GA-A16000

UC-77

NONDESTRUCTIVE EXAMINATION OF 51 FUEL AND REFLECTOR ELEMENTS FROM FORT ST. VRAIN CORE SEGMENT 1

by

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

**GENERAL ATOMIC PROJECT 6400
DATE PUBLISHED: DECEMBER 1980**

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ABSTRACT

Fifty-one fuel and reflector elements irradiated in core segment 1 of the Fort St. Vrain High-Temperature Gas-Cooled Reactor (HTGR) were inspected dimensionally and visually in the Hot Service Facility at Fort St. Vrain in July 1979. These inspections were performed by a robotic device developed by General Atomic Company (GA) in a fraction of the time and at a fraction of the cost required for conventional inspection methods.

Time- and volume-averaged graphite temperatures for the examined fuel elements ranged from $\sim 400^{\circ}$ to 750°C . Fast neutron fluences varied from $\sim 0.3 \times 10^{25} \text{ n/m}^2$ to $1.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. Nearly all of the examined elements shrank in both axial and radial dimensions. The maximum average shrinkages observed for the elements were 1.85 mm (0.073 in.) in the length and 0.79 mm (0.031 in.) across opposing side faces. These shrinkages correspond to axial and radial strains of 0.23% and 0.22%, respectively. The maximum bow observed was 0.30 mm (0.012 in.). All of the elements were in good condition. No cracks were observed on the element surfaces. With the exception of two large chips (both noted during preirradiation visual inspections), all blemishes observed were surface markings only.

The measured data were compared with strain and bow predictions obtained from SURVEY/STRESS, a computer code that employs viscoelastic beam theory to calculate stresses and deformations in HTGR fuel elements. Differences between measured and predicted strains were small: less than 0.002 in./in. for radial strain and 0.0045 mm/mm for axial strain. Differences between measured and predicted bow were also small: less than 0.40 mm. The maximum predicted bow was about 0.50 mm and the maximum observed bow was 0.30 mm.

Although the measurements and predictions are in agreement, in that small dimensional changes and bow were both predicted and measured, some discrepancies were observed:

1. As a group, the axial strains in elements having time-averaged irradiation temperatures less than about 550°C were significantly (at the 90% confidence level) overpredicted.
2. The variation in axial strain with temperature was overpredicted.
3. There was very little correlation (correlation coefficient ≈ 0.15) between measured and predicted bow.

These discrepancies are apparently the result of inaccuracy in the design curves that define the irradiation-induced axial strain at low irradiation temperatures and fast neutron fluences. Very little low temperature, low fluence design data are available.

Because they are so small, the differences between the measurements and predictions have no significant effect on the acceptability of the performance of the fuel elements. As to the accuracy of the SURVEY/STRESS calculations, more in-pile data over a wider range of irradiation temperatures and fast neutron fluences are required before overall conclusions can be made. These data will be obtained from future inspections of FSV reload segments.

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1. INTRODUCTION

From July 6 through August 1, 1979, dimensional measurements and visual examinations of 51 fuel and reflector elements from core segment 1 were conducted in the Hot Service Facility (HSF) at Fort St. Vrain (FSV). The inspected elements included all 42 fuel blocks from region 17, half-sized top and bottom reflectors from region 17, two fuel blocks from region 5, and one fuel block from each of regions 22, 24, 25, 27, and 30. Time- and volume-averaged graphite temperatures for the examined fuel elements ranged from $\sim 400^{\circ}\text{C}$ to 750°C and element average fluences ranged from approximately $0.3 \times 10^{25} \text{ n/m}^2$ to $1.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. Five of the fuel blocks and the two reflectors were surveillance elements. These elements, readily recognized by the fiducial holes drilled in their corners, were extensively characterized prior to irradiation (Ref. 1). A summary of the segment 1 surveillance is given in Table 1-1*. These inspections were performed by a robotic device developed by General Atomic (GA) in a fraction of the time and at a fraction of the cost required for conventional inspection methods. The data obtained from these inspections of core components are used to monitor the performance of graphite blocks in the core and for verification of HTGR design methods.

*Tables and Figures appear in Sections 10 and 11, respectively.

2. DESCRIPTION OF METROLOGY ROBOT

The metrology robot (Fig. 2-1) consists of a rotary table that positions a hexagonal core component in a vertical configuration and a two-finger replaceable probe (Fig. 2-2) that can move in an x, y, and z Cartesian coordinate system (Fig. 2-3). The drive systems are powered by four programmable stepping motors. Each full step of the motors allows 0.025 mm (0.001 in.) movement in the x and y directions, 0.032 mm (0.00125 in.) movement in the z direction, and 0.03 deg of rotation. The stepping motors are coupled with free-wheeling dc motors, which serve as auxiliary drive systems. The motor drives are modularized for quick replacement and maintenance. The coordinates of the probe are predetermined by three drives including rotation, with the fourth system driving the probe into the test object. The probe contains a displacement system to allow activation of two redundant microswitch systems.

The coordinates of the probe table are determined by a magnetic encoder system (Sony Magnescales), with rotary potentiometers as a redundant backup system. The displacement of the probe itself has two Cartesian measurement systems, i.e., linear potentiometers and linear variable differential transformers (LVDTs). The position of the rotary table is measured by a dual resolver system.

Data are recorded by a microprocessor controlled data logger (Accurex Autodata 9) with paper printout and magnetic tape deck. For automated operation and on-line evaluation, an LSI 11 minicomputer system (Nuclear Data ND6620) is used. The control and data acquisition units are shown in Fig. 2-4.

The robot is instrumented with ten resistivity thermometers (RTDs) for temperature monitoring. System heatup occurs from decay heat of the irradiated fuel elements and the heat generated by the lighting required for visual inspections. Radiation- and temperature-resistant components are used as much as practicable.

Three remotely controlled black and white television camera systems for performing visual inspections are mounted on the robot. A color camera system located some distance from the robot is also used for performing visual inspections.

The metrology robot is operated in a fully automated closed-loop mode. This includes computer verification of proper movement and corrective actions with minimum or no operator interface. Intrinsic search routines are available to account for irradiation-induced shrinkage and bow of the graphite core components. Comparison of redundant measurement devices, as well as on-line data reduction, is done by the computer. This allows the system to automatically overcome potential malfunctions, such as motor stalling or missing an intended hole or surface. System redundancy is used to maximize data output and minimize downtime.

3. DESCRIPTION OF METROLOGICAL AND VISUAL INSPECTIONS

A metrological inspection consists of two calibration and five test modules:

1. Calibration Module I is conducted on the calibration cube to characterize probe deflection and robot precision and accuracy.
2. Calibration Module II is conducted on the rotary table for table orientation.
3. Test Module I consists of chord measurements at the top of the element to determine the distance across the flats [radial strain (see Fig. 3-1)].
4. Test Module II is an inspection of the six vertical block surfaces. Each surface is mapped via measurements at up to 55 points to determine the axial bow distribution (see Fig. 3-2).
5. Test Module III is an inspection of the top surface of the block at up to 54 locations to determine length changes (axial strain) and radial bow distribution (see Fig. 3-3).
6. Test Module IV measures the diameters and distances between up to 40 coolant holes at the top surface [incremental radial strain (see Fig. 3-4)].
7. Test Module V measures changes in axial length (incremental axial strain) from fiducial holes drilled into each of the six corners of special surveillance and test elements (see Fig. 3-5).

The time required for a metrological inspection of a full-size fuel element depends on the thoroughness of the inspection. The full-length inspection of a surveillance element includes 604 measurements on the block and requires ~4-1/2 h. The abbreviated inspection generally employed for nonsurveillance elements includes 370 measurements and requires ~3 h.

Visual inspections, which are performed concurrently with the metrological inspections, are done with four remotely controlled television camera systems and recorded on videotape in black and white or in color. All six sides and the top and bottom surfaces of the block are inspected. All surfaces of the block are also photographed as part of the visual inspection.

4. ROBOT PERFORMANCE

The robot and its control and peripheral hardware performed extremely well over the 27 days of nearly continuous operation at FSV. Robot components were exposed to doses of up to 3×10^6 R and temperatures close to 60°C without any observable detrimental effects. The few equipment failures that did occur are summarized in Table 4-1. None of these failures affected the robot's availability for the task, which was 100%. The failure of the video recorder did, however, prohibit videotaping of the final 12 visual inspections. The doses and maximum temperatures experienced by selected robot components are given in Table 4-2. The doses are based on readings taken by FSV Health Physics. The detector failed after the seventh element. The dose rate measurements taken in the HSF are given in Table 4-3. The measurements at 1 m are correlated with fast neutron fluences calculated for the elements in Fig. 4-1. An average dose rate of 430 R/h for all 49 inspected fuel elements was approximated based on this correlation and the average fast neutron fluence for the elements. The reflector blocks were not included in the above calculation since their contribution to total doses was assumed to be negligible. Dose rates for the robot's components were calculated from the average dose rate at 1 m and the data given in Fig. 4-2 (Ref. 2). The relationship between dose rate and distance from a spent fuel block given in this figure is corroborated by the three measurements for element 1.

The total time of irradiated fuel element residence on the robot turntable was 305 h. (The residence time for the two reflector elements was about 20 h.) In most cases, the temperatures reported in Table 4-2 are estimates, since the majority of the components were not monitored with RTDs. For these components, either the peak temperature recorded by the nearest RTD or the peak HSF air temperature is reported, depending on which

was more representative. Heatup of components can be attributed primarily to the HSF lighting, rather than the spent fuel elements. This conclusion is based on the thermal response of the probe head RTD during heatup tests* and inspections of irradiated fuel elements (Table 4-4). The relatively low thermal response of the probe head RTD to spent fuel elements when the HSF air temperature was near 50°C and comparison of the RTD response during heatup tests and spent fuel element inspections point to fuel block surface temperatures in the vicinity of 50° to 70°C.

After undergoing preliminary decontamination at FSV, the robot was shipped back to San Diego. Final decontamination was performed at the GA hot cell and the robot was returned to the laboratory. Accessible areas of the robot have been cleaned to $<25 \text{ d/m beta/100 cm}^2$, a level permitting hands-on maintenance.

*Heatup tests were performed at element surface temperatures of 50°, 100°, 150°, 200°, and 300°C, using a heatable dummy fuel block.

5. RESULTS OF METROLOGICAL INSPECTIONS

5.1. MEASURED STRAIN AND BOW

Results of the metrological inspections of the 51 fuel and reflector elements from FSV core segment 1 are presented in Tables 5-1 and 5-2. Axial strains are element averages determined from element length measurements. Radial strains are average strains at the tops of the elements, as determined from across-flats measurements.* Preirradiation measurements were performed by GA (Ref. 1) and the Great Lakes Carbon Company (CORDAX machine measurements). The calculations employed to obtain strain and bow from preirradiation data and postirradiation metrology robot measurements are described in Ref. 3. Fast neutron fluences and temperatures given in Tables 5-1 and 5-2 were obtained from SURVEY (Ref. 4) code calculations based on the GAUGE (Ref. 5) code depletion analysis of FSV cycle 1, as operated. Time- and volume-averaged graphite temperatures for the examined elements range from $\sim 400^{\circ}\text{C}$ to 750°C . Element average fast neutron fluences range from $\sim 0.3 \times 10^{25} \text{ n/m}^2$ to $1.0 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. Based on the results of thermal and nuclear design verification studies that were performed with data from the Peach Bottom HTGR (Ref. 6), the uncertainty in the fast neutron fluence is assumed to be $\pm 10\%$ (1σ) and the uncertainty in the temperature is assumed to result from the $\pm 10\%$ (1σ) uncertainty in power. As such, the temperature uncertainty can be approximated by 10% of the difference between the local temperature and the gas inlet temperature (330°C , time averaged). It should be pointed out that the doses received by the segment 1 elements, having been irradiated for

*Wobbling of the turntable (see Section 6) prevented radial strains at other axial positions along the elements from being computed from side-face measurements as had been planned. Measurements of coolant hole diameter and distance between coolant holes are too inaccurate to be used to determine radial strains in the segment 1 elements, because of the very small dimensional changes involved.

only one cycle, are significantly less than the lifetime dose which would be received by most fuel elements in an HTGR. Also, since the FSV reactor operated at much less than full power during cycle 1, the elements experienced lower temperatures than would generally be experienced by HTGR fuel elements except those in the top layers of the core. At these low temperatures and fluences, the strains are relatively small. Figures 5-1 and 5-2 are provided to give the reader some perspective as to how the segment 1 strain data relate to the range of potential strains in HTGR fuel elements.*

The axial and radial dimensions of nearly all of the 49 examined fuel elements were observed to have decreased as a result of irradiation. A few of the elements expanded slightly in the radial direction. The maximum element average axial and radial shrinkages measured for segment 1 fuel elements were 1.85 mm (0.073 in.) and 0.79 mm (0.031 in.), respectively. The maximum expansion was 0.10 mm (0.004 in.). The maximum observed bow was 0.30 mm (0.012 in.). Both of the examined reflector elements underwent very little dimensional change. Comparisons of axial strains determined from total length changes and from changes in the distances between fiducial holes (Table 5-3) indicate that the axial shrinkage was uniform over the length of the elements.

One of the objectives of the FSV surveillance program is to inspect one complete core region from each reload segment. For segment 1, region 17 was inspected. Axial strain and bow distributions measured for region 17 elements are shown in Fig. 5-3. Thermal and nuclear calculations for region 17 indicate that temperatures and neutron fluxes increased gradually from one side of the region to the other due to the presence of a partially inserted control rod in region 34. The axial strain distribution in region 17 follows the same pattern. The bow in the elements corresponds to the

*Some liberty has been taken in showing the irradiation strain in Figs. 5-1 and 5-2. Although the measured strain, which is the total strain, is not directly comparable with irradiation strain, the irradiation strain is approximately equal to the total strain in an irradiated fuel element measured at room temperature, as is later discussed.

observed axial strains. Generally speaking, faces A and D, B and E, and C and F for a given element are bowed about the same amount in opposite directions. The sides having the lower (more positive) axial strains are convex and the opposite sides are concave.

