	0	0	0	0
9	0	0.001	0	0.001	0.001	0	0.001	±0.001
10	0	0.001	0.001	0.001	0.001	0.001	0.001	0
Mean	0	0	0	0	0	0	0	--
SD	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-41
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation			
Probe table position:		Sony Magnescales	
Probe displacement:		Linear potentiometers	
Recalibration run:		Run 9, 3/26/82	
Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.004
2	321-322	31.223	-0.006
3	S-319	31.223	-0.007
4	316-317	31.223	-0.003
5	C-314	31.223	-0.009
6	275-289	31.223	-0.001
7	293-294	31.222	-0.006
8	296-297	31.222	-0.002
9	288-301	31.223	-0.001
10	S-259	31.222	-0.002
11	257-272	31.222	-0.002
12	237-254	31.223	-0.004
13	251-252	31.222	0
14	233-249	31.222	-0.006
15	246-262	31.222	-0.002
16	S-244	31.222	-0.010
17	190-209	31.223	-0.006
18	192-211	31.222	-0.004
19	195-214	31.222	-0.005
20	203-221	31.222	-0.003
21	206-224	31.222	-0.008
22	208-226	31.222	-0.005
23	C-171	31.223	-0.002
24	165-166	31.222	-0.005
25	HH-163	31.222	-0.008
26	HH-200	31.222	-0.008
27	HH-198	31.222	-0.005
28	HH-127	31.222	-0.007
29	HH-125	31.222	-0.006
30	HH-162	31.222	-0.008
31	159-160	31.222	-0.003
32	C-154	31.223	-0.005
33	99-117	31.223	-0.007
34	101-119	31.222	-0.006
35	104-122	31.222	-0.006
36	111-130	31.222	-0.006
37	114-133	31.222	-0.003
38	116-135	31.223	-0.002
39	S-81	31.222	-0.004

TABLE A-41 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	-0.001
41	76-92	31.222	-0.005
42	73-74	31.222	-0.006
43	71-88	31.222	-0.011
44	53-68	31.222	-0.012
45	S-66	31.223	-0.005
46	24-37	31.223	-0.007
47	28-29	31.222	-0.007
48	31-32	31.222	-0.007
49	36-50	31.222	-0.010
50	C-11	31.222	-0.005
51	8-9	31.222	-0.004
52	5-6	31.222	-0.006
53	3-4	31.222	-0.004
54	C-1	31.222	-0.006
Mean			-0.005
SD(b)			±0.003

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-42
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run 9, 3/26/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.590	-0.005
270 to 219	1.594	1.590	-0.004
219 to 106	3.814	3.812(b)	-0.002(b)
106 to 55	1.594	1.587	-0.007
55 to 13	1.593	1.587	-0.006
312 to 13	12.693	12.682(b)	-0.011(b)
319 to 295	0.656	0.652	-0.004
295 to 267	0.657	0.652	-0.005
267 to 235	0.656	0.652	-0.004
235 to 90	4.500	4.494(b)	-0.006(b)
90 to 58	0.656	0.652	-0.004
58 to 30	0.655	0.650	-0.005
30 to 6	0.655	0.648	-0.007
319 to 6	12.189	12.179(b)	-0.010(b)
303 to 264	1.595	1.592	-0.003
264 to 216	1.594	1.589	-0.005
216 to 109	3.814	3.812(b)	-0.002(b)
109 to 61	1.593	1.589	-0.004
61 to 22	1.593	1.587	-0.006
303 to 22	12.693	12.688(b)	-0.005(b)
170 to 167	1.594	1.590	-0.004
167 to 164	1.595	1.592	-0.003
164 to 161	3.815	3.817(b)	0.002(b)
161 to 158	1.594	1.592	-0.002
158 to 155	1.594	1.591	-0.003
170 to 155	12.695	12.697(b)	0.002(b)
13 to 22	6.034	6.038	0.004
22 to 170	6.033	6.030	-0.003
170 to 312	6.033	6.020(b)	-0.013(b)
312 to 303	6.034	6.036	0.002
303 to 155	6.034	6.027	-0.007
155 to 13	6.033	6.025(b)	-0.008(b)
Mean			-0.004(d)
SD(c)			±0.004

(a)QC = Quality Control.

(b)Rotational position of block different for measurements on the two holes.

(c)SD = standard deviation.

(d)Without (b)'s $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.003}$; (b)'s only $\frac{\text{Mean}}{-0.005}$ $\frac{\text{SD}}{\pm 0.005}$.

TABLE A-43
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run 9, 3/26/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.633	0.006
13	0.627	0.632	0.005
22	0.627	0.632	0.005
30	0.627	0.632	0.005
55	0.626	0.630	0.004
58	0.627	0.631	0.004
61	0.627	0.631	0.004
66	0.626	0.629	0.003
81	0.626	0.631	0.005
90	0.626	0.630	0.004
103	0.626	0.630	0.004
106	0.626	0.630	0.004
109	0.626	0.630	0.004
112	0.626	0.630	0.004
126	0.498	0.502	0.004
144	0.498	0.502	0.004
145	0.498	0.502	0.004
155	0.626	0.630	0.004
158	0.626	0.629	0.003
161	0.625	0.629	0.004
164	0.626	0.628	0.002
167	0.626	0.631	0.005
170	0.626	0.631	0.005
180	0.498	0.502	0.004
181	0.498	0.501	0.003
199	0.498	0.501	0.003
213	0.625	0.630	0.005
216	0.626	0.629	0.003
219	0.626	0.628	0.002
222	0.626	0.627	0.001
235	0.626	0.629	0.003
244	0.626	0.631	0.005
259	0.626	0.628	0.002
264	0.626	0.629	0.003
267	0.626	0.629	0.003
270	0.625	0.629	0.004

TABLE A-43 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.630	0.004
303	0.626	0.630	0.004
312	0.626	0.628	0.002
319	0.626	0.629	0.003
Mean			0.004
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-44
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation					
Probe table position:			Sony Magnescales		
Probe displacement:			Linear potentiometers		
Recalibration run:			Run 9, 3/26/82		
Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.000	8.999	8.995	26.995
	Robot - QC	-0.003	-0.003	-0.005	-0.010
2	QC	9.003	9.001	9.000	27.004
	Robot	9.000	9.005	9.000	27.006
	Robot - QC	-0.003	0.004	0	0.002
3	QC	9.003	9.001	9.001	27.005
	Robot	9.002	8.994	8.999	26.996
	Robot - QC	-0.001	-0.007	-0.002	-0.009
4	QC	9.004	9.001	9.001	27.007
	Robot	9.007	8.996	9.002	27.006
	Robot - QC	0.003	-0.005	0.001	-0.001
5	QC	9.004	9.002	9.001	27.006
	Robot	9.005	9.000	8.999	27.005
	Robot - QC	0.001	-0.002	-0.002	-0.001
6	QC	9.002	9.002	9.001	27.005
	Robot	9.003	9.004	9.006	27.014
	Robot - QC	0.001	0.002	0.005	0.009
Robot - QC(b)					
Mean		0	-0.002	-0.001	-0.002
SD(c)		± 0.002	± 0.004	± 0.003	± 0.007

(a) QC = Quality Control.