Comparisons of robot measurements with measurements for surveillance element S/N 1-0743, performed with conventional hot cell measuring techniques, and with QC measurements for calibration element S/N 8-0182 (Section 6) have shown the accuracy of the metrology robot to be ± 0.18 mm (0.007 in.) 1σ , or better, for all measurements on these two elements. During each inspection at FSV, repeated measurements were made on a precisely machined 25.4-mm (1.000-in.) cube mounted on the turntable platform of the robot, to check the precision and accuracy of robot measurements. Standard deviations for these measurements are given in Table 5-3. These data confirm the quality of robot measurements for all of the examined elements.

5.2. COMPARISONS OF MEASURED AND CALCULATED STRAINS AND BOW

Strain and bow predictions obtained using the SURVEY/STRESS (Ref. 7) code are presented along with the corresponding measurements in Tables 5-1 and 5-2. SURVEY/STRESS calculates stresses, strains, and deformations in an LHTGR fuel block based on viscoelastic beam theory. It 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 these elements are identified, they are subjected to more refined analyses using the GBEAM (Ref. 8) and SAFIRE (Ref. 9) codes. Since SURVEY/STRESS is used to calculate all important physical effects and structural interactions, the results obtained from this code should correlate reasonably well with results from the more refined analyses.

Differences between calculated and measured strains for the segment 1 elements are plotted versus fast neutron fluence in Figs. 5-4 and 5-5. Also shown in each figure is the approximate uncertainty* in the differences. The results of these comparisons are itemized below.

1. Axial Strain

- a. Differences between measured and calculated strains are less than 0.0045 in./in. In most cases, the differences are less than the progressed uncertainty (1σ).
- b. As a group, the axial strains in elements having time-averaged irradiation temperatures less than about 550°C are significantly (at the 90% confidence level) overpredicted.
- c. The agreement between measured and calculated strains varies significantly with temperature, indicating that the variation in strain with temperature is overpredicted at low fluence.
- d. For a given range of irradiation temperatures, the agreement between measured and calculated strains does not vary significantly with fast neutron fluence, indicating that the variation in strain with fluence is well predicted.

2. Radial Strain

- a. Differences between measured and calculated strains are less than 0.002 mm/mm. This is less than the uncertainty (1σ). Statistical tests show that the differences as a group can

*The uncertainty in the measured strain is negligible compared to the uncertainty in the calculated strain. The uncertainties in calculated strains were approximated using Eq. 5-2.

also be accounted for at 0.05 significance level by the progressed uncertainty.

- b. The agreement between measured and calculated strains varies mildly with both fast neutron fluence and temperature, but in general, the variation in strain with both of these parameters is well predicted.

A plot of calculated bow versus measured bow is given in Fig. 5-6. It is evident that there is little correlation (correlation coefficient ≈ 0.15) between measured and calculated bow. This result is not surprising, since it has already been observed (Fig. 5-4) that the variation in axial strain with temperature is overpredicted.

At room temperature, the total strain in an irradiated fuel element is given by

$$(\epsilon_{\text{tot}})_{\text{RT}} = \epsilon_{\text{E}} + \epsilon_{\text{CR}} + \epsilon_{\text{I}} ,$$

where ϵ_{E} = the elastic strain.

ϵ_{CR} = the creep strain.

ϵ_{I} = the irradiation strain.

Based on the stresses calculated by SURVEY/STRESS, elastic and creep strains in the segment 1 elements are relatively small. Consequently, at room temperature, the total strain should be approximately equal to the irradiation strain. This was verified via a comparison of calculated irradiation strains with total strains calculated by SURVEY/STRESS for shutdown at end-of-life.*

*The thermal strain at the 350°F shutdown temperature was subtracted from the total strain.

Irradiation strains are calculated by SURVEY/STRESS from a polynomial expression in two independent variables, temperature and fast neutron fluence. The general polynomial form presently used is

$$\begin{aligned}\epsilon_I = & (C_1 + C_2T + C_3T^2 + C_4T^3 + C_5T^4) \phi \\ & + (C_6 + C_7T + C_8T^2 + C_9T^3 + C_{10}T^4) \phi^2 \\ & + (C_{11} + C_{12}T + C_{13}T^2 + C_{14}T^3 + C_{15}T^4) \phi^3.\end{aligned}\tag{5-1}$$

The coefficients of the polynomial are found by applying the FUNFIT (Ref. 10) code to correlate a large quantity of data obtained from essentially isothermal irradiations of graphite samples. Since the irradiation strain is not linear with temperature and the temperature history for an element in a commercial reactor will never be isothermal, the irradiation strain cannot be obtained merely by plugging the current temperature and fast fluence into the polynomial. Nonisothermal irradiations are currently handled by an incremental procedure known as the "constant dose shifting rule." In a given time step, the incremental irradiation strain is the difference along an isothermal path between the strain at the end-of-step dose and the strain at the start-of-step dose. When the temperature changes, a shift is made from one isothermal path to another. The irradiation strain is obtained by summing the incremental irradiation strains.

If the total strain at room temperature is approximately equal to the irradiation strain, the uncertainty in the total strain is approximated by the uncertainty in the irradiation strain. This uncertainty is given by the equation

$$s_{\epsilon_I} = \left[\left(s_T \frac{\partial \epsilon_I}{\partial T} \right)^2 + \left(s_\phi \frac{\partial \epsilon_I}{\partial \phi} \right)^2 + s_{Fit}^2 \right]^{1/2},\tag{5-2}$$

where S_T = the uncertainty in the temperature.

S_ϕ = the uncertainty in the fast neutron fluence.

S_{Fit} = the standard deviation of the data about the design surface (0.3×10^{-2} mm/mm for axial strain and 0.375×10^{-2} mm/mm for radial strain).

$\frac{\partial \epsilon}{\partial T}$ and $\frac{\partial \epsilon}{\partial \phi}$ = the partial derivatives of the polynomial with respect to temperature and fluence.

The uncertainties shown in Figs. 5-4 and 5-5 were obtained using the above equation.

Since the calculated strain at room temperature is almost entirely irradiation strain, the observed discrepancies between measured and calculated axial strains and how can reasonably be attributed to problems in predicting the irradiation strain. Measured axial strains are compared with the design curves for dimensional change of H-327 graphite at low temperatures and fluences in Fig. 5-7.*

Two conclusions are apparent:

1. Measured axial strains in elements with time- and volume-averaged irradiation temperatures less than $\sim 550^\circ\text{C}$ are systematically lower than expected, based on the design curves.
2. Axial strains at temperatures below 750°C are less temperature-dependent than indicated by the design curves.

*The comparison is reasonably valid not only because the strain is almost entirely irradiation strain, but also because the variations in temperature and fast neutron fluence within the segment 1 elements were relatively small (see footnotes to Table 5-1). Consequently, the average strain for an element should be approximately equivalent to the strain determined from the design strain curves using the element-averaged fast neutron fluence and the element- and time-averaged irradiation temperature.

It appears that the design curves do not accurately represent the axial irradiation strain at low temperatures and fluences, particularly at temperatures below $\sim 550^{\circ}\text{C}$. Since there are little low-temperature, low-fluence strain data available for H-327 graphite, the polynomial that represents the design data is largely determined by the more abundant data at higher fluences and temperatures. The design curves at the low fluences and temperatures are probably mathematical artifacts of the polynomial, and may have no physical significance.

Because they are so small, the differences between measured and calculated strains and bow have no significant effect on the acceptability of the performance of the fuel elements. As to the accuracy of the SURVEY/STRESS calculations, more in-pile data over a wider range of irradiation temperatures and fast neutron fluences are required before overall conclusions can be made. These data will be obtained from future inspections of FSV reload segments. The approximate ranges of fast neutron fluence over which graphite strain data will be obtained from the examinations of elements from each of the original FSV core reload segments are shown in Figs. 5-1 and 5-2. In general, the data obtained at the lower end of each fast fluence range will be for lower irradiation temperatures and the data obtained at the upper end will be for high irradiation temperatures.

6. VERIFICATION OF METROLOGY ROBOT MEASUREMENTS

Comparisons of robot measurements with QC measurements on a calibration block (S/N 8-0182) and with measurements made in the GA hot cell on surveillance element S/N 1-0743* were performed to determine the accuracy of robot measurements. These comparisons are shown in Tables 6-1 through 6-13. If it is assumed that the QC measurements and the hot cell measurements are true values, the difference between one of these measurements and the corresponding robot measurement represents a metrology robot measurement error. The average difference for a given type of measurement represents a measurement bias. The variance in the differences defines the accuracy of the measurements, providing the measurements are corrected for the bias. Accuracies and biases for metrology robot measurements, as determined from these comparisons, are given in Table 6-14.

The accuracy of the metrology robot is observed to be ± 0.18 mm (0.007 in.) or, or better, for each type of robot measurement. Measurement biases were determined to be 0.05 mm (0.002 in.), or less, for all robot measurements except length measurements. The bias (ACTUAL-ROBOT) in the length measurements is 0.18 to 0.28 mm (0.007 to 0.011 in.). The reason for this bias is not currently known, but will be identified and corrected prior to the inspection of FSV segment 2. All length measurements for segment 1 fuel elements were increased by 0.18 mm (0.007 in.) to account for this bias.**

*Surveillance element S/N 1-0743 was returned to GA for destructive examination following nondestructive examination in the hot service facility at FSV.

**Length measurements were increased by 0.18 mm, rather than by the average of 0.18 and 0.28 mm, because the comparison between robot and QC measurements on the unirradiated block is thought to provide the more accurate estimate of the bias.

Comparisons of metrology robot data with the corresponding QC and hot cell postirradiation examination (PIE) measurements also revealed two mechanical defects in the robot. Errors in robot bow measurements determined from four such comparisons are shown in Table 6-15. These data clearly identify a position-dependent bias in robot bow measurements and are interpreted to indicate a slight bow in the robot structure. All bow measurements for FSV segment 1 elements were corrected for this bias.

The second mechanical defect, wobbling of the robot turntable, was deduced from comparisons of side-face displacement measurements. These comparisons are shown in Table 6-16. Unlike the bias in bow measurements, the face-dependent bias in the displacement measurements varies significantly from comparison to comparison. Consequently, no correction could be applied to the side-face displacement measurements for segment 1 elements. This precluded the calculation of radial strain at axial locations other than the top of the element. The turntable bearing has been upgraded to eliminate this problem.

7. VISUAL INSPECTION

All of the inspected elements were in good condition. No cracks were observed on any of the element surfaces. With the exception of two large chips on chamfers (both noted during preirradiation visual inspection), all observed abnormalities were surface markings only. These markings had not etched the graphite to any harmful extent. The observed abnormalities are discussed below and photographs are provided as illustrations. The first three abnormalities discussed (stains, rub marks, and interface marks) were previously observed during the inspection of core region 35 and have been well documented in Ref. 11. The format used in that report to identify the locations of these abnormalities has been adopted for Tables 7-1 through 7-3. All markings appearing on each of the examined elements are photographically documented in Ref. 12.

7.1. STAINS

Markings that can best be described as "stains" were observed on the side faces of many elements. These stains were often wavy, very dark, usually about 6 mm (0.25 in.) wide, and traversed the full length of the block in a free flowing manner. It is assumed that they resulted from water in the core that evaporated, leaving a surface residue behind. These stains were most often seen on face E of the elements; less often on faces A, D, and F; and only rarely on faces B and C. Photographs of one such stain are given in Figs. 7-1 through 7-4. The locations of all observed stains are identified in Table 7-1.

7.2. RUB MARKS

The presence of surface rub marks confirms that some relative motion occurs between adjacent elements within the core. These rub marks were

generally vertical columns of short, horizontal and parallel markings. Each marking was ~10 mm (0.375 in.) long and spaced 6 mm (0.25 in.) apart. The columns are located about 25 mm (1 in.) from both the right and left corners of the side faces. Faces A, C, D, and F of every element had these rub marks; they were occasionally observed on faces B and E as well. Rub marks were the most prevalent of all distinguishing characteristics, appearing on 34 of the 39 elements for which videotapes were made. A photograph of these rub marks is given in Fig. 7-5. The locations of all rub marks are identified in Table 7-2.

7.3. INTERFACE MARKS

Interface marks are dark or light colored bands, 45 mm (1-3/4 in.) wide, extending across the full width of the block. They were observed on all sides of control elements (column 1) and on face E of most of the regular elements. The core configuration is such that face E is always the surface of the regular elements that faces the control-rod elements. The 45-mm (1-3/4-in.)-wide band represents two chamfer widths of 22 mm (7/8 in.) each for two elements on top of each other. The control-rod column is offset vertically from the six surrounding columns by one-quarter of a block length, which coincides with the axial position observed for interface marks. It is likely that the interface marks resulted from columns that had leaned together for extended periods during operation. Over time, soot deposits or some other chemical process stained the areas above and below or between the chamfers of vertically adjacent elements and the side faces of elements in neighboring columns. A photograph of an interface mark is given in Fig. 7-6. The locations of all observed interface marks are given in Table 7-3.

7.4. SOOT DEPOSITS

Many of the elements had very dark stains along the left or right corners of the side faces, usually located near the top or bottom of the

block or adjacent to an interface mark (Fig. 7-7). Some of the soot deposits appeared to begin where rub marks ended.