(b) All robot - QC mean = -0.001, standard deviation = ± 0.004 .

(c) SD = standard deviation.

TABLE A-45
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run 10, 3/31/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.173	14.163	14.173		
	Robot - QC	-0.002	-0.013	-0.002	-0.006	±0.006
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.172	14.172	14.174		
	Robot - QC	-0.004	-0.004	-0.002	-0.003	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.174	14.173	14.174		
	Robot - QC	-0.001	-0.001	0	-0.001	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.174	14.173	14.172		
	Robot - QC	0	-0.001	-0.002	-0.001	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.172	14.175	14.173		
	Robot - QC	-0.004	-0.001	-0.003	-0.003	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.169		
	Robot - QC	-0.003	-0.003	-0.007	-0.004	±0.002
Robot - QC						
Mean		-0.002	-0.004	-0.003	-0.003	
SD		±0.002	±0.005	±0.002	±0.003	

(a)SD = standard deviation.

(b)QC = Quality Control.

TABLE A-46
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear potentiometers

Recalibration run: Run 10, 3/31/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	0	0	0	0	0	0	0	0
3	0	0	0	-0.001	0	-0.001	0	±0.001
4	-0.001	-0.001	0	0	-0.001	-0.001	-0.001	±0.001
5	0	0	0	0	0	0	0	0
6	0	0	0	0	-0.001	0	0	0
7	-0.001	0	-0.001	0	-0.001	-0.001	-0.001	0
8	0	0	0	0	-0.001	0	0	0
9	0	0	0.001	0	0	0	0	0
10	0	0	0	0	0	0	0	0
Mean	0	0	0	0	0	0	0	--
SD	0	0	0	0	±0.001	±0.001	0	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-47
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation			
Probe table position:		Sony Magnescales	
Probe displacement:		Linear potentiometers	
Recalibration run:		Run 10, 3/31/82	
Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.004
2	321-322	31.223	-0.002
3	S-319	31.223	-0.004
4	316-317	31.223	-0.005
5	C-314	31.223	-0.003
6	275-289	31.223	-0.001
7	293-294	31.222	0.002
8	296-297	31.222	0
9	288-301	31.223	-0.005
10	S-259	31.222	-0.004
11	257-272	31.222	-0.004
12	237-254	31.223	0.002
13	251-252	31.222	-0.001
14	233-249	31.222	-0.003
15	246-262	31.222	-0.002
16	S-244	31.222	-0.006
17	190-209	31.223	-0.004
18	192-211	31.222	-0.004
19	195-214	31.222	-0.002
20	203-221	31.222	-0.002
21	206-224	31.222	-0.006
22	208-226	31.222	-0.004
23	C-171	31.223	-0.008
24	165-166	31.222	-0.004
25	HH-163	31.222	-0.004
26	HH-200	31.222	-0.001
27	HH-198	31.222	-0.005
28	HH-127	31.222	-0.006
29	HH-125	31.222	-0.003
30	HH-162	31.222	-0.005
31	159-160	31.222	-0.003
32	C-154	31.223	-0.007
33	99-117	31.223	-0.008
34	101-119	31.222	0.001
35	104-122	31.222	-0.002
36	111-130	31.222	-0.003
37	114-133	31.222	-0.004
38	116-135	31.223	-0.003
39	S-81	31.222	0

TABLE A-47 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	-0.007
41	76-92	31.222	0
42	73-74	31.222	-0.004
43	71-88	31.222	-0.005
44	53-68	31.222	-0.006
45	S-66	31.223	-0.004
46	24-37	31.223	-0.003
47	28-29	31.222	-0.004
48	31-32	31.222	-0.008
49	36-50	31.222	-0.001
50	C-11	31.222	-0.005
51	8-9	31.222	-0.004
52	5-6	31.222	-0.003
53	3-4	31.222	-0.005
54	C-1	31.222	0
Mean			-0.003
SD(b)			±0.002

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-48
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run 10, 3/31/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.590	-0.005
270 to 219	1.594	1.591	-0.003
219 to 106	3.814	3.811(b)	-0.003(b)
106 to 55	1.594	1.590	-0.004
55 to 13	1.593	1.588	-0.005
312 to 13	12.693	12.681(b)	-0.012(b)
319 to 295	0.656	0.652	-0.004
295 to 267	0.657	0.655	-0.002
267 to 235	0.656	0.653	-0.003
235 to 90	4.500	4.496(b)	-0.004(b)
90 to 58	0.656	0.653	-0.003
58 to 30	0.655	0.652	-0.003
30 to 6	0.655	0.650	-0.005
319 to 6	12.189	12.178(b)	-0.011(b)
303 to 264	1.595	1.594	-0.001
264 to 216	1.594	1.591	-0.003
216 to 109	3.814	3.814(b)	0(b)
109 to 61	1.593	1.591	-0.002
61 to 22	1.593	1.591	-0.002
303 to 22	12.693	12.691(b)	-0.002(b)
170 to 167	1.594	1.590	-0.004
167 to 164	1.595	1.593	-0.002
164 to 161	3.815	3.819(b)	0.004(b)
161 to 158	1.594	1.594	0
158 to 155	1.594	1.591	-0.003
170 to 155	12.695	12.698(b)	0.003(b)
13 to 22	6.034	6.025	-0.009
22 to 170	6.033	6.024	-0.009
170 to 312	6.033	6.036(b)	0.003(b)
312 to 303	6.034	6.025	-0.009
303 to 155	6.034	6.030	-0.004
155 to 13	6.033	6.043(b)	0.010(b)
Mean			-0.003(d)
SD(c)			±0.004

(a) QC = Quality Control.

(b) Rotational position of block different for measurements on the two holes.

(c) SD = standard deviation.

(d) Without (b)'s $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.001}$ $\frac{\text{SD}}{\pm 0.007}$.