7.5. SIDE FACE C SCRATCH OR STAIN

On 21 of the elements,* side face C had a straight, long vertical line down the middle of the face extending the full length of the element. Some markings had the appearance of stains while others looked like scratches. A few of these lines were very light, and, upon closer examination, appeared to be dashed lines. Several of the markings consisted of two closely spaced parallel lines rather than a single line.

Because of the straightness of the line and the fact that face C is the only surface with this particular marking, this abnormality is believed to have resulted from element handling, probably caused by the fuel-handling machine, which has a constant element orientation. An example of this is shown in Figs. 7-8 through 7-11.

7.6. FINGERPRINTS

A few elements had what appeared to be fingerprints, usually at the bottom of the side face (Fig. 7-12). These undoubtedly resulted from preirradiation handling of the element.

7.7. CHIPS OF CHAMFERS AND SCRAPED CORNERS

Two elements had large chips on the chamfer, one at the top surface and one at the bottom (Fig. 7-13). Both had been noted during the preirradiation inspection of the elements. Several corners between adjacent side faces were scraped or in some way dulled, leaving a portion of the corner flat. These scraped corners were often shiny in appearance.

*Poor illumination during some of the side face inspections may have prevented detection on more elements.

7.8. TOP SURFACE DOWELS

Many top surface inspections showed a dowel with a small chip on the flat top surface. Again, because of the consistency of this type of marking, it is believed to be a result of the fuel-handling machine interface.

A few dowels also had wear debris, which came to rest on the top of the dowels (Fig. 7-14). Apparently, material was shaved off dowel holes in the bottom of one element by dowel pins on the top of an element stacked below, and the shavings tended to accumulate on the upper dowel surface.

7.9. TOP SURFACE CIRCLE AROUND FUEL-HANDLING HOLE

Many of the elements had a dark concentric circle, approximately 150 mm (6 in.) in diam, surrounding the centrally located fuel-handling hole in the top surface (Fig. 7-15). This discoloration is also assumed to have resulted from the fuel-handling machine interface.

7.10. PAINTED LETTERS AND NUMBERS ON TOP SURFACE

Several elements were observed to have a letter H and numbers such as 101 and 111 painted on the top surfaces (Fig. 7-16). This agrees with preirradiation documentation, which states that the fuel assembly type and number were stenciled on the top surface. For most elements, the fuel assembly type was either A or H and the numbers were 101, 102, 113, 114, 125, 131, 168, 169, and 1976.

8. ACKNOWLEDGMENTS

The authors wish to acknowledge the following individuals for their contributions to the task reported in this document.

Preparation and Preirradiation 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. Cicotte (Simpact Associates)

Metrological and Visual Examination of Core Components at FSV:

C. F. Wallroth, T. L. Smith, N. I. Marsh, J. P. Smith, G. L. Hein,
F. McCord, B. L. Norman, R. D. Phelps, and all employees of Public
Services of Colorado (PSC) who participated.

Data Reduction:

F. McCord, L. I. Jameson, P. K. Koch, and R. H. Leary

Nuclear, Thermal, and Strain Calculations:

V. Malakhof, S. C. Bachelor, and W. Shen

Hot Cell Measurements:

H. O. Johnson and staff

QC Measurements:

L. E. King

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7-2. Locations of rub marks observed during surveillance of core segment 1.

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TABLE 1-1
SUMMARY OF FSV CORE SEGMENT 1 SURVEILLANCE

Element	Element Serial No.	Core Location(a)	Date (1979)	Time on Robot(b)	Number of Inspections	Inspection Version(c)
1	01-0743	17.04.F.06(d)	7/6	13:52	1	F
2	01-1989	17.04.F.09(d)	7/6	7:55	1	F
3	02-2187	17.01.F.03(d)	7/6,7/9	14:50	3	F,F _p ,F _p
4	42-1004	17.05.R.10(d)	7/10	13:28	3	F,F,F _p
5	42-1012	17.05.R.03(d)	7/11	6:00	1	F
6	01-2935	17.05.F.06	7/11	8:15	2	F,F _p
7	01-1253	05.07.F.06(d)	7/13-7/16	71:15	4	F _p ,F _p ,F _p ,F _p
8	01-0867	05.07.F.09(d)	7/16	8:35	2	F _p ,F _p
9	01-0681	17.06.F.06	7/17	3:00	1	A
10	01-0204	17.07.F.06	7/17	2:56	1	A
11	02-0286	17.01.F.05	7/17	2:42	1	A
12	01-0049	17.02.F.06	7/18	7:30	2	A,A
13	01-1624	17.03.F.06	7/18	4:25	1	A
14	01-1714	17.04.F.08	7/18	3:05	1	A
15	01-2309	17.04.F.07	7/18,7/19	8:50	2	F,A
16	01-1346	17.04.F.05	7/19	3:07	1	A
17	01-1035	17.04.F.04	7/19	3:10	1	A
18	01-2352	17.05.F.09	7/19	3:55	1	A
19	01-1032	17.06.F.09	7/19	3:10	1	A
20	01-1949	17.07.F.09	7/19,7/20	8:00	2	F,F
21	01-0891	17.02.F.09	7/20	4:25	1	A
22	01-1054	17.03.F.09	7/20	2:55	1	A
23	03-1711	17.01.F.08	7/20	2:38	1	A
24	01-1861	17.03.F.08	7/20,7/23	3:00	2	A _p ,A _p
25	01-2798	17.05.F.08	7/23	2:19	1	A
26	01-2086	17.06.F.08	7/23	6:15	2	A _p ,A _p
27	01-1574	17.07.F.08	7/24	2:17	1	A
28	02-1468	17.01.F.07	7/24	2:10	1	A _p
29	01-2035	17.02.F.08	7/24	2:30	1	A
30	01-0733	17.02.F.05	7/24,7/25	3:35	2	A _p ,A _p
31	01-1658	17.03.F.05	7/25	7:15	3	A _p ,A _p ,A
32	01-0993	17.05.F.05	7/25	3:05	1	A
33	01-4381	17.06.F.05	7/25	2:50	2	A _p ,A _p
34	01-0641	17.07.F.05	7/25	3:22	1	A
35	02-2548	17.01.F.04	7/25,7/26	1:58	1	A
36	02-2722	17.01.F.06	7/26	7:23	2	A,A
37	01-1136	17.02.F.07	7/26	2:54	1	A
38	01-1450	17.03.F.07	7/26	5:30	2	A,A _p
39	01-2008	17.05.F.07	7/26	4:16	1	A
40	01-1923	17.06.F.07	7/27	7:35	2	A,A
41	01-1446	17.07.F.07	7/27	3:15	1	A
42	04-1050	17.07.F.04	7/27	3:05	1	A
43	01-0003	17.02.F.04	7/27	3:00	1	A
44	01-0148	17.03.F.04	7/27	4:25	1	A
45	01-1215	17.05.F.04	7/30	7:30	1	A
46	01-1055	17.06.F.04	7/30	5:10	1	A
47	01-0424	25.07.F.06	7/31	2:52	1	A
48	01-0990	22.06.F.06	7/31	4:15	1	A
49	01-2928	30.04.F.06	7/31,8/1	8:45	2	A,A
50	05-2089	24.03.F.06	8/1	3:00	1	A
51	01-1262	27.02.F.06	8/1	3:15	1	A

(a) Core location 17.04.F.06 indicates core region 17, column 4, and axial layer 6. "F" indicates a fuel block element; "R" indicates a reflector.

(b) Given in hours and minutes.

(c) F = full-length inspection, A = abbreviated inspection; the subscript p indicates the inspection was only partially completed.

(d) Surveillance element.

TABLE 4-1
FAILURES IN SURVEILLANCE EQUIPMENT

Component	Reason for Failure	Comment
Sony magnescale	Broken wire in robot control cabinet	Problem diagnosed and corrected in approximately 24 h
TV camera	Power supply in camera head failed	Could not be repaired until removed from the HSF after all inspections completed
Video recorder	Random failure in control circuit caused recorder to jam in rewind mode	Failure occurred after completion of inspection for 39th element. Inoperable for remainder of inspections.
Floodlights	Burned out	Inability to turn lights off resulted in failure relatively early in life of project
Geiger-Müller counter and CdTe crystal	Never properly implemented	Not really a failure, since they never were operable
2 Stepping motor	Inleakage of cleaning fluid during decontamination	No effect on surveillance since failure occurred after completion of task

TABLE 4-2
ENVIRONMENTAL CONDITIONS FOR SELECTED ROBOT COMPONENTS

Component	Approximate Average Distance from Block (cm)	Dose(a) (R)	Approximate Peak Temperature (°C)	Maximum Rated Temperature (°C)
Nearest Sony magnescale	30	7.1×10^5	57	40
Nearest rotary potentiometer	30	7.1×10^5	57(b)	125
Nearest linear potentiometer	8	2.0×10^6	53(b)	175
Nearest LVDT	8	2.0×10^6	53(b)	149
Motor relays	46	4.3×10^5	50(b)	125
Nearest motor	30	7.1×10^5	50(b)	65
Probe limit microswitches	5	2.4×10^6	53(b)	260
Table limit microswitches	23	9.4×10^5	51(b)	538
Resolver	13	1.5×10^6	54	125
Wiring	10	1.7×10^6	53(b)	200
Nearest RTD	3	2.9×10^6	53(b)	500
Nearest TV camera	41	5.0×10^5	50(b)	50

(a) Average dose rate of 430 R/h at 1 m assumed for all fuel elements. Total residence time for irradiated fuel blocks on robot was 305 h. Dose rates at locations of components were calculated from the average dose rate at 1 m and the data given in Fig. 4-2.

(b) No direct temperature reading available. Either temperature of nearest resistivity thermometer (RTD) air temperature has been given, depending on which seems most appropriate.

TABLE 4-3
GAMMA DOSE RATE READINGS IN FSV HOT SERVICE FACILITY

Element Serial Number	Core Location	Measured Dose Rate		Date
		R/h	Distance	
01-0743	17.04.F.06	500	3 ft	7/6/79
		225	6 ft	
		200	7.5 ft	
01-1989	17.04.F.09	300	3 ft	7/6/79
		125	6 ft	
		90	7.5 ft	
02-2187	17.01.F.03	350	3 ft	7/6/69
		175	6 ft	
		100	7.5 ft	
42-1004	17.05.R.10	4.5	1 ft	7/10/79
42-1012	17.05.R.03	4.5	1 ft	7/11/79
01-2935	17.05.F.06	500	3 ft	7/11/79
01-1253	05.07.F.06	700	3 ft	7/13/79
		400	6 ft	
		200	9 ft	

TABLE 4-4
THERMAL RESPONSE OF PROBE HEAD RTD DURING HEATUP TESTS AND
SELECTED FUEL ELEMENT INSPECTIONS

Test Type	Element Surface Temperature (°C)	Fast Neutron Exposure (10^{25} n/m ²) (E > 29fJ) _{HTGR}	Probe Head RTD(a) (°C)	HSF Air Temperature(b) (°C)	Thermal Response (RTD-Air) (°C)
Heatup	300	--	77.4	42.2	35.2
Heatup	150	--	58.2	40.2	18.0
Heatup	50	--	46.4	38.3	7.9
Element inspection 1	--	0.91	43.2	35.6	7.6
Element inspection 2	--	0.30	41.7	39.4	2.3
Element inspection 49	--	0.90	48.7	47.1	1.6
Element inspection 51	--	0.95(c)	50.3	46.8	3.5

(a) Peak temperature recorded during inspection.

(b) HSF air temperature monitored by RTD mounted on camera 1 at a distance of approximately 2 m from the top of an element situated on the robot turntable.

(c) Peak fast neutron fluence calculated for the 51 inspected elements.

TABLE 5-1
RESULTS OF METROLOGICAL INSPECTIONS OF FSV SEGMENT 1 CORE COMPONENTS - AXIAL STRAIN AND BOW

Element Serial Number	Core Location	Irradiation Conditions(a)		Axial Strain(b)				Bow			Calculated Stresses(c)	
		Temperature(d) (°C)	Fast Fluence(e) ($\times 10^{25}$ n/a ²)	Measured		Calc.(f)	Difference	Measured (mm)	Calc.(g) (mm)	Difference C - M (mm)	Maximum Stress (MPa)	Maximum Stress - Strength Ratio
				(ϵ_x) _m (%)	-1 ϵ (%)	(ϵ_x) _c (%)	(ϵ_x) _c - (ϵ_x) _m (%)					
2-2187	17.01.F.03	433	0.476	-0.123	0.014	-0.473	-0.350	0.10	0.04	-0.06	6.63	0.25
1-0003	17.02.F.04	412	0.470	-0.102	0.014	-0.525	-0.423	0.10	0.16	0.06	5.96	0.22
1-0148	17.03.F.04	439	0.576	-0.136	0.017	-0.536	-0.400	0.10	0.20	0.10	6.61	0.22
1-1035	17.04.F.04	444	0.613	-0.186	0.017	-0.552	-0.366	0.13	0.21	0.08	6.67	0.24
1-1215	17.05.F.04	433	0.585	-0.138	0.017	-0.561	-0.423	0.10	0.25	0.15	6.59	0.22
1-1055	17.06.F.04	419	0.519	-0.119	0.014	-0.541	-0.422	0.08	0.27	0.19	6.45	0.24
4-1050	17.07.F.04	403	0.444	-0.091	0.017	-0.523	-0.432	0.05	0.19	0.14	5.52	0.21
2-2548	17.01.F.04	520	0.670	NA(b)	—	-0.357	—	0.15	0.11	-0.04	6.59	0.25
1-0733	17.02.F.05	485	0.678	-0.177	0.014	-0.448	-0.271	0.13	0.33	0.20	6.07	0.22
1-1658	17.03.F.05	533	0.820	-0.211	0.014	-0.374	-0.163	0.23	0.17	-0.06	6.26	0.27
1-1346	17.04.F.05	551	0.893	-0.233	0.017	-0.349	-0.116	0.28	0.03	-0.25	6.47	0.28
1-0993	17.05.F.05	528	0.852	-0.232	0.014	-0.393	-0.161	0.23	0.23	0.00	6.40	0.27
1-4381	17.06.F.05	494	0.737	-0.196	0.014	-0.444	-0.248	0.18	0.34	0.16	6.28	0.23
1-0641	17.07.F.05	467	0.641	-0.154	-0.011	-0.478	-0.324	0.05	0.41	0.36	5.76	0.21
2-0286	17.01.F.05	570	0.732	-0.110	0.017	-0.209	-0.099	0.10	0.16	0.06	5.10	0.19
1-0049	17.02.F.06	543	0.737	-0.159	0.011	-0.289	-0.130	0.18	0.38	0.20	5.32	0.20
1-1624	17.03.F.06	607	0.889	-0.178	0.014	-0.190	-0.012	0.25	0.17	-0.08	4.57	0.17
1-0743	17.04.F.06	632	0.972	-0.182	0.014	-0.158	0.024	0.30	0.05	-0.25	4.54	0.17
1-2935	17.05.F.06	601	0.927	-0.184	0.011	-0.203	-0.019	0.25	0.18	-0.08	5.02	0.19
1-0681	17.06.F.06	553	0.799	NA	—	-0.277	—	0.18	0.33	0.15	5.18	0.19
1-0204	17.07.F.06	518	0.696	NA	—	-0.336	—	0.08	0.47	0.39	5.31	0.20
2-2722	17.01.F.06	609	0.611	-0.065	0.017	-0.125	-0.060	0.05	0.13	0.08	2.97	0.11
1-1136	17.02.F.07	577	0.614	-0.090	0.014	-0.176	-0.086	0.10	0.30	0.20	3.37	0.13
1-1450	17.03.F.07	650	0.740	-0.136	0.014	-0.098	0.38	0.18	0.12	-0.06	2.68	0.10
1-2309	17.04.F.07	682	0.811	-0.120	0.014	-0.077	0.043	0.20	0.04	-0.16	1.92	0.07
1-2008	17.05.F.07	645	0.774	-0.122	0.014	-0.105	0.017	0.15	0.11	-0.04	2.70	0.10
1-1923	17.06.F.07	587	0.665	-0.095	0.014	-0.166	-0.071	0.10	0.24	0.14	3.23	0.12
1-1446	17.07.F.07	548	0.580	-0.098	0.011	-0.217	-0.119	0.05	0.27	0.22	3.43	0.13
1-1468	17.01.F.07	643	0.497	-0.033	0.014	-0.079	-0.046	0.05	0.10	0.05	1.84	0.10
1-2035	17.02.F.08	608	0.500	-0.059	0.014	-0.109	-0.050	0.05	0.22	0.17	2.12	0.08
1-1861	17.03.F.08	690	0.598	-0.055	0.017	-0.054	0.001	0.08	0.07	-0.01	1.47	0.06
1-1714	17.04.F.08	726	0.657	-0.058	0.014	-0.044	0.014	0.10	0.01	-0.09	1.00	0.05
1-2798	17.05.F.08	683	0.627	-0.061	0.011	-0.059	0.002	0.08	0.07	-0.01	1.90	0.08
1-2086	17.06.F.08	618	0.537	-0.048	0.021	-0.101	-0.053	0.05	0.17	0.12	1.94	0.08
1-1574	17.07.F.08	574	0.472	-0.055	0.014	-0.142	-0.087	0.05	0.30	0.25	2.50	0.10
3-1711	17.01.F.08	658	0.324	-0.008	0.017	-0.050	-0.042	0.03	0.06	0.03	1.63	0.12
1-0891	17.02.F.09	620	0.327	-0.013	0.017	-0.067	-0.054	0.03	0.14	0.11	2.06	0.10
1-1054	17.03.F.09	710	0.391	-0.025	0.014	-0.033	-0.008	0.03	0.04	0.01	1.95	0.09
1-1989	17.04.F.09	750	0.436	-0.035	0.011	-0.029	-0.006	0.03	0.00	-0.03	1.30	0.06
1-2352	17.05.F.09	704	0.416	-0.030	0.021	-0.036	-0.006	0.03	0.04	0.01	2.50	0.12
1-1032	17.06.F.09	633	0.352	-0.023	0.014	-0.062	-0.039	0.03	0.11	0.08	1.18	0.05
1-1949	17.07.F.09	586	0.309	-0.026	0.014	-0.089	-0.063	0.05	0.19	0.14	2.08	0.08
1-1253	5.07.F.06	594	0.815	NA	—	-0.197	—	0.20	0.17	-0.03	4.38	0.16
1-0424	25.07.F.06	603	0.631	-0.100	0.017	-0.146	-0.046	0.15	0.16	0.01	3.41	0.13
1-0990	22.06.F.06	661	0.640	-0.081	0.017	-0.094	-0.013	0.13	0.37	0.24	3.48	0.14
1-2928	30.04.F.06	599	0.747	-0.123	0.017	-0.184	-0.061	0.13	0.09	-0.04	4.04	0.19
5-2089	24.03.F.06	556	0.501	-0.073	0.014	-0.193	-0.120	0.10	0.44	0.34	3.85	0.21
1-1262	27.02.F.06	690	0.974	-0.152	0.017	-0.092	0.060	0.18	0.05	-0.13	2.61	0.13
1-0867	05.07.F.09	687	NC	-0.041	0.011	NC	—	0.03	NC	—	NC	NC
42-1004	17.05.R.10	NC(1)	NC	0.005	0.027	NC	—	0.03	NC	—	NC	NC
42-1012	17.05.R.03	NC	NC	NC	—	NC	—	NC	NC	—	NC	NC

(a) Irradiation conditions were obtained from SURVEY (Ref. 4) code calculations based on the GADGE (Ref. 5) code depletion analysis of FSV cycle 1, as operated.

(b) Axial strains are element averages.

(c) Calculated stresses were obtained from SURVEY/STRESS.

(d) Temperatures are time and volume averaged. The 1 σ uncertainty in the time- and volume-averaged temperature is estimated by the equation: $\sigma_T = 0.1 (T - 330)$, where 330°C is the time-averaged gas inlet temperature. The root mean square (RMS) variations in temperature with time were approximately 45°, 65°, 75°, 80°, 85°, and 90°C for fuel blocks in core layers 4, 5, 6, 7, 8, and 9, respectively. The RMS variation in time-averaged temperature with volume was approximately 30°C for all fuel elements. These RMS variations were obtained from the temperatures for the elements in column 1 of region 17. The temperatures for these elements are fairly representative of the temperatures for the entire region.

(e) Fast neutron fluences, ($E > 29$ fJ)_{HTGR}, are volume averaged. The uncertainty in the fluence is assumed to be $\pm 10\%$ (1 σ). The RMS variation in fast neutron fluence with volume is less than 0.2×10^{25} n/a² for all elements.

(f) Calculated strains were obtained from SURVEY/STRESS (Ref. 7). The strains listed in this table were obtained by subtracting the thermal strain for 350°F, (0.027×10^{-2} in./in.), from the end-of-life shutdown strain given by SURVEY/STRESS for axial point 3, the element midplane.

(g) Calculated bow was obtained from SURVEY/STRESS.

(h) NA = Not available.

(i) NC = Not calculated.

TABLE 5-2
RESULTS OF METROLOGICAL INSPECTIONS OF FSV SEGMENT 1 CORE COMPONENTS - RADIAL STRAIN

Element Serial Number	Core Location	Irradiation Conditions(a)		Radial Strain(b)			
		Temperature(c) (°C)	Fast Fluence(d) ($\times 10^{25}$ n/m ²)	Measured		Calculated(e) (ϵ_x) _c	Difference (ϵ_x) _c - (ϵ_x) _M
				(ϵ_x) _M %	$\pm 1\sigma$ %		
2-2187	17.01.F.03	408	0.245	-0.038	0.029	0.021	0.059
1-0003	17.02.F.04	394	0.207	-0.003	0.025	0.019	0.022
1-0148	17.03.F.04	410	0.266	-0.022	0.025	0.022	0.044
1-1035	17.04.F.04	419	0.271	-0.070	0.020	0.021	0.091
1-1215	17.05.F.04	410	0.259	-0.063	0.071	0.021	0.084
1-1055	17.06.F.04	395	0.240	-0.046	0.047	0.021	0.067
4-1050	17.07.F.04	387	0.196	-0.020	0.025	0.018	0.038
2-2548	17.01.F.04	474	0.591	-0.086	0.018	0.016	0.102
1-0733	17.02.F.05	448	0.593	-0.091	0.015	0.026	0.117
1-1658	17.03.F.05	484	0.722	-0.100	0.042	0.010	0.110
1-1346	17.04.F.05	496	0.775	-0.142	0.021	0.003	0.145
1-0993	17.05.F.05	479	0.740	-0.120	0.025	0.011	0.131
1-4381	17.06.F.05	455	0.649	-0.107	0.042	0.021	0.128
1-0641	17.07.F.05	434	0.560	-0.070	0.011	0.030	0.100
2-0286	17.01.F.05	546	0.717	-0.071	0.032	-0.019	0.052
1-0049	17.02.F.06	516	0.725	-0.150	0.030	-0.005	0.145
1-1624	17.03.F.06	572	0.873	-0.219	0.031	-0.036	0.183
1-0743	17.04.F.06	594	0.956	-0.130	0.026	-0.052	0.078
1-2935	17.05.F.06	567	0.913	-0.152	0.032	-0.038	0.114
1-0681	17.06.F.06	525	0.786	-0.162	0.029	-0.013	0.149
1-0204	17.07.F.06	494	0.685	-0.129	0.024	-0.005	0.134
2-2722	17.01.F.06	582	0.678	-0.009	0.044	-0.036	-0.045
1-1136	17.02.F.07	533	0.692	-0.096	0.027	-0.021	0.075
1-1450	17.03.F.07	620	0.831	-0.086	0.035	-0.056	0.030
1-2309	17.04.F.07	649	0.912	-0.103	0.042	-0.075	0.028
1-2008	17.05.F.07	616	0.870	-0.087	0.020	-0.060	0.027
1-1923	17.06.F.07	563	0.746	-0.075	0.019	-0.030	0.045
1-1446	17.07.F.07	527	0.653	-0.064	0.015	-0.010	0.054
1-1468	17.01.F.07	627	0.562	-0.015	0.025	-0.043	-0.028
1-2035	17.02.F.08	593	0.564	-0.030	0.014	-0.029	0.001
1-1861	17.03.F.08	672	0.678	-0.029	0.035	-0.063	-0.034
1-1714	17.04.F.08	706	0.743	-0.017	0.029	-0.081	-0.064
1-2798	17.05.F.08	666	0.709	-0.036	0.021	-0.065	-0.029
1-2086	17.06.F.08	604	0.609	-0.043	0.021	-0.037	0.006
1-1574	17.07.F.08	562	0.533	0.015	0.033	-0.018	0.033
3-1711	17.01.F.08	652	0.411	0.022	0.034	-0.038	0.060
1-0891	17.02.F.09	616	0.420	0.012	0.030	-0.028	0.040
1-1054	17.03.F.09	701	0.500	0.010	0.032	-0.055	0.045
1-1989	17.04.F.09	741	0.556	0.014	0.025	-0.071	0.057
1-2352	17.05.F.09	696	0.531	0.009	0.023	-0.058	0.049
1-1032	17.06.F.09	626	0.450	0.016	0.030	-0.034	0.018
1-1949	17.07.F.09	581	0.397	0.002	0.020	-0.019	0.017
1-1253	05.07.F.06	557	0.818	0.121	0.039	-0.029	0.092
1-0424	25.07.F.06	565	0.638	0.051	0.027	-0.021	0.030
1-0990	22.06.F.06	612	0.633	0.029	0.024	-0.040	0.011
1-2928	30.04.F.06	560	0.739	0.104	0.029	-0.024	0.080
5-2089	24.03.F.06	523	0.498	0.029	0.061	-0.003	0.032
1-1262	27.02.F.06	642	0.971	0.100	0.024	-0.078	0.022
1-0867	05.07.F.09	680	0.428	0.004	0.019	NC(f)	--
42-1004	17.05.R.10	NC	NC	-0.013	0.017	NC	--
42-1012	17.05.R.03	NC	NC	NC	--	NC	--

(a) Irradiation conditions obtained from SURVEY (Ref. 4) code calculations based on the GAUGE (Ref. 5) code depletion analysis of FSV cycle 1, as operated. Conditions are those near the top of the block.

(b) Radial strains are element averages at the top of the block.

(c) Temperatures are time and volume averaged. The 1 σ uncertainty in temperature is estimated by $S_T = 0.1$ (T-330), where 330°C is the time-averaged gas inlet temperature.

(d) Fast neutron fluences are volume averaged (actually averaged over the cross sectional area near the top of the element, as are temperatures). The uncertainty in the fast fluence, ($E > 29$ fJ) HTGR is assumed to be $\pm 10\%$ (1 σ).

(e) The strains listed in this table were obtained by subtracting the thermal strain for 350°F, (0.056×10^{-2} in./in.), from the end-of-life shutdown strain given by SURVEY/STRESS for axial point 1, the top of the elements.

(f) NC = Not calculated.