TABLE A-49
 COOLANT HOLE DIAMETERS OF
 CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run 10, 3/31/82

Hole	QC(a)	Robot	Robot - QC
------	-------	-------	------------

6	0.627	0.631	0.004
13	0.627	0.631	0.004
22	0.627	0.630	0.003
30	0.627	0.629	0.002
55	0.626	0.628	0.002
58	0.627	0.629	0.002
61	0.627	0.629	0.002
66	0.626	0.628	0.002
81	0.626	0.630	0.004
90	0.626	0.628	0.002
103	0.626	0.628	0.002
106	0.626	0.628	0.002
109	0.626	0.628	0.002
112	0.626	0.628	0.002
126	0.498	0.501	0.003
144	0.498	0.501	0.003
145	0.498	0.501	0.003
155	0.626	0.628	0.002
158	0.626	0.628	0.002
161	0.625	0.627	0.002
164	0.626	0.627	0.001
167	0.626	0.630	0.004
170	0.626	0.631	0.005
180	0.498	0.500	0.002
181	0.498	0.500	0.002
199	0.498	0.499	0.001
213	0.625	0.629	0.004
216	0.626	0.627	0.001
219	0.626	0.627	0.001
222	0.626	0.628	0.002
235	0.626	0.627	0.001
244	0.626	0.629	0.003
259	0.626	0.628	0.002
264	0.626	0.627	0.001
267	0.626	0.627	0.001
270	0.625	0.628	0.003

TABLE A-49 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.627	0.001
303	0.626	0.628	0.002
312	0.626	0.629	0.003
319	0.626	0.630	0.004
Mean			0.002
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-50
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run 10, 3/31/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.000	9.000	8.998	26.997
	Robot - QC	-0.003	-0.002	-0.002	-0.008
2	QC	9.003	9.001	9.000	27.004
	Robot	9.003	9.003	9.000	27.005
	Robot - QC	0	0.002	0	0.001
3	QC	9.003	9.001	9.001	27.005
	Robot	8.999	8.996	8.995	26.989
	Robot - QC	-0.004	-0.005	-0.006	-0.016
4	QC	9.004	9.001	9.001	27.007
	Robot	9.005	9.004	9.001	27.009
	Robot - QC	0.001	0.003	0	0.002
5	QC	9.004	9.002	9.001	27.006
	Robot	9.002	8.998	9.007	27.006
	Robot - QC	-0.002	-0.004	0.006	0
6	QC	9.002	9.002	9.001	27.005
	Robot	8.999	9.002	9.006	27.006
	Robot - QC	-0.003	0	0.005	0.001
Robot - QC(b)					
Mean		-0.002	-0.001	0.001	-0.003
SD(c)		±0.002	±0.003	±0.004	±0.007

(a) QC = Quality Control.

(b) All robot - QC mean = -0.001, standard deviation = ±0.005.

(c) SD = standard deviation.

TABLE A-51
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run FSV1, 4/12/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.170	14.163	14.170		
	Robot - QC	-0.005	-0.013(c)	-0.005	-0.005	0
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.173	14.173	14.172		
	Robot - QC	-0.003	-0.003	-0.004	-0.003	±0.001
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.171	14.170	14.171		
	Robot - QC	-0.004	-0.004	-0.003	-0.004	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.172	14.172	14.171		
	Robot - QC	-0.002	-0.002	-0.003	-0.002	±0.001
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.167	14.169	14.170		
	Robot - QC	-0.009(d)	-0.007	-0.006	-0.007	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.165	14.171	14.173		
	Robot - QC	-0.011(d)	-0.005	-0.003	-0.006	±0.004
Robot - QC						
Mean		-0.006	-0.004	-0.004	-0.005	
SD		±0.004	±0.002	±0.001	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

(c)Low measurement believed to be the result of an irregularity in the block surface which occurred after the QC measurements were performed. This dimension has been omitted from the bias and accuracy calculations.

(d)Low measurements due to rotation of the block when contacted by the probe. These dimensions are included in the bias and accuracy calculations since the same measurements on all blocks should reflect this problem.

TABLE A-52
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position:

Sony Magnescales

Probe displacement:

Linear potentiometers

Recalibration run:

Run FSV1, 4/12/82

Axial Level ^(b)	Face A ^(c)	Face B ^(c)	Face C ^(c)	Face D ^(c)	Face E ^(c)	Face F ^(c)	Mean	SD ^(d)
2	-0.001	0	0	0	0	0	0	0
3	-0.001	0	0	0	0	0	0	0
4	-0.001	0	-0.001	0	0	0	0	±0.001
5	-0.001	0.001	0	0	0	0	0	±0.001
6	0	0	0	0	0	0	0	0
7	-0.001	0	0	0	0	0	0	0
8	-0.001	0	0	0	0	0	0	0
9	-0.001	0	0	0	0.001	0	0	±0.001
10	-0.001	0.001	0.001	0.001	0	0.001	0.001	±0.001
Mean	-0.001	0	0	0	0	0	0	--
SD	0	0	±0.001	0	0	0	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-53
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation			
Probe table position:		Sony Magnescales	
Probe displacement:		Linear potentiometers	
Recalibration run:		Run FSV1, 4/12/82	
Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.008
2	321-322	31.223	-0.009
3	S-319	31.223	-0.010
4	316-317	31.223	-0.009
5	C-314	31.223	-0.011
6	275-289	31.223	-0.011
7	293-294	31.222	-0.004
8	296-297	31.222	-0.004
9	288-301	31.223	-0.003
10	S-259	31.222	-0.007
11	257-272	31.222	-0.006
12	237-254	31.223	-0.007
13	251-252	31.222	-0.008
14	233-249	31.222	-0.008
15	246-262	31.222	-0.007
16	S-244	31.222	-0.010
17	190-209	31.223	-0.011
18	192-211	31.222	-0.014
19	195-214	31.222	-0.006
20	203-221	31.222	-0.008
21	206-224	31.222	-0.007
22	208-226	31.222	-0.006
23	C-171	31.223	-0.010
24	165-166	31.222	-0.010
25	HH-163	31.222	-0.013
26	HH-200	31.222	-0.009
27	HH-198	31.222	-0.010
28	HH-127	31.222	-0.015
29	HH-125	31.222	-0.011
30	HH-162	31.222	-0.007
31	159-160	31.222	-0.006
32	C-154	31.223	-0.009
33	99-117	31.223	-0.007
34	101-119	31.222	-0.005
35	104-122	31.222	-0.007
36	111-130	31.222	-0.009
37	114-133	31.222	-0.006
38	116-135	31.223	-0.012
39	S-81	31.222	-0.006

TABLE A-53 (Continued)

Measurement	Location	QC ^(a)	Robot - QC
40	63-79	31.222	-0.009
41	76-92	31.222	-0.008
42	73-74	31.222	-0.013
43	71-88	31.222	-0.011
44	53-68	31.222	-0.011
45	8-66	31.223	-0.017
46	24-37	31.223	-0.009
47	28-29	31.222	-0.007
48	31-32	31.222	-0.007
49	36-50	31.222	-0.010
50	C-11	31.222	-0.011
51	8-9	31.222	-0.011
52	5-6	31.222	-0.013
53	3-4	31.222	-0.009
54	C-1	31.222	-0.009
Mean			-0.009
SD ^(b)			±0.003

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-54
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run FSV1, 4/12/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.589	-0.006
270 to 219	1.594	1.589	-0.005
219 to 106	3.814	3.801(b)	-0.013(b)
106 to 55	1.594	1.585	-0.009
55 to 13	1.593	1.587	-0.006
312 to 13	12.693	12.677(b)	-0.016(b)
319 to 295	0.656	0.650	-0.006
295 to 267	0.657	0.651	-0.006
267 to 235	0.656	0.652	-0.004
235 to 90	4.500	4.490(b)	-0.010(b)
90 to 58	0.656	0.650	-0.006
58 to 30	0.655	0.648	-0.007
30 to 6	0.655	0.648	-0.007
319 to 6	12.189	12.175(b)	-0.014(b)
303 to 264	1.595	1.589	-0.006
264 to 216	1.594	1.587	-0.007
216 to 109	3.814	3.812(b)	-0.002(b)
109 to 61	1.593	1.586	-0.007
61 to 22	1.593	1.586	-0.007
303 to 22	12.693	12.688(b)	-0.005(b)
170 to 167	1.594	1.590	-0.004
167 to 164	1.595	1.591	-0.004
164 to 161	3.815	3.823(b)	0.008(b)
161 to 158	1.594	1.589	-0.005
158 to 155	1.594	1.587	-0.007
170 to 155	12.695	12.704(b)	0.009(b)
13 to 22	6.034	6.034	0
22 to 170	6.033	6.029	-0.004
170 to 312	6.033	6.022(b)	-0.011(b)
312 to 303	6.034	6.028	-0.006
303 to 155	6.034	6.029	-0.005
155 to 13	6.033	6.033(b)	0(b)
Mean			-0.006(d)
SD(c)			±0.005

(a) QC = Quality Control.

(b) Holes measured with element in different rotational positions.

(c) SD = standard deviation.

(d) Without (b)'s $\frac{\text{Mean}}{-0.006}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.005}$ $\frac{\text{SD}}{\pm 0.009}$.

TABLE A-55
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run FSV1, 4/12/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.634	0.007
13	0.627	0.634	0.007
22	0.627	0.633	0.006
30	0.627	0.633	0.006
55	0.626	0.632	0.006
58	0.627	0.633	0.006
61	0.627	0.634	0.007
66	0.626	0.630	0.004
81	0.626	0.632	0.006
90	0.626	0.631	0.005
103	0.626	0.631	0.005
106	0.626	0.634	0.008
109	0.626	0.632	0.006
112	0.626	0.632	0.006
126	0.498	0.505	0.007
144	0.498	0.504	0.006
145	0.498	0.503	0.005
155	0.626	0.632	0.006
158	0.626	0.632	0.006
161	0.625	0.632	0.007
164	0.626	0.630	0.004
167	0.626	0.631	0.005
170	0.626	0.632	0.006
180	0.498	0.505	0.007
181	0.498	0.503	0.005
199	0.498	0.504	0.006
213	0.625	0.632	0.007
216	0.626	0.631	0.005
219	0.626	0.631	0.005
222	0.626	0.631	0.005
235	0.626	0.631	0.005
244	0.626	0.633	0.007
259	0.626	0.632	0.006
264	0.626	0.632	0.006
267	0.626	0.630	0.004
270	0.625	0.630	0.005

TABLE A-55 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.630	0.004
303	0.626	0.630	0.004
312	0.626	0.630	0.004
319	0.626	0.633	0.007
Mean			0.006
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-56
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation					
Probe table position:			Sony Magnescales		
Probe displacement:			Linear potentiometers		
Recalibration run:			Run FSV1, 4/12/82		
Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	8.999	9.006	8.997	27.002
	Robot - QC	-0.004	0.004	-0.003	-0.003
2	QC	9.003	9.001	9.000	27.004
	Robot	9.002	9.000	9.002	27.004
	Robot - QC	-0.001	-0.001	0.002	0
3	QC	9.003	9.001	9.001	27.005
	Robot	9.003	9.003	8.996	27.002
	Robot - QC	0	0.002	-0.005	-0.003
4	QC	9.004	9.001	9.001	27.007
	Robot	8.994	8.999	9.002	26.995
	Robot - QC	-0.010	-0.002	0.001	-0.012
5	QC	9.004	9.002	9.001	27.006
	Robot	8.999	9.000	9.002	27.001
	Robot - QC	-0.005	-0.002	0.001	-0.005
6	QC	9.002	9.002	9.001	27.005
	Robot	8.996	9.002	9.000	26.998
	Robot - QC	-0.006	0	-0.001	-0.007
Robot - QC(b)					
Mean		-0.004	0	-0.001	-0.005
SD(c)		±0.004	±0.002	±0.003	±0.004

(a)QC = Quality Control.

(b)Total L, M, and N dimension robot - QC mean = -0.002, standard deviation = ±0.003.

(c)SD = standard deviation.

TABLE A-57
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run FSV2, 4/12/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.166	14.161	14.165		
	Robot - QC	-0.009	-0.015(c)	-0.010	-0.010	±0.001
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.168	14.164	14.166		
	Robot - QC	-0.008	-0.012	-0.010	-0.010	±0.002
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.167	14.164	14.167		
	Robot - QC	-0.008	-0.010	-0.007	-0.008	±0.002
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.165	14.166	14.163		
	Robot - QC	-0.009	-0.008	-0.011	-0.009	±0.002
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.164	14.165	14.167		
	Robot - QC	-0.012	-0.011	-0.009	-0.011	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.159	14.166	14.166		
	Robot - QC	-0.017(d)	-0.010	-0.010	-0.012	±0.004
Robot - QC						
Mean		-0.010	-0.010	-0.010	-0.010	
SD		±0.004	±0.001	±0.001	±0.002	

(a)SD = standard deviation.

(b)QC = Quality Control.