TABLE 5-3
COMPARISON OF AXIAL STRAINS DETERMINED FROM DISTANCE BETWEEN FIDUCIAL HOLE
AND ELEMENT LENGTH MEASUREMENTS

Element Serial Number	Core Location	Dimension(a)	Axial Strain (%)						Block Average (%)
			Corner 1 (%)	Corner 2 (%)	Corner 3 (%)	Corner 4 (%)	Corner 5 (%)	Corner 6 (%)	
1-0743	17.04.F.06	L	-0.222	-0.244	-0.302	-0.096	-0.080	-0.230	-0.196
		M	-0.256	-0.346	-0.191	-0.108	-0.113	-0.296	-0.218
		N	-0.289	-0.246	-0.152	-0.063	-0.096	-0.108	-0.159
		L, M, & N	-0.256	-0.279	-0.215	-0.089	-0.096	-0.211	-0.191
		Element length	-0.239	-0.244	-0.205	-0.129	-0.127	-0.189	-0.189
1-1989	17.04.F.09	L	-0.043	-0.104	-0.007	-0.014	-0.098	-0.072	-0.056
		M	-0.042	0.016	-0.082	-0.083	0.019	0.003	-0.028
		N	-0.031	-0.073	0.038	-0.092	-0.003	-0.014	-0.029
		L, M, & N	-0.039	-0.054	-0.017	-0.063	-0.027	-0.028	-0.038
		Element length	-0.039	-0.039	-0.045	-0.030	-0.023	-0.042	-0.036
2-2187	17.01.F.03	L	-0.097	-0.158	0.031	-0.069	-0.092	-0.092	-0.079
		M	-0.080	-0.108	-0.103	-0.047	-0.119	-0.064	-0.087
		N	-0.097	-0.119	-0.075	-0.108	-0.064	-0.136	-0.100
		L, M, & N	-0.091	-0.128	-0.049	-0.075	-0.092	-0.097	-0.089
		Element length	-0.147	-0.141	-0.112	-0.109	-0.112	-0.142	-0.127
1-1253	05.07.F.06	L	-0.194	-0.235	-0.205	-0.192	-0.141	-0.247	-0.202
		M	-0.213	-0.281	-0.188	-0.092	-0.104	-0.135	-0.169
		N	-0.192	-0.188	-0.202	-0.099	-0.075	-0.110	-0.144
		L, M, & N	-0.200	-0.235	-0.198	-0.128	-0.107	-0.164	-0.172
		Element length	-0.168	-0.192	-0.179	-0.127	-0.112	-0.138	-0.153
Average for four elements		L							-0.133
		M							-0.126
		N							-0.108
		L, M, & N							-0.123
		Element length							-0.126

(a) See Fig. 3-5.

TABLE 5-4
STANDARD DEVIATIONS (PRECISION) FOR ROBOT MEASUREMENTS
PERFORMED ON CALIBRATION CUBE

Inspection Number	Precision $\pm 1\sigma$				
	ΔX Measured with Z leg (in.)	ΔY Measured with Z leg (in.)	Z Coordinate Measured with Z leg (in.)	Y Coordinate measured with Y leg (in.)	Z Coordinate measured with Y leg (in.)
1	0.001	0.001	0.002	0.001	0.001
2	0.001	0.001	0.001	0.001	0.003
3	0.001	0.001	0.002	0.000	0.003
4	0.001	0.001	0.002	0.000	0.002
5	0.001	0.000	0.002	0.000	0.001
6	0.002	0.001	0.001	0.000	0.002
7a	0.003	0.002	0.002	0.001	0.001
7b	0.001	0.000	0.002	0.000	0.002
8	0.001	0.001	0.001	0.001	0.002
9	0.002	0.002	0.001	0.000	0.000
10	0.001	0.002	0.001	0.001	0.000
11	0.001	0.001	0.003	0.000	0.001
12	0.002	0.002	0.001	0.001	0.004
13	0.002	0.000	0.002	0.000	0.002
14	0.002	0.001	0.002	0.001	0.002
15	0.002	0.001	0.002	0.001	0.001
16	0.001	0.000	0.003	0.001	0.002
17	0.001	0.001	0.003	0.000	0.001
18	0.002	0.001	0.004	0.001	0.003
19	0.001	0.000	0.002	0.000	0.002
20	0.001	0.001	0.002	0.000	0.002
21	0.001	0.001	0.003	0.000	0.002
22	0.002	0.001	0.002	0.001	0.002
23	0.001	0.001	0.003	0.001	0.002
24a	0.003	0.001	0.003	0.001	0.001
24b	0.001	0.001	0.002	0.001	0.001
25	0.001	0.001	0.001	0.001	0.002
26a	0.000	0.000	0.002	0.001	0.001
26b	0.000	0.000	0.004	0.000	0.001
27	0.001	0.001	0.002	0.001	0.003
28	0.001	0.001	0.002	0.001	0.002
29	0.001	0.001	0.002	0.000	0.003
30a	0.001	0.001	0.002	0.001	0.000
30b	0.001	0.001	0.002	0.000	0.002
31a	0.001	0.001	0.002	0.000	0.003
31b	0.000	0.001	0.002	0.000	0.002
32	0.001	0.003	0.002	0.001	0.002
33a	0.001	0.000	0.002	0.001	0.002
33b	0.001	0.000	0.002	0.000	0.003
34	0.000	0.000	0.001	0.000	0.001
35	0.001	0.001	0.002	0.001	0.002
36a	0.001	0.001	0.003	0.000	0.002
37	0.001	0.001	0.002	0.001	0.001
38	0.001	0.001	0.002	0.001	0.001
39	0.001	0.001	0.002	0.001	0.002
40	0.001	0.001	0.002	0.000	0.002
41	0.001	0.001	0.001	0.000	0.000
42	0.001	0.003	0.003	0.001	0.002
43	0.001	0.001	0.002	0.001	0.002
44	0.000	0.001	0.003	0.001	0.002
45	0.001	0.001	0.003	0.001	0.003
46	0.001	0.000	0.002	0.001	0.003
47	0.001	0.001	0.003	0.001	0.002
48	0.002	0.001	0.003	0.000	0.001
49	0.002	0.001	0.003	0.000	0.001
50	0.002	0.001	0.002	0.001	0.001
51	0.002	0.001	0.003	0.000	0.002
Av	0.001	0.001	0.002	0.001	0.002

TABLE 6-1
COMPARISON OF ROBOT AND HOT CELL AXIAL DIMENSION
MEASUREMENTS FOR SURVEILLANCE ELEMENT S/N 1-0743

Corner Number	Measurements ^(a)	L(b) Dimension	M(b) Dimension	N(b) Dimension	P(b) Dimension	R(b) Dimension	S(b) Dimension
1	Robot	8.975	8.979	8.981	2.270	26.935	31.150
	PIE	8.964	8.976	8.985	2.258	26.925	31.167
	PIE-Robot	-0.011	-0.003	0.004	-0.012	-0.010	0.017
2	Robot	8.980	8.970	8.979	2.261	26.929	31.147
	PIE	8.987	8.979	8.980	2.258	26.946	31.165
	PIE-Robot	0.007	0.009	0.001	-0.003	0.017	0.018
3	Robot	8.987	8.984	8.973	2.273	26.944	31.159
	PIE	8.989	8.984	8.982	2.252	26.955	31.180
	PIE-Robot	0.002	0	0.009	-0.021	0.011	0.021
4	Robot	8.996	8.990	8.993	2.260	26.979	31.182
	PIE	8.991	8.996	8.986	2.256	26.973	31.195
	PIE-Robot	-0.005	0.006	-0.007	-0.004	-0.006	0.013
5	Robot	8.993	8.990	8.994	2.261	26.977	31.182
	PIE	8.993	8.994	8.991	2.252	26.978	31.196
	PIE-Robot	0	0.004	-0.003	-0.009	0.001	0.014
6	Robot	8.992	8.975	8.980	2.278	26.947	31.164
	PIE	8.977	8.986	8.988	2.252	26.951	31.180
	PIE-Robot	-0.015	0.011	0.008	-0.026	0.004	0.016
Average	PIE-Robot						
	Average	-0.004	0.005	0.002	-0.012	0.003	0.017
	Standard Deviation	±0.008	±0.005	±0.006	±0.009	±0.010	±0.003

(a) All dimensions in inches.

(b) See Fig. 3-5.

TABLE 6-2
COMPARISON OF ROBOT AND HOT CELL DISTANCE BETWEEN COOLANT HOLE MEASUREMENTS FOR
SURVEILLANCE ELEMENT S/N 1-0743

Measurement	Distance Between Coolant Holes (Inches)								Mean	Standard Deviation
	312-270	270-219	219-106	106-55	55-13	312-13				
Robot	1.593	1.593	3.814	1.593	1.594	12.688				
PIE	1.591	1.598	3.813	1.594	1.594	12.681				
PIE-Robot	-0.002	0.005	-0.001	0.001	0	0.007			-0.001	±0.004
	319-295	295-267	267-235	235-90	90-58	58-30	30-6	319-6		
Robot	0.646	0.665	0.639	4.514	0.657	0.648	0.658	12.181		
PIE	0.655	0.660	0.657	4.498	0.660	0.655	0.658	12.179		
PIE-Robot	0.009	-0.005	0.018	-0.016	0.003	0.006	0	-0.002	0.002	±0.010
	303-264	264-216	216-109	109-61	61-22	303-22				
Robot	1.589	1.590	3.819	1.585	1.586	12.669				
PIE	1.595	1.594	3.814	1.593	1.594	12.681				
PIE-Robot	0.006	0.004	-0.005	0.008	0.008	0.012			0.005	±0.006
	170-167	167-164	164-161	161-158	158-155	170-155				
Robot	1.585	1.589	3.826	1.593	1.590	12.684				
PIE	1.593	1.591	3.817	1.593	1.593	12.678				
PIE-Robot	0.008	0.002	-0.009	0	0.003	-0.006			0	±0.006
	13-22	22-170	170-312	312-303	303-155	155-13				
Robot	6.028	6.026	6.025	6.024	6.027	6.025				
PIE	6.033	6.022	6.024	6.028	6.028	6.031				
PIE-Robot	0.005	-0.004	-0.001	0.004	0.001	0.006				
Average									0.002	±0.004
PIE-Robot									0.002	±0.007

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TABLE 6-3
COMPARISON OF ROBOT AND HOT CELL ACROSS-FLATS
MEASUREMENTS FOR SURVEILLANCE ELEMENT S/N 1-0743

Faces	Measurement ^(a)	1	2	3	4	5	6	Average	Standard Deviation
A-D	Robot	14.147	14.150	14.149	14.155	14.156	14.148	0.003	±0.003
	PIE	14.151	14.151	14.154	14.154	14.156	14.157		
	PIE-Robot	0.004	0.001	0.005	-0.001	0	0.009		
B-E	Robot	14.153	14.150	14.152	14.150	14.150	14.150	0.003	±0.001
	PIE	14.154	14.154	14.154	14.154	14.153	14.154		
	PIE-Robot	0.001	0.004	0.002	0.004	0.003	0.004		
C-F	Robot	14.150	14.151	14.154	14.153	14.154	14.157	0.001	±0.005
	PIE	14.159	14.157	14.154	14.154	14.152	14.151		
	PIE-Robot	0.009	0.006	0	0.001	-0.002	-0.006		
Block Average	PIE-Robot							0.002	±0.004

(a) All dimensions in inches.

TABLE 6-4
COMPARISON OF ROBOT AND HOT CELL LENGTH
MEASUREMENTS FOR SURVEILLANCE ELEMENT
S/N 1-0743

Measurement	Location	Robot (in.)	PIE (in.)	PIE- Robot (in.)
1	C-324	31.150	31.170	+0.020
2	321-322	31.154	31.169	+0.015
3	S-319	31.147	31.168	+0.021
4	316-317	31.148	31.168	+0.020
5	C-314	31.147	31.167	+0.020
6	275-289	31.147	31.170	+0.023
7	293-294	31.155	31.171	+0.016
8	296-297	31.154	31.173	+0.019
9	288-301	31.163	31.173	+0.010
10	S-259	31.163	31.175	+0.012
11	257-272	31.164	31.176	+0.012
12	237-254	31.162	31.178	+0.016
13	251-252	31.160	ND(a)	ND
14	233-249	31.156	31.178	+0.022
15	246-262	31.153	31.175	+0.022
16	S-244	31.155	31.173	+0.018
17	190-209	31.156	31.178	+0.022
18	192-211	31.162	31.179	+0.017
19	195-214	31.162	31.181	+0.019
20	203-221	31.166	31.181	+0.015
21	206-224	31.168	31.180	+0.012
22	208-226	31.166	31.179	+0.013
23	C-171	31.164	31.182	+0.018
24	165-166	31.163	31.182	+0.019
25	HH-163	31.169	ND	ND
26	HH-200	31.161	ND	ND
27	HH-198	31.164	ND	ND
28	HH-127	31.166	ND	ND
29	HH-125	31.167	ND	ND
30	HH-162	31.162	ND	ND
31	159-160	31.165	31.184	+0.019
32	C-154	31.159	31.182	+0.023
33	99-117	31.173	31.185	+0.012
34	101-119	31.174	31.189	+0.015
35	104-122	31.171	ND	ND
36	111-130	31.167	ND	ND
37	114-133	31.173	31.189	+0.016
38	116-135	31.169	31.186	+0.017
39	S-81	31.174	31.190	+0.016
40	63-79	31.173	31.192	+0.019
41	76-92	31.171	ND	ND
42	73-74	31.172	ND	ND
43	71-88	31.178	ND	ND
44	53-68	31.179	31.193	+0.014
45	S-66	31.175	31.190	+0.015
46	24-37	31.183	31.192	+0.009
47	28-29	31.178	31.196	+0.018
48	31-32	31.180	31.197	+0.017
49	36-50	31.177	31.193	+0.016
50	C-11	31.182	31.197	+0.015
51	8-9	31.180	31.196	+0.016
52	S-6	31.182	31.191	+0.009
53	3-4	31.185	31.196	+0.011
54	C-1	31.182	31.197	+0.015
Mean				
Standard		31.1662	31.1824	+0.0165
Deviation				±0.0037

(a) ND = Not determined.