(c)Low measurement believed to be the result of an irregularity in the block surface which occurred after the QC measurements were performed. This dimension has been omitted from the bias and accuracy calculations.

(d)Low measurements due to rotation of the block when contacted by the probe. These dimensions are included in the bias and accuracy calculations since the same measurements on all blocks should reflect this problem.

TABLE A-58
SIDE-FACE BOW^(a) OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential transformers

Recalibration run: Run FSV2, 4/12/82

Axial Level(b)	Face A(c)	Face B(c)	Face C(c)	Face D(c)	Face E(c)	Face F(c)	Mean	SD(d)
2	0	0	0	0.001	0	0	0	0
3	0	0.001	0	0.001	0	0.001	0.001	±0.001
4	0	0	0.001	0	0.001	0.001	0.001	±0.001
5	0.001	0.002	0	0.001	0.001	0.001	0.001	±0.001
6	0	0.002	0	0	0	0.001	0.001	±0.001
7	0	0.001	0	0.001	0	0.001	0.001	±0.001
8	0	0.002	0	0	0	0	0	±0.001
9	-0.001	0.001	0	0	-0.001	0	0	±0.001
10	-0.001	0.001	0	0	0	0.001	0	±0.001
Mean	0	0.001	0	0	0	0.001	0	--
SD	±0.001	±0.001	0	±0.001	±0.001	±0.001	±0.001	--

(a) Average for five points.

(b) Both measured and actual bow are 0 at levels 1 and 11, by definition.

(c) The measured bow represents a measurement error since the actual bow (determined from Quality Control measurements) is 0 (<0.0005 in.) at all axial levels for all faces.

(d) SD = standard deviation.

TABLE A-59
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential
transformers

Recalibration run: Run FSV2, 4/12/82

Measurement	Location	QC ^(a)	Robot - QC
1	C-324	31.223	-0.010
2	321-322	31.223	-0.007
3	S-319	31.223	-0.008
4	316-317	31.223	-0.006
5	C-314	31.223	-0.012
6	275-289	31.223	-0.007
7	293-294	31.222	-0.006
8	296-297	31.222	-0.005
9	288-301	31.223	-0.011
10	S-259	31.222	-0.007
11	257-272	31.222	-0.007
12	237-254	31.223	-0.006
13	251-252	31.222	-0.005
14	233-249	31.222	-0.004
15	246-262	31.222	-0.012
16	S-244	31.222	-0.016
17	190-209	31.223	-0.013
18	192-211	31.222	-0.010
19	195-214	31.222	-0.007
20	203-221	31.222	-0.008
21	206-224	31.222	-0.012
22	208-226	31.222	-0.009
23	C-171	31.223	-0.012
24	165-166	31.222	-0.008
25	HH-163	31.222	-0.009
26	HH-200	31.222	-0.010
27	HH-198	31.222	-0.010
28	HH-127	31.222	-0.009
29	HH-125	31.222	-0.010
30	HH-162	31.222	-0.009
31	159-160	31.222	-0.014
32	C-154	31.223	-0.015
33	99-117	31.223	-0.010
34	101-119	31.222	-0.007
35	104-122	31.222	-0.007
36	111-130	31.222	-0.007
37	114-133	31.222	-0.007
38	116-135	31.223	-0.010
39	S-81	31.222	-0.008

TABLE A-59 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	-0.007
41	76-92	31.222	-0.011
42	73-74	31.222	-0.015
43	71-88	31.222	-0.010
44	53-68	31.222	-0.014
45	S-66	31.223	-0.014
46	24-37	31.223	-0.009
47	28-29	31.222	-0.008
48	31-32	31.222	-0.009
49	36-50	31.222	-0.011
50	C-11	31.222	-0.012
51	8-9	31.222	-0.018
52	5-6	31.222	-0.010
53	3-4	31.222	-0.007
54	C-1	31.222	-0.011
Mean			-0.010
SD(b)			±0.003

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-60
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable differential transformers

Recalibration run: Run FSV2, 4/12/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.584	-0.011
270 to 219	1.594	1.582	-0.012
219 to 106	3.814	3.797(b)	-0.017(b)
106 to 55	1.594	1.581	-0.013
55 to 13	1.593	1.583	-0.010
312 to 13	12.693	12.671(b)	-0.022(b)
319 to 295	0.656	0.647	-0.009
295 to 267	0.657	0.647	-0.010
267 to 235	0.656	0.648	-0.008
235 to 90	4.500	4.479(b)	-0.021(b)
90 to 58	0.656	0.648	-0.008
58 to 30	0.655	0.643	-0.012
30 to 6	0.655	0.643	-0.012
319 to 6	12.189	12.167(b)	-0.021(b)
303 to 264	1.595	1.586	-0.009
264 to 216	1.594	1.583	-0.011
216 to 109	3.814	3.803(b)	-0.011(b)
109 to 61	1.593	1.584	-0.009
61 to 22	1.593	1.583	-0.010
303 to 22	12.693	12.680(b)	-0.013(b)
170 to 167	1.594	1.583	-0.011
167 to 164	1.595	1.579	-0.016
164 to 161	3.815	3.819	0.004
161 to 158	1.594	1.579	-0.015
158 to 155	1.594	1.584	-0.010
170 to 155	12.695	12.688(b)	-0.007(b)
13 to 22	6.034	6.024	-0.010
22 to 170	6.033	6.019	-0.014
170 to 312	6.033	6.021	-0.012
312 to 303	6.034	6.022	-0.012
303 to 155	6.034	6.022	-0.012
155 to 13	6.033	6.024(b)	-0.009(b)
Mean			-0.012(d)
SD(c)			±0.005

(a)QC = Quality Control.

(b)Holes measured with element in different rotational positions.

(c)SD = standard deviation.

(d)Without (b)'s $\frac{\text{Mean}}{-0.011}$ $\frac{\text{SD}}{\pm 0.002}$; (b)'s only $\frac{\text{Mean}}{-0.013}$ $\frac{\text{SD}}{\pm 0.008}$.

TABLE A-61
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers

Probe displacement: Linear variable
differential

transformers

Recalibration run: Run FSV2, 4/12/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.638	0.011
13	0.627	0.638	0.011
22	0.627	0.635	0.008
30	0.627	0.638	0.011
55	0.626	0.635	0.009
58	0.627	0.637	0.010
61	0.627	0.637	0.010
66	0.626	0.638	0.012
81	0.626	0.637	0.011
90	0.626	0.636	0.010
103	0.626	0.636	0.010
106	0.626	0.637	0.011
109	0.626	0.635	0.009
112	0.626	0.632	0.006
126	0.498	0.507	0.009
144	0.498	0.508	0.010
145	0.498	0.509	0.011
155	0.626	0.636	0.010
158	0.626	0.638	0.012
161	0.625	0.634	0.009
164	0.626	0.636	0.010
167	0.626	0.637	0.011
170	0.626	0.637	0.011
180	0.498	0.509	0.011
181	0.498	0.508	0.010
199	0.498	0.509	0.011
213	0.625	0.633	0.008
216	0.626	0.634	0.008
219	0.626	0.636	0.008
222	0.626	0.634	0.008
235	0.626	0.635	0.009
244	0.626	0.639	0.013
259	0.626	0.637	0.011
264	0.626	0.636	0.010
267	0.626	0.634	0.008
270	0.625	0.636	0.011

TABLE A-61 (Continued)

Hole	QC ^(a)	Robot	Robot - QC
295	0.626	0.634	0.008
303	0.626	0.633	0.007
312	0.626	0.635	0.009
319	0.626	0.636	0.010
Mean			0.010
SD ^(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-62
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Rotary potentiometers
 Probe displacement: Linear variable differential transformers
 Recalibration run: Run FSV2, 4/12/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	9.005	9.000	9.004	27.009
	Robot - QC	0.002	-0.002	0.004	0.004
2	QC	9.003	9.001	9.000	27.004
	Robot	9.000	9.000	9.000	27.000
	Robot - QC	-0.003	-0.001	0	-0.004
3	QC	9.003	9.001	9.001	27.005
	Robot	9.006	9.000	8.997	27.003
	Robot - QC	0.003	-0.001	-0.004	-0.002
4	QC	9.004	9.001	9.001	27.007
	Robot	9.000	8.999	9.003	27.002
	Robot - QC	-0.004	-0.002	0.002	-0.005
5	QC	9.004	9.002	9.001	27.006
	Robot	9.001	9.002	8.998	27.001
	Robot - QC	-0.003	0	-0.003	-0.005
6	QC	9.002	9.002	9.001	27.005
	Robot	8.998	9.005	9.001	27.004
	Robot - QC	-0.004	0.003	0	-0.001
Robot - QC(b)					
Mean		-0.002	-0.001	0.001	-0.002
SD(c)		±0.003	±0.002	±0.003	±0.003

(a)QC = Quality Control.

(b)Total L, M, and N dimension robot - QC mean = -0.001, standard deviation = ±0.003.

(c)SD = standard deviation.

TABLE A-63
ACROSS-FLATS DIMENSIONS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run FSV3, 4/13/82

Faces/Corner	Measurement	Test Combination			Mean	SD(a)
		1-2	3-4	5-6		
A-D/2	QC(b)	14.175	14.176	14.175		
	Robot	14.171	14.167	14.172		
	Robot - QC	-0.004	-0.009(c)	-0.003	-0.004	±0.001
A-D/5	QC	14.176	14.176	14.176		
	Robot	14.175	14.172	14.172		
	Robot - QC	-0.001	-0.004	-0.004	-0.003	±0.002
B-E/3	QC	14.175	14.174	14.174		
	Robot	14.174	14.172	14.172		
	Robot - QC	-0.001	-0.002	-0.002	-0.002	±0.001
B-E/6	QC	14.174	14.174	14.174		
	Robot	14.170	14.172	14.172		
	Robot - QC	-0.004	-0.002	-0.002	-0.003	±0.0
C-F/1	QC	14.176	14.176	14.176		
	Robot	14.172	14.170	14.173		
	Robot - QC	-0.004	-0.006	-0.003	-0.004	±0.002
C-F/4	QC	14.176	14.176	14.176		
	Robot	14.164	14.175	14.173		
	Robot - QC	-0.012(d)	-0.001	-0.003	-0.005	±0.006
Robot - QC						
Mean		-0.004	-0.003	-0.003	-0.003	
SD		±0.004	±0.002	±0.001	±0.003	

(a)SD = standard deviation.

(b)QC = Quality Control.

(c)Low measurement believed to be the result of an irregularity in the block surface which occurred after the QC measurements were performed. This dimension has been omitted from the bias and accuracy calculations.

(d)Low measurements due to rotation of the block when contacted by the probe. These dimensions are included in the bias and accuracy calculations since the same measurements on all blocks should reflect this problem.

TABLE A-64
ELEMENT LENGTHS OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear potentiometers

Recalibration run: Run FSV3, 4/13/82

Measurement	Location	QC(a)	Robot - QC
1	C-324	31.223	-0.003
2	321-322	31.223	-0.003
3	S-319	31.223	-0.011
4	316-317	31.223	-0.006
5	C-314	31.223	-0.010
6	275-289	31.223	-0.008
7	293-294	31.222	-0.006
8	296-297	31.222	-0.007
9	288-301	31.223	-0.006
10	S-259	31.222	-0.004
11	257-272	31.222	-0.008
12	237-254	31.223	-0.009
13	251-252	31.222	-0.008
14	233-249	31.222	-0.008
15	246-262	31.222	-0.008
16	S-244	31.222	-0.008
17	190-209	31.223	-0.014
18	192-211	31.222	-0.011
19	195-214	31.222	-0.009
20	203-221	31.222	-0.010
21	206-224	31.222	-0.011
22	208-226	31.222	-0.011
23	C-171	31.223	-0.013
24	165-166	31.222	-0.011
25	HH-163	31.222	-0.010
26	HH-200	31.222	-0.008
27	HH-198	31.222	-0.007
28	HH-127	31.222	-0.010
29	HH-125	31.222	-0.010
30	HH-162	31.222	-0.010
31	159-160	31.222	-0.008
32	C-154	31.223	-0.010
33	99-117	31.223	-0.010
34	101-119	31.222	-0.004
35	104-122	31.222	-0.009
36	111-130	31.222	-0.008
37	114-133	31.222	-0.007
38	116-135	31.223	-0.011
39	S-81	31.222	-0.009

TABLE A-64 (Continued)

Measurement	Location	QC(a)	Robot - QC
40	63-79	31.222	-0.009
41	76-92	31.222	-0.008
42	73-74	31.222	-0.010
43	71-88	31.222	-0.012
44	53-68	31.222	-0.010
45	S-66	31.223	-0.014
46	24-37	31.223	-0.010
47	28-29	31.222	-0.012
48	31-32	31.222	-0.011
49	36-50	31.222	-0.009
50	C-11	31.222	-0.015
51	8-9	31.222	-0.013
52	5-6	31.222	-0.010
53	3-4	31.222	-0.012
54	C-1	31.222	-0.007
Mean			-0.009
SD(b)			±0.003