TABLE 6-5
COMPARISON OF ROBOT AND HOT CELL COOLANT HOLE DIAMETER
MEASUREMENTS FOR SURVEILLANCE ELEMENT S/N 1-0743

Hole	Coolant Hole Diameters (Inches)		
	Robot	PIE	PIE-Robot
6	0.625	0.623	-0.002
13	0.625	0.623	-0.002
22	0.626	0.622	-0.004
30	0.624	0.623	-0.001
55	0.623	0.622	-0.001
58	0.625	0.623	-0.002
61	0.625	0.622	-0.003
66	0.624	0.623	-0.001
81	0.624	0.623	-0.001
90	0.624	0.623	-0.001
103	0.624	0.623	-0.001
106	0.624	0.623	-0.001
109	0.624	0.623	-0.001
112	0.625	0.622	-0.003
126	0.499	0.498	-0.001
144	0.500	0.497	-0.003
145	0.499	0.498	-0.001
155	0.623	0.623	0
158	0.623	0.623	0
161	0.623	0.623	0
164	0.624	0.622	-0.002
167	0.624	0.623	-0.001
170	0.624	0.623	-0.001
180	0.500	0.497	-0.003
181	0.499	0.498	-0.001
199	0.499	0.497	-0.002
213	0.623	0.623	0
216	0.624	0.623	-0.001
219	0.624	0.623	-0.001
222	0.624	0.623	-0.001
235	0.624	0.623	-0.001
244	0.624	0.622	-0.002
259	0.624	0.623	-0.001
264	0.623	0.623	0
267	0.622	0.622	0
270	0.623	0.622	-0.001
295	0.625	0.623	-0.002
303	0.623	0.622	-0.001
312	0.624	0.623	-0.001
319	0.622	0.622	0
Average			-0.001
Std Dev.			±0.001

TABLE 6-6
ROBOT AND HOT CELL BOW MEASUREMENTS FOR SURVEILLANCE
ELEMENT S/N 1-0743
(inches) (a)

Position	Face A		Face B		Face C		Face D		Face E		Face F	
	Robot (b)	PIE	Robot	PIE	Robot	PIE	Robot	PIE	Robot	PIE	Robot	PIE
6 (c)	+0.0040	+0.0036	+0.0047	+0.0047	+0.0044	+0.0021	-0.0016	-0.0019	-0.0026	-0.0034	-0.0004	-0.0018
7	+0.0049	+0.0023	+0.0064	+0.0046	+0.0042	+0.0021	-0.0017	-0.0018	-0.0006	-0.0031	-0.0003	-0.0020
8	+0.0050	+0.0023	+0.0074	+0.0019	+0.0042	+0.0028	-0.0008	-0.0014	-0.0024	-0.0047	-0.0012	-0.0021
9	+0.0049	+0.0026	+0.0055	+0.0043	+0.0044	+0.0031	-0.0007	-0.0016	-0.0025	-0.0035	-0.0002	-0.0021
10	+0.0031	+0.0019	+0.0066	+0.0047	+0.0053	+0.0032	+0.0015	-0.0009	-0.0024	-0.0034	-0.0013	-0.0021
11	+0.0052	+0.0034	+0.0112	+0.0081	+0.0076	+0.0053	0	-0.0017	-0.0048	-0.0063	-0.0016	-0.0039
12	+0.0068	+0.0044	+0.0100	+0.0077	+0.0058	+0.0052	+0.0006	-0.0027	-0.0040	-0.0057	-0.0024	-0.0040
13	+0.0060	+0.0041	+0.0118	+0.0039	+0.0074	+0.0045	-0.0016	-0.0027	-0.0028	-0.0066	-0.0024	-0.0040
14	+0.0058	+0.0037	+0.0108	+0.0074	+0.0074	+0.0044	-0.0014	-0.0033	-0.0042	-0.0059	-0.0006	-0.0033
15	+0.0070	+0.0056	+0.0094	+0.0079	+0.0068	+0.0037	-0.0022	-0.0031	-0.0032	-0.0066	+0.0002	-0.0030
16	+0.0090	+0.0066	+0.0121	+0.0097	+0.0092	+0.0054	-0.0028	-0.0040	-0.0058	-0.0088	+0.0008	-0.0040
17	+0.0087	+0.0048	+0.0132	+0.0093	+0.0106	+0.0055	-0.0021	-0.0044	-0.0048	-0.0084	-0.0009	-0.0044
18	+0.0080	+0.0055	+0.0132	+0.0058	+0.0086	+0.0058	-0.0004	-0.0034	-0.0052	-0.0096	-0.0026	-0.0052
19	+0.0087	+0.0053	+0.0125	+0.0098	+0.0092	+0.0063	-0.0001	-0.0032	-0.0055	-0.0084	-0.0016	-0.0051
20	+0.0073	+0.0046	+0.0128	+0.0100	+0.0089	+0.0065	+0.0005	-0.0023	-0.0062	-0.0087	-0.0019	-0.0052
21	+0.0084	+0.0054	+0.0144	+0.0110	+0.0092	+0.0073	0	-0.0027	-0.0066	-0.0099	-0.0032	-0.0058
22	+0.0086	+0.0060	+0.0150	+0.0111	+0.0106	+0.0068	+0.0002	-0.0035	-0.0070	-0.0100	-0.0018	-0.0056
23	+0.0090	+0.0064	+0.0146	+0.0078	+0.0098	+0.0066	-0.0002	-0.0038	-0.0066	-0.0109	-0.0018	-0.0058
24	+0.0096	+0.0058	+0.0136	+0.0106	+0.0108	+0.0061	-0.0008	-0.0049	-0.0064	-0.0098	-0.0002	-0.0052
25	+0.0100	+0.0069	+0.0138	+0.0109	+0.0096	+0.0062	-0.0014	-0.0047	-0.0064	-0.0101	+0.0004	-0.0045
26	+0.0100	+0.0070	+0.0145	+0.0114	+0.0110	+0.0064	-0.0020	-0.0047	-0.0070	-0.0107	-0.0010	-0.0042
27	+0.0095	+0.0059	+0.0150	+0.0109	+0.0110	+0.0067	-0.0015	-0.0015	-0.0060	-0.0103	-0.0015	-0.0053
28	+0.0090	+0.0058	+0.0140	+0.0097	+0.0100	+0.0069	0	-0.0042	-0.0060	-0.0113	-0.0020	-0.0060
29	+0.0095	+0.0060	+0.0135	+0.0109	+0.0110	+0.0070	+0.0005	-0.0039	-0.0065	-0.0105	-0.0020	-0.0060
30	+0.0085	+0.0054	+0.0140	+0.0113	+0.0095	+0.0074	+0.0015	-0.0028	-0.0070	-0.0104	-0.0035	-0.0064
31	+0.0086	+0.0053	+0.0136	+0.0106	+0.0088	+0.0068	+0.0010	-0.0026	-0.0064	-0.0097	-0.0028	-0.0059
32	+0.0074	+0.0057	+0.0130	+0.0101	+0.0094	+0.0065	-0.0002	-0.0036	-0.0060	-0.0099	-0.0032	-0.0056
33	+0.0080	+0.0057	+0.0124	+0.0111	+0.0082	+0.0064	-0.0018	-0.0035	-0.0064	-0.0108	-0.0032	-0.0052
34	+0.0084	+0.0056	+0.0124	+0.0104	+0.0092	+0.0063	-0.0012	-0.0049	-0.0066	-0.0098	-0.0008	-0.0046
35	+0.0090	+0.0066	+0.0122	+0.0104	+0.0104	+0.0059	-0.0016	-0.0042	-0.0066	-0.0097	+0.0046	-0.0039
36	+0.0070	+0.0056	+0.0089	+0.0088	+0.0088	+0.0050	-0.0022	-0.0041	-0.0062	-0.0084	-0.0008	-0.0028
37	+0.0073	+0.0051	+0.0098	+0.0083	+0.0074	+0.0052	-0.0019	-0.0041	-0.0062	-0.0083	-0.0021	-0.0042
38	+0.0060	+0.0049	+0.0098	+0.0092	+0.0064	+0.0052	-0.0016	-0.0037	-0.0058	-0.0089	-0.0024	-0.0048
39	+0.0073	+0.0050	+0.0105	+0.0081	+0.0068	+0.0055	-0.0009	-0.0032	-0.0065	-0.0081	-0.0024	-0.0036
40	+0.0057	+0.0046	+0.0102	+0.0089	+0.0061	+0.0059	-0.0005	-0.0021	-0.0058	-0.0080	-0.0031	-0.0053
41	+0.0038	+0.0032	+0.0068	+0.0058	+0.0044	+0.0041	0	-0.0012	-0.0032	-0.0052	-0.0034	-0.0036
42	+0.0032	+0.0036	+0.0070	+0.0054	+0.0052	+0.0036	-0.0006	-0.0022	-0.0050	-0.0053	-0.0016	-0.0020
43	+0.0040	+0.0036	+0.0062	+0.0063	+0.0046	+0.0040	-0.0024	-0.0026	-0.0032	-0.0056	-0.0026	-0.0033
44	+0.0052	+0.0037	+0.0072	+0.0053	+0.0046	+0.0039	-0.0016	-0.0031	-0.0048	-0.0055	-0.0014	-0.0027
45	+0.0040	+0.0040	+0.0056	+0.0060	+0.0052	+0.0035	-0.0008	-0.0025	-0.0058	-0.0061	-0.0002	-0.0019
46	+0.0020	+0.0018	+0.0013	+0.0025	+0.0016	+0.0014	-0.0014	-0.0006	-0.0032	-0.0025	-0.0006	-0.0003
47	+0.0021	+0.0017	+0.0026	+0.0023	+0.0008	+0.0018	-0.0013	-0.0010	-0.0014	-0.0020	-0.0007	-0.0007
48	+0.0010	+0.0017	+0.0026	+0.0028	+0.0008	+0.0017	-0.0012	-0.0008	-0.0006	-0.0025	+0.0022	-0.0012
49	+0.0011	+0.0018	+0.0025	+0.0021	+0.0016	+0.0018	-0.0003	-0.0006	-0.0025	-0.0019	-0.0008	-0.0011
50	+0.0019	+0.0017	+0.0024	-0.0021	-0.0003	+0.0017	+0.0005	0	-0.0016	-0.0014	-0.0017	-0.0015
Mean (d)	+0.0064	+0.0045	+0.0099	+0.0075	+0.0070	+0.0049	-0.0008	-0.0029	-0.0048	-0.0073	-0.0013	-0.0038
Std. Dev.	0.0026	0.0016	0.0040	0.0033	0.0031	0.0018	0.0010	0.0013	0.0019	0.0029	0.0015	0.0016

(a) If bow is +, surface is concave; if bow is -, surface is convex.

(b) Robot measurements not corrected for bias in robot bow measurements.

(c) Positions 1-5 and 51-55 have zero values.

(d) Excluding 1-5 and 51-55.

TABLE 6-7
COMPARISON OF ROBOT AND HOT CELL BOW MEASUREMENTS FOR
SURVEILLANCE ELEMENT S/N 1-0743

Position	PIE-Robot ^(a) (Inches)						Block Average
	Face A	Face B	Face C	Face D	Face E	Face F	
6(b)	0.001	0.001	-0.001	0.001	0.000	0.000	
7	-0.002	-0.001	-0.001	0.001	-0.002	-0.001	
8	-0.002	-0.005	0.000	0.000	-0.001	0.000	
9	-0.001	0.000	0.000	0.000	0.000	-0.001	
10	0.000	-0.001	-0.001	-0.001	0.000	0.000	
11	0.000	-0.001	0.000	0.000	0.001	0.000	
12	0.000	0.000	0.001	-0.001	0.000	0.000	
13	0.000	-0.006	-0.001	0.001	0.002	0.000	
14	0.000	-0.001	-0.001	0.000	0.000	-0.001	
15	0.001	0.001	-0.001	0.001	-0.001	-0.001	
16	0.000	0.000	-0.002	0.001	-0.001	-0.003	
17	-0.002	-0.002	-0.003	0.000	-0.002	-0.002	
18	0.000	-0.005	-0.001	-0.001	-0.002	-0.001	
19	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	
20	-0.001	-0.001	0.000	-0.001	0.001	-0.001	
21	0.000	0.000	0.001	0.000	0.000	0.000	
22	0.000	-0.001	-0.001	-0.001	0.000	-0.001	
23	0.000	-0.004	0.000	-0.001	-0.001	-0.001	
24	-0.001	0.000	-0.002	-0.001	0.000	-0.002	
25	0.000	0.000	0.000	0.000	-0.001	-0.002	
26	0.000	0.000	-0.002	0.000	-0.001	0.000	
27	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	
28	0.000	-0.001	-0.001	-0.001	-0.002	-0.001	
29	-0.001	0.000	-0.001	-0.001	-0.001	-0.001	
30	0.000	0.000	0.001	-0.001	0.000	0.000	
31	-0.001	-0.001	0.000	-0.002	-0.001	-0.001	
32	0.001	-0.001	-0.001	-0.001	-0.002	0.000	
33	0.000	0.001	0.000	0.000	-0.002	0.000	
34	-0.001	0.000	-0.001	-0.002	-0.001	-0.002	
35	0.000	0.000	-0.002	-0.001	-0.001	-0.006	
36	0.001	0.002	-0.002	0.000	0.000	0.000	
37	0.000	0.001	0.000	0.000	0.000	0.000	
38	0.001	0.001	0.001	0.000	-0.001	0.000	
39	0.000	0.000	0.001	0.000	0.000	0.001	
40	0.001	0.001	0.002	0.000	0.000	0.000	
41	0.000	0.000	0.001	0.000	-0.001	0.001	
42	0.001	-0.001	-0.001	-0.001	0.001	0.001	
43	0.001	0.001	0.000	0.001	-0.001	0.000	
44	-0.001	-0.001	0.000	-0.001	0.000	0.000	
45	0.001	0.001	-0.001	-0.001	0.001	-0.001	
46	0.000	0.001	0.000	0.001	0.001	0.000	
47	0.000	0.000	0.001	0.000	0.001	0.000	
48	0.001	0.000	0.001	0.000	-0.002	-0.003	
49	0.001	0.000	0.000	0.000	0.001	0.000	
50	0.000	0.000	0.002	-0.001	0.000	0.000	
Average	0.000	-0.001	0.000	0.000	-0.001	-0.001	0.000
Standard Deviation	±0.001	±0.002	±0.001	±0.001	±0.001	±0.001	±0.001

(a) Robot measurements corrected for bias in robot bow measurements.