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-65
DISTANCES BETWEEN COOLANT HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales

Probe displacement: Linear potentiometers

Recalibration run: Run FSV3, 4/13/82

Hole to Hole	QC(a)	Robot	Robot - QC
312 to 270	1.595	1.590	-0.005
270 to 219	1.594	1.591	-0.003
219 to 106	3.814	3.805(b)	-0.009(b)
106 to 55	1.594	1.588	-0.006
55 to 13	1.593	1.588	-0.005
312 to 13	12.693	12.681(b)	-0.012(b)
319 to 295	0.656	0.652	-0.004
295 to 267	0.657	0.652	-0.005
267 to 235	0.656	0.652	-0.004
235 to 90	4.500	4.495(b)	-0.005(b)
90 to 58	0.656	0.652	-0.004
58 to 30	0.655	0.650	-0.005
30 to 6	0.655	0.649	-0.006
319 to 6	12.189	12.179(b)	-0.010(b)
303 to 264	1.595	1.591	-0.004
264 to 216	1.594	1.589	-0.005
216 to 109	3.814	3.813(b)	-0.001(b)
109 to 61	1.593	1.589	-0.004
61 to 22	1.593	1.587	-0.006
303 to 22	12.693	12.689(b)	-0.004(b)
170 to 167	1.594	1.590	-0.004
167 to 164	1.595	1.592	-0.003
164 to 161	3.815	3.821(b)	0.006(b)
161 to 158	1.594	1.591	-0.003
158 to 155	1.594	1.590	-0.004
170 to 155	12.695	12.703(b)	0.008(b)
13 to 22	6.034	6.032	-0.002
22 to 170	6.033	6.028	-0.005
170 to 312	6.033	6.027(b)	-0.006(b)
312 to 303	6.034	6.033	-0.001
303 to 155	6.034	6.030	-0.004
155 to 13	6.033	6.031(b)	-0.002(b)
Mean			-0.004(d)
SD(c)			±0.004

(a) QC = Quality Control.

(b) Holes measured with element in different rotational positions.

(c) SD = standard deviation.

(d) Without (b)'s $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.001}$; (b)'s only $\frac{\text{Mean}}{-0.004}$ $\frac{\text{SD}}{\pm 0.007}$.

TABLE A-66
COOLANT HOLE DIAMETERS OF
CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation

Probe table position: Sony Magnescales
Probe displacement: Linear potentiometers
Recalibration run: Run FSV3, 4/13/82

Hole	QC(a)	Robot	Robot - QC
6	0.627	0.632	0.005
13	0.627	0.632	0.005
22	0.627	0.632	0.005
30	0.627	0.631	0.004
55	0.626	0.631	0.005
58	0.627	0.631	0.004
61	0.627	0.631	0.004
66	0.626	0.630	0.004
81	0.626	0.630	0.004
90	0.626	0.629	0.003
103	0.626	0.631	0.005
106	0.626	0.631	0.005
109	0.626	0.630	0.004
112	0.626	0.629	0.003
126	0.498	0.503	0.005
144	0.498	0.503	0.005
145	0.498	0.502	0.004
155	0.626	0.630	0.004
158	0.626	0.630	0.004
161	0.625	0.630	0.005
164	0.626	0.630	0.004
167	0.626	0.630	0.004
170	0.626	0.632	0.006
180	0.498	0.503	0.005
181	0.498	0.502	0.004
199	0.498	0.502	0.004
213	0.625	0.631	0.006
216	0.626	0.630	0.004
219	0.626	0.629	0.003
222	0.626	0.629	0.003
235	0.626	0.629	0.003
244	0.626	0.631	0.005
259	0.626	0.630	0.004
264	0.626	0.630	0.004
267	0.626	0.630	0.004
270	0.625	0.629	0.004

TABLE A-66 (Continued)

Hole	QC(a)	Robot	Robot - QC
295	0.626	0.629	0.003
303	0.626	0.629	0.003
312	0.626	0.629	0.003
319	0.626	0.630	0.004
Mean			0.004
SD(b)			±0.001

(a)QC = Quality Control.

(b)SD = standard deviation.

TABLE A-67
DISTANCES BETWEEN FIDUCIAL HOLES OF CALIBRATION ELEMENT 8-0182 (IN.)

Instrumentation
 Probe table position: Sony Magnescales
 Probe displacement: Linear potentiometers
 Recalibration run: Run FSV3, 4/13/82

Corner No.	Measurement	L Dim	M Dim	N Dim	R Dim
1	QC	9.003	9.002	9.000	27.005
	Robot	8.998	9.003	9.001	27.002
	Robot - QC	-0.005	0.001	0.001	-0.003
2	QC	9.003	9.001	9.000	27.004
	Robot	8.996	9.010	8.989	26.995
	Robot - QC	-0.007	0.009	-0.011	-0.009
3	QC	9.003	9.001	9.001	27.005
	Robot	8.997	9.003	9.001	27.001
	Robot - QC	-0.006	0.002	0	-0.004
4	QC	9.004	9.001	9.001	27.007
	Robot	8.999	8.998	9.004	27.001
	Robot - QC	-0.005	-0.003	0.003	-0.006
5	QC	9.004	9.002	9.001	27.006
	Robot	9.005	9.002	9.002	27.009
	Robot - QC	0.001	0	0.001	0.003
6	QC	9.002	9.002	9.001	27.005
	Robot	9.002	8.999	8.999	27.000
	Robot - QC	0	-0.003	-0.002	-0.005
Robot - QC(b)					
Mean		-0.004	0.001	-0.001	-0.004
SD(c)		±0.003	±0.004	±0.005	±0.004

(a) QC = Quality Control

(b) Total L, M, and N dimension robot - QC mean = -0.001, standard deviation = ±0.004.

(c) SD = standard deviation.

APPENDIX B
GAMMA AND NEUTRON DOSE RATE CALCULATIONS

by
M. Y. WAN

B.1. GAMMA DOSE RATE CALCULATIONS

The PATH code calculated (Ref. B-1) the gamma dose rate at 91.5 cm (3 ft) from a fuel element. This analysis calculated nuclide densities of the major gamma dose contributors with the 524-nuclide FEVER model. Dose rates calculated by the PATH model were then scaled according to the nuclide densities of the major contributors to give the calculated dose rate for each fuel element. The major contributors made the following percent contributions to the total dose rate:

<u>Nuclides</u>	<u>Contribution (%)</u>
Nb-95	35.2
Cs-134	20.2
Ba-137m	18.6
Zn-95	14.1
Pr-144	7.2
Ph-106	3.7
Sb-125	0.6
Ru-103	0.4

B.2. NEUTRON COUNT RATE CALCULATIONS

B.2.1. Neutron Source Calculations

A "stand-alone burnup" code calculated the atom densities of the important neutron source isotopes Pu-238, Cm-242, and Cm-244. Table B-1

summarizes the results of the neutron source calculations. It shows that the calculated neutron source per element is extremely sensitive to burnup. A factor of 2 change in fissions per initial metal atom (FIMA) is equivalent to a factor of 10 change in the neutron source strength. Values of FIMA assumed in this analysis were taken from the GATT accountability calculation.