(b) Positions 1-5 and 51-55 have zero values.

TABLE 6-8
DISTANCE BETWEEN FIDUCIAL HOLE MEASUREMENTS FOR CALIBRATION ELEMENT S/N 8-0182

Corner	Dimension	QC	Robot Measurements (Inches)						
			Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Average	Standard Deviation ($\pm$)
1	L	9.003	9.002	8.999	9.001	9.000	9.001	9.001	0.001
	M	9.002	9.005	9.008	9.001	8.997	9.005	9.003	0.004
	N	9.000	9.003	8.999	9.000	9.007	9.002	9.002	0.003
2	L	9.003	8.996	8.997	9.005	9.001	8.995	8.999	0.004
	M	9.001	9.003	9.001	9.001	8.995	9.005	9.001	0.004
	N	9.000	9.005	9.003	8.999	9.003	9.001	9.002	0.002
3	L	9.003	9.000	8.998	9.003	9.004	9.006	9.002	0.003
	M	9.001	9.002	9.001	9.000	9.000	9.003	9.001	0.001
	N	9.001	8.999	9.002	9.005	9.001	8.999	9.001	0.002
4	L	9.004	9.002	9.000	9.004	9.001	9.002	9.002	0.002
	M	9.001	9.004	9.004	9.004	9.004	9.002	9.004	0.001
	N	9.001	8.999	9.001	8.996	8.998	9.001	8.999	0.002
5	L	9.004	9.007	9.007	8.999	8.996	9.001	9.002	0.005
	M	9.002	9.004	8.998	9.005	9.005	9.003	9.003	0.003
	N	9.001	9.000	9.003	9.002	9.002	9.006	9.003	0.002
6	L	9.002	8.999	8.994	8.999	9.006	9.000	9.000	0.004
	M	9.002	8.999	9.001	9.000	8.998	9.002	9.000	0.002
	N	9.001	9.000	9.004	9.002	9.004	9.001	9.002	0.002

TABLE 6-9
COMPARISON OF ROBOT AND QC DISTANCE BETWEEN FIDUCIAL HOLE MEASUREMENTS FOR CALIBRATION ELEMENT S/N 8-0182

Corner	Dimension	QC - Robot (Inches)						
		Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Average	Standard Deviation ($\pm$)
1	L	0.001	0.004	0.002	0.003	0.002	0.002	0.001
	M	-0.003	-0.006	0.001	0.005	-0.003	-0.001	0.004
	N	-0.003	0.001	0	-0.007	-0.002	-0.002	0.003
2	L	0.007	0.006	-0.002	0.002	0.008	0.004	0.004
	M	-0.002	0	0	0.006	-0.004	0	0.004
	N	-0.005	-0.003	0.001	-0.003	-0.001	-0.002	0.002
3	L	0.003	0.005	0	-0.001	-0.003	0.001	0.003
	M	-0.001	0	0.001	0.001	-0.002	0	0.001
	N	0.002	-0.001	-0.004	0	0.002	0	0.002
4	L	0.002	0.004	0	0.003	0.002	0.002	0.002
	M	-0.003	-0.003	-0.003	-0.003	-0.001	-0.003	0.001
	N	0.002	0	0.005	0.003	0	0.002	0.002
5	L	-0.003	-0.003	0.005	0.008	0.003	0.002	0.005
	M	-0.002	0.004	-0.003	-0.003	-0.001	-0.001	0.003
	N	0.001	-0.002	-0.001	-0.001	-0.005	-0.002	0.002
6	L	0.003	0.008	0.003	-0.004	0.002	0.002	0.004
	M	0.003	0.001	0.002	0.004	0	0.002	0.002
	N	0.001	-0.003	-0.001	-0.003	0	-0.001	0.002
Average		0.000	0.001	0.000	0.001	0.000	0.000	
Standard Deviation		± 0.003	± 0.004	± 0.003	± 0.004	± 0.003	± 0.003	

TABLE 6-10
ACROSS-FLATS MEASUREMENTS FOR CALIBRATION ELEMENT S/N 8-0182

Corner	Dimension	QC	Robot Measurements (Inches)							
			Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Inspection 6	Average	Standard Deviation ($\pm$)
1	1-2	14.176	14.178	14.176	14.177	14.177	14.177	14.179	14.177	0.001
	3-4	14.176		14.172	14.172	14.182	14.178	14.183	14.177	0.005
	5-6	14.176		14.177	14.174	14.179	14.175	14.179	14.177	0.002
2	1-2	14.175	14.177	14.176	14.177	14.178	14.177	14.180	14.178	0.001
	3-4	14.176		14.1	14.174	14.180	14.178	14.179	14.175	0.006
	5-6	14.175		14.173	14.170	14.180	14.176	14.179	14.176	0.004
3	1-2	14.175	14.175	14.174	14.173	14.178	14.176	14.178	14.176	0.002
	3-4	14.174		14.176	14.169	14.178	14.175	14.179	14.175	0.004
	5-6	14.174		14.171	14.169	14.175	14.177	14.174	14.173	0.003
4	1-2	14.176	14.179	14.175	14.174	14.179	14.177	14.177	14.177	0.002
	3-4	14.176		14.175	14.171	14.181	14.180	14.179	14.177	0.004
	5-6	14.176		14.170	14.168	14.180	14.176	14.178	14.175	0.005
5	1-2	14.176	14.176	14.177	14.173	14.180	14.178	14.178	14.177	0.002
	3-4	14.176		14.170	14.170	14.177	14.177	14.178	14.174	0.004
	5-6	14.175		14.175	14.172	14.177	14.176	14.176	14.175	0.002
6	1-2	14.174	14.174	14.174	14.170	14.174	14.174	14.174	14.173	0.002
	3-4	14.174		14.172	14.168	14.173	14.175	14.175	14.173	0.003
	5-6	14.174		14.169	14.167	14.178	14.171	14.173	14.172	0.004

TABLE 6-11
COMPARISON OF ROBOT AND QC ACROSS-FLATS MEASUREMENTS FOR CALIBRATION ELEMENT S/N 8-0182

Corner	Dimension	QC - Robot (Inches)						Average	Standard Deviation ($\pm$)
		Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Inspection 6		
1	1-2	-0.002	0	-0.001	-0.001	-0.001	-0.003	-0.001	0.001
	3-4		0.004	0.004	-0.006	-0.002	-0.007	-0.001	0.005
	5-6	-0.004	-0.001	0.002	-0.003	0.001	-0.003	-0.001	0.002
2	1-2	-0.002	-0.001	-0.002	-0.003	-0.002	-0.005	-0.002	0.001
	3-4		+0.010	0.002	-0.004	-0.002	-0.003	0.001	0.006
	5-6	-0.003	0.002	0.005	-0.005	-0.001	-0.004	-0.001	0.004
3	1-2	0	0.001	0.002	-0.003	-0.001	-0.003	-0.001	0.002
	3-4		-0.002	0.005	-0.004	-0.001	-0.005	-0.001	0.004
	5-6	0	0.003	0.005	-0.001	-0.003	0	0.001	0.003
4	1-2	-0.003	0.001	0.002	-0.003	-0.001	-0.001	-0.001	0.002
	3-4		0.001	0.005	-0.005	-0.004	-0.003	-0.001	0.004
	5-6	-0.003	0.006	0.008	-0.004	0	-0.002	0.001	0.005
5	1-2	0	-0.001	0.003	-0.004	-0.002	-0.002	-0.001	0.002
	3-4	0	0.006	0.006	-0.001	-0.001	-0.002	0.002	0.004
	5-6	0.001	0	0.003	-0.002	-0.001	-0.001	0	0.002
6	1-2	0	0	0.004	0	0	0	0.001	0.002
	3-4		0.002	0.006	0.001	-0.001	-0.001	0.001	0.003
	5-6	0.001	0.005	0.007	-0.004	0.003	0.001	0.002	0.004
Average Standard Deviation		-0.001 ± 0.002	0.002 ± 0.003	0.004 ± 0.003	-0.003 ± 0.002	-0.001 ± 0.002	-0.002 ± 0.002	0 ± 0.003	

TABLE 6-12
LENGTH MEASUREMENTS FOR CALIBRATION ELEMENT S/N 8-0182

Measurement Point	Robot Measurements (Inches)						
	QC	Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Inspection 6
1	31.222	31.217	31.213	31.216	31.220	31.215	31.219
2	31.222	31.214	31.211	31.209	31.214	31.212	31.214
3	31.222	31.216	31.207	31.211	31.211	31.211	31.211
4	31.222	31.212	31.207	31.212	31.214	31.214	31.209
5	31.222	31.209	31.206	31.205	31.207	31.211	31.205
6	31.222	31.215	31.212	31.211	31.218	31.217	31.216
7	31.222	31.214	31.207	31.210	31.212	31.210	31.210
8	31.222	31.215	31.213	31.212	31.217	31.217	31.215
9	31.222	31.214	31.217	31.218	31.221	31.216	31.216
10	31.222	31.227	31.217	31.226	31.225	31.224	31.224
11	31.222	31.220	31.218	31.221	31.217	31.218	31.220
12	31.222	31.215	31.215	31.217	31.217	31.218	31.212
13	31.222	31.217	31.204	31.207	31.212	31.210	31.214
14	31.222	31.216	31.214	31.214	31.218	31.213	31.217
15	31.222	31.217	31.212	31.210	31.214	31.214	31.211
16	31.222	31.215	31.212	31.207	31.214	31.214	31.212
17	31.223	31.213	31.209	31.206	31.216	31.211	31.204
18	31.222	31.211	31.205	31.216	31.218	31.210	31.211
19	31.222	31.211	31.209	31.213	31.214	31.211	31.207
20	31.222	31.220	31.213	31.215	31.220	31.215	31.214
21	31.222	31.223	31.219	31.220	31.219	31.224	31.223
22	31.223	31.219	31.216	31.220	31.220	31.221	31.221
23	31.222	31.224	31.225	31.220	31.221	31.223	31.221
24	31.222	31.219	31.218	31.216	31.221	31.220	31.212
25	31.222	31.221	31.215	31.213	31.218	31.218	31.212
26	31.222	31.215	31.210	31.213	31.212	31.215	31.215
27	31.222	31.217	31.206	31.212	31.219	31.211	31.209
28	31.223	31.214	31.213	31.217	31.214	31.216	31.214
29	31.223	31.220	31.214	31.208	31.218	31.217	31.217
30	31.222	31.212	31.214	31.215	31.215	31.211	31.214
31	31.223	31.214	31.211	31.213	31.215	31.215	31.214
32	31.223	31.213	31.206	31.207	31.212	31.204	31.208
33	31.223	31.216	31.217	31.214	31.215	31.214	31.213
34	31.222	31.217	31.213	31.216	31.212	31.211	31.212
35	31.222	31.213	31.216	31.212	31.216	31.215	31.211
36	31.223	31.214	31.216	31.216	31.220	31.216	31.219
37	31.222	31.228	31.226	31.224	31.224	31.226	31.225
38	31.222	31.219	31.215	31.217	31.220	31.220	31.219
39	31.222	31.219	31.211	31.213	31.215	31.211	31.214
40	31.222	31.216	31.209	31.216	31.213	31.214	31.210
41	31.223	31.212	31.213	31.208	31.209	31.209	31.208
42	31.222	31.215	31.215	31.216	31.213	31.212	31.210
43	31.222	31.216	31.209	31.211	31.219	31.214	31.205
44	31.222	31.220	31.210	31.214	31.214	31.212	31.211
45	31.222	31.216	31.211	31.211	31.216	31.211	31.213
46	31.222	31.211	31.213	31.211	31.210	31.211	31.207
47	31.222	31.218	31.215	31.220	31.219	31.214	31.218
48	31.222	31.220	31.225	31.217	31.222	31.222	31.221
49	31.223	31.220	31.220	31.217	31.219	31.214	31.216
50	31.222	31.219	31.221	31.217	31.215	31.216	31.219
51	31.222	31.223	31.220	31.220	31.214	31.219	31.214
52	31.222	31.218	31.217	31.213	31.217	31.212	31.210
53	31.222	31.213	31.207	31.211	31.215	31.214	31.214
54	31.222	31.214	31.205	31.212	31.213	31.208	31.209