B.2.2. MORSE Analysis

B.2.2.1. Geometry. Figure B-1 depicts the geometric layout of the MORSE model. The fuel element is represented by a cylinder with an effective radius of 18.9 cm and a height of 79.3 cm. The SNOOPY moderator/attenuator system is placed 5.08 cm (2 in.) from the fuel element surface. The attenuator, which is composed of natural boron in rubber, is represented explicitly in the model. Holes in the attenuator are represented by rings of slits with equivalent surface areas. Due to the high thermal absorption cross section of the attenuator, most thermal neutrons reaching the attenuator will be absorbed.

B.2.2.2. Materials. The composition of materials used in the MORSE model are as follows:

	<u>Nuclides</u>	<u>Atom Density</u>
Fuel element	Th-232	3.230-4
	U-233	4.800-6
	U-235	1.022-5
	U-238	2.790-6
	B-10	1.000-6
	Carbon	6.227-2
	Silicon	1.000-3
Moderator	Hydrogen	8.380-2
	Carbon	4.300-2

TABLE B-1
NEUTRON SOURCE TERMS IN FSV SEGMENT 2 ELEMENTS

Elements	FIMA	Pu-238		Cm-242		Cm-244		Total n/element- s(a)
		Ci/ element	n/element- s(a)	Ci/ element	n/element- s(a)	Ci/ element	n/element- s(a)	
08.05.F.07	8.28	3.737	3.48+3	0.896	7.37+3	3.055-2	4.46+3	1.53+4
08.05.F.09	4.76	0.693	6.45+2	0.146	1.20+3	1.022-3	1.49+2	2.00+3
08.05.F.04	6.10	1.736	1.61+3	0.395	3.25+3	4.802-3	7.01+2	5.57+3
08.05.F.05	7.85	4.000	3.72+3	0.980	8.06+3	2.500-2	3.65+3	1.54+4
15.06.F.06	7.85	3.844	3.61+3	0.952	7.83+3	2.430-2	3.55+3	1.50+4
08.05.F.06	8.35	4.820	4.48+3	1.155	9.50+3	4.140-2	6.04+3	2.00-4
04.04.F.06	8.93	5.404	5.03+3	1.310	1.08+4	5.760-2	8.41+3	2.42+4

(a)Source conversion factors [(n/s)/Ci]:

Pu-238 = 9.3+3

Cm-242 = 8.23+3

Cm-244 = 1.46+5

Fig. B-1. Geometric layout of the neutron count rate measurements

	<u>Nuclides</u>	<u>Atom Density</u>
Attenuator	Hydrogen	4.860-2
	Natural boron	1.680-2
	Carbon	1.620-2
	Oxygen	8.100-3
	Silicon	8.100-3

B.2.2.3. Source Particle Biasing. The neutron source in the fuel element was biased such that more particles will travel in the direction of the detector. The weight of each particle was appropriately adjusted to reflect the biasing.

Figure B-2 summarizes the biasing technique. The cylindrical fuel element is divided into three equal slices. The middle slice generates 60% of the particle, and the top and bottom slices generate 20% each. In the middle slice, 75% of the neutron is generated in the front half (near the detector) and 25% in the rear half. Of the 75% neutron in the front half, 75% has a positive y direction cosine component and 25% has a negative y direction cosine component. In the top slice, 75% of the neutron has a negative z direction cosine component and 25% has a positive z direction cosine component. The opposite is true for the bottom slice.

B.2.2.4. Scoring Method. Two methods were used to calculate the thermal neutron flux in the neutron detector. In the first method, a point detector was placed in the center of the 12.7-cm (5-in.) long fission counter, and the point detector scoring method detailed in Ref. B-2 was used. This method calculates the thermal neutron flux at the center of the fission counter. The second method uses the track-length method detailed in Ref. B-3. This method calculates the average thermal flux in the fission counter. Results so far indicate that thermal neutron fluxes calculated with the two methods are generally in good agreement. Results generated using the second method were used throughout this analysis because they were more representative of the real situation.

Fig. B-2. Source biasing scheme

using the second method were used throughout this analysis because they were more representative of the real situation.

B.2.3. Detector Calibration

The SNOOPY detector system was calibrated with a Cf-252 source with source strength of 3.714 ± 6 n/s. At 10 cm from the nose of the detector, the measured count rate was 5.9 counts per second (CPS).

A MORSE calculation was performed with the calibration configuration, and the result indicated that the thermal neutron flux (group 13 through 16) due to the Cf-252 source was 3.242 ± 2 n/cm²-s in the fission counter. The sensitivity of the fission counter is, therefore,

$$\text{CPS/nv} = \frac{5.90}{3.242 \pm 2} = 1.82 \times 10^{-2} \quad .$$

B.2.4. MORSE Calculation

A MORSE calculation was performed with the geometric layout and source biasing depicted in Figs. B-1 and B-2. The calculation indicated that the average thermal neutron flux in the fission counter due to one source neutron per second in the fuel block is 9.577 ± 6 n/cm²-s ($\sigma = 50\%$). The CPS per source neutron per second is obtained by multiplying the neutron flux by the CPS/nv value obtained from the calibration calculation:

$$\text{CPS/(n/s)} = 9.577 \pm 6 \times 1.82 \times 10^{-2} = 1.744 \times 10^{-7} \quad .$$

The CPS of each fuel block may be calculated by multiplying this value with the neutron source term given in Table B-1.

B.3. REFERENCES

- B-1. Su, S., "Shielding Input for FSV Segment 2 Spent Fuel Shipping," General Atomic Company unpublished data, February 9, 1982.
- B-2. Su, S., "MORSE Calculation of Neutron Dose Rate and SNOOPY Detector Responses from Peach Bottom FTE-6 Fuel," General Atomic Company unpublished data, February 6, 1976.
- B-3. Su, S., "The Use of the MORSE Code," General Atomic Company unpublished data, August 16, 1976.