TABLE 6-13
COMPARISON OF ROBOT AND QC LENGTH MEASUREMENTS FOR CALIBRATION S/N 8-0182

Measurement Point	QC - Robot (Inches)						Average	Standard Deviation (±)
	Inspection 1	Inspection 2	Inspection 3	Inspection 4	Inspection 5	Inspection 6		
1	0.005	0.009	0.006	0.002	0.007	0.003	0.005	0.003
2	0.008	0.011	0.013	0.008	0.010	0.008	0.010	0.002
3	0.006	0.015	0.011	0.011	0.011	0.011	0.011	0.003
4	0.010	0.015	0.010	0.008	0.008	0.013	0.011	0.003
5	0.013	0.016	0.017	0.015	0.011	0.017	0.015	0.002
6	0.007	0.010	0.011	0.004	0.005	0.006	0.007	0.003
7	0.008	0.015	0.012	0.010	0.012	0.012	0.012	0.002
8	0.007	0.009	0.010	0.005	0.005	0.007	0.007	0.002
9	0.008	0.005	0.004	0.001	0.006	0.006	0.005	0.002
10	-0.005	0.005	-0.004	-0.003	-0.002	-0.002	-0.004	0.001
11	0.002	0.004	0.001	0.005	0.004	0.002	0.003	0.002
12	0.007	0.007	0.005	0.005	0.004	0.010	0.006	0.002
13	0.005	0.018	0.015	0.010	0.012	0.008	0.011	0.005
14	0.006	0.008	0.008	0.004	0.009	0.005	0.007	0.002
15	0.005	0.010	0.012	0.008	0.008	0.011	0.009	0.002
16	0.007	0.010	0.015	0.008	0.008	0.010	0.010	0.003
17	0.010	0.014	0.017	0.007	0.012	0.019	0.013	0.004
18	0.011	0.017	0.006	0.004	0.012	0.011	0.010	0.005
19	0.011	0.013	0.009	0.008	0.011	0.015	0.011	0.003
20	0.002	0.009	0.007	0.002	0.007	0.008	0.006	0.003
21	-0.001	0.003	0.002	0.003	-0.002	-0.001	0.001	0.002
22	0.004	0.007	0.003	0.003	0.002	0.002	0.004	0.002
23	-0.002	-0.003	-0.002	0.001	-0.001	0.001	0	0.002
24	0.003	0.004	0.006	0.001	0.002	0.010	0.004	0.003
25	0.001	0.007	0.009	0.004	0.004	0.010	0.006	0.003
26	0.007	0.012	0.009	0.010	0.007	0.007	0.009	0.002
27	0.005	0.016	0.010	0.003	0.011	0.013	0.010	0.005
28	0.009	0.010	0.006	0.009	0.007	0.009	0.008	0.002
29	0.003	0.009	0.015	0.005	0.006	0.006	0.007	0.004
30	0.010	0.008	0.007	0.007	0.011	0.008	0.008	0.002
31	0.009	0.012	0.010	0.008	0.008	0.009	0.009	0.002
32	0.010	0.017	0.016	0.011	0.019	0.015	0.015	0.004
33	0.007	0.006	0.009	0.008	0.009	0.010	0.008	0.002
34	0.005	0.009	0.006	0.010	0.011	0.010	0.008	0.002
35	0.009	0.006	0.010	0.006	0.007	0.011	0.008	0.002
36	0.009	0.007	0.007	0.003	0.007	0.004	0.006	0.002
37	-0.006	-0.004	-0.002	-0.002	-0.004	-0.003	-0.004	0.002
38	0.003	0.007	0.005	0.002	0.002	0.003	0.004	0.002
39	0.003	0.011	0.009	0.007	0.011	0.008	0.008	0.003
40	0.006	0.013	0.006	0.009	0.008	0.012	0.009	0.003
41	0.011	0.010	0.015	0.014	0.014	0.015	0.013	0.002
42	0.007	0.007	0.006	0.009	0.010	0.012	0.008	0.002
43	0.006	0.013	0.011	0.003	0.008	0.017	0.010	0.005
44	0.002	0.012	0.008	0.008	0.010	0.011	0.008	0.004
45	0.006	0.011	0.011	0.006	0.011	0.009	0.009	0.002
46	0.011	0.009	0.011	0.012	0.011	0.015	0.012	0.002
47	0.004	0.007	0.002	0.003	0.008	0.004	0.005	0.002
48	0.002	-0.003	0.005	0	0	0.001	0.001	0.003
49	0.003	0.003	0.006	0.004	0.009	0.007	0.005	0.002
50	0.003	0.001	0.005	0.007	0.006	0.003	0.004	0.002
51	-0.001	0.002	0.002	0.008	0.003	0.008	0.004	0.004
52	0.004	0.005	0.009	0.005	0.010	0.012	0.008	0.003
53	0.009	0.015	0.011	0.007	0.008	0.008	0.010	0.003
54	0.008	0.017	0.010	0.009	0.014	0.013	0.012	0.003
Average	0.006	0.009	0.008	0.006	0.018	0.008	0.007	
Standard Deviation	±0.004	±0.005	±0.005	±0.004	±0.004	±0.005	±0.005	

TABLE 6-14
ACCURACY OF METROLOGY ROBOT MEASUREMENTS

Type of Measurement	Robot vs PIE ^(a)			Robot vs QC ^(b)		
	Number of Comparisons	Accuracy (1 σ) (Inches)	BIAS $\pm$ 1 σ ^(c) (Inches)	Number of Comparisons	Accuracy (1 σ) (Inches)	BIAS ^(d,e) (Inches)
Fuel element length	42	± 0.004	0.011 ± 0.001	324	± 0.005	0.007
Distance between fiducial holes	18	± 0.007	0.000 ± 0.002	90	± 0.003	0.000
Distance between coolant holes	30	± 0.007	0.002 ± 0.001	--	ND ^(f)	ND
Distance across flats	15	± 0.003	0.000 ± 0.001	102	± 0.003	0.000
Coolant hole diameters	40	± 0.001	-0.001 ± 0.000	--	ND	ND
Side face bow	270	± 0.001	0.000 ± 0.000	--	ND	ND

- (a) Comparison of robot and hot cell measurements for surveillance element S/N 1-0743.
 (b) Comparison of robot and Quality Control measurements on calibration element S/N 8-0182.
 (c) BIAS = PIE - Robot.
 (d) BIAS = QC - Robot.
 (e) Undertainty on bias is less than ± 0.005 .
 (f) ND = not determined.

TABLE 6-15
APPARENT BOW IN BLOCK RESULTING FROM BOW IN ROBOT STRUCTURE

Axial(a) Position (Inches)	QC - Robot(b) July 1978 (Inches)	QC - Robot(c) September 1979 (Inches)	QC - Robot(d) August 1980 (Inches)	Robot - PIE(e) July 1979 (Inches)	Average	
					Difference (Inches)	Standard Deviation (±Inches)
1.25	0	0	0	0	0	0
4.25	-0.001	-0.001	-0.001	-0.002	-0.001	0.0005
7.25	-0.002	-0.002	-0.002	-0.002	-0.002	0
10.25	-0.002	-0.002	-0.003	-0.003	-0.002	0.0006
13.25	-0.002	-0.002	-0.003	-0.004	-0.003	0.001
16.25	-0.003	-0.002	-0.003	-0.004	-0.003	0.0008
19.25	-0.002	-0.002	-0.003	-0.003	-0.002	0.0006
22.25	-0.002	-0.001	-0.002	-0.002	-0.002	0.0005
25.25	-0.002	-0.001	-0.001	-0.001	-0.001	0.0005
28.25	-0.001	-0.000	-0.000	-0.000	-0.000	0.0005
30.25	0	0	0	0	0	0

(a) Distance relative to bottom of fuel element.

(b) Robot measurements represent average values for two complete inspections of all six side faces of calibration element 8-0182.

(c) Robot measurements represent average values for five complete inspections of all six side faces of calibration element 8-0182.

(d) Robot measurements represent average values for four inspections of all six side faces of calibration element 8-0182, one column of measurements per face per inspection.

(e) Robot measurements performed in HSF at FSV during July 1979.

TABLE 6-16
DISPLACEMENT OF SIDE FACES AT TOP OF BLOCK RELATIVE TO SIDE FACES AT BOTTOM OF BLOCK

Face	QC - Robot(a) July 1978 (Inches)	QC - Robot(b) September 1979 (Inches)	QC - Robot(c) August 1980 (Inches)	PIE - Robot(d) July 1979 (Inches)	Average	
					Difference (Inches)	(±Inches)
A	0.003(e)	0.016	0.028	0.012	0.015	0.010
B	0.004	0.016	0.012	0.013	0.011	0.005
C	0.003	0.005	0.008	0.001	0.004	0.003
D	0.014	0.011	0.025	0.004	0.013	0.009
E	0.013	0.013	0.032	0.000	0.014	0.013
F	0.006	0.020	0.031	0.008	0.016	0.012

(a) Robot measurements represent average values for two complete inspections of all six side faces of calibration element 8-0182.

(b) Robot measurements represent average values for five complete inspections of all six side faces of calibration element 8-0182.

(c) Robot measurements represent average values for four inspections of all six side faces of calibration element 8-0182, one column of measurements per face per inspection.

(d) Robot measurements performed in hot service facility at FSV during July 1979.

(e) Positive displacement indicates the element is tilted toward the robot structure.

TABLE 7-1
LOCATIONS OF STAINS OBSERVED DURING SURVEILLANCE OF CORE SEGMENT 1(a)

	Column 01 Face A B C D E F	Column 02 Face A B C D E F	Column 03 Face A B C D E F	Column 04 Face A B C D E F	Column 05 Face A B C D E F	Column 06 Face A B C D E F	Column 07 Face A B C D E F
Region 17							
Layer 3							
Layer 4	X			X			
Layer 5						X X X	X
Layer 6	X	X X		X X	X		
Layer 7	X	X X	X	X X			
Layer 8		X X	X	X X	X	X	X X
Layer 9		X	X X	X	X	X	
Layer 10							
Region 5							
Layer 6	(b)	(b)	(b)	(b)	(b)	(b)	X
Layer 9							

(a) Inspected elements 40 through 51 not included.

(b) Not inspected.

TABLE 7-2
LOCATIONS OF RUB MARKS OBSERVED DURING SURVEILLANCE OF CORE SEGMENT 1(a)

	Column 01 Face A B C D E F	Column 02 Face A B C D E F	Column 03 Face A B C D E F	Column 04 Face A B C D E F	Column 05 Face A B C D E F	Column 06 Face A B C D E F	Column 07 Face A B C D E F
Region 17							
Layer 3					X X X X		
Layer 4							
Layer 5	X X X X	X X X		X		X X	
Layer 6		X X X X	X X X X		X X X	X X X X	X X X X
Layer 7			X X X	X X X X	X X X		
Layer 8		X X X X	X X X X		X X X	X X X X	
Layer 9	X X X X		X	X X X X	X X X	X X X	X X
Layer 10							
Region 5							
Layer 6	(b)	(b)	(b)	(b)	(b)	(b)	X X X
Layer 9							

(a) Inspected elements 40 through 51 not included.

(b) Not inspected.

TABLE 7-3
LOCATIONS OF INTERFACE MARKS OBSERVED DURING SURVEILLANCE OF CORE SEGMENT 1(a)

	Column 01 Face A B C D E F	Column 02 Face A B C D E F	Column 03 Face A B C D E F	Column 04 Face A B C D E F	Column 05 Face A B C D E F	Column 06 Face A B C D E F	Column 07 Face A B C D E F
Region 17							
Layer 3	X X X X X X						
Layer 4	X X X X X X			X			
Layer 5	X X X X X X	X	X				
Layer 6	X X X X X X	X	X	X	X	X	X
Layer 7	X X X X X X	X	X	X	X		
Layer 8	X X X X X X	X	X	X	X	X	X
Layer 9			X	X		X	X
Layer 10							
Region 5							
Layer 6	(b)	(b)	(b)	(b)	(b)	(b)	X X X
Layer 9							

(a) Inspected elements 40 through 51 not included.

(b) Not inspected.

11. FIGURES

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- 7-10. Scratch on side face C of element 17.06.F.05. (Mosaic 3 of 4).
- 7-11. Scratch on side face C of element 17.06.F.05. (Mosaic 4 of 4).
- 7-12. Fingerprints on bottom side face B of element 17.01.F.07.
- 7-13. Large chip on bottom chamfer of side face F of element 17.04.F.06.
- 7-14. Debris on dowel of element 17.04.F.07.
- 7-15. Circle around fuel handling hole on top surface of element
17.07.F.07.
- 7-16. Painted H on top surface of element 17.02.F.06.

Fig. 2-1. Metrology robot in HSF at FSV

Fig. 2-2. Front view of metrology robot probe; Z probe leg in contact with top surface of fuel block

Fig. 2-3. Metrology robot coordinate system

Fig. 2-4. Metrology robot data acquisition and control system.

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. 3-1. Chord Measurements

FULL-LENGTH INSPECTION

ABBREVIATED INSPECTION

Fig. 3-2. Side face measurements

(a) REGULAR FUEL ELEMENT; FULL LENGTH
AND ABBREVIATED INSPECTIONS

Fig. 3-3. Top surface measurements (page 1 of 2)

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

Fig. 3-3. Top surface measurements (page 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. 3-4. Coolant hole measurements

Fig. 3-5. Fiducial hole measurements

Fig. 4-1. Determination of average radiation level for inspected fuel elements

Fig. 4-2. Dose rate versus distance from spent fuel block surface

Fig. 5-1. Envelope of axial strains observed in FSV segment 1 fuel elements

Fig. 5-2. Envelope of radial strains observed in FSV segment 1 fuel elements

Fig. 5-3. Axial strain distribution and side face bow in FSV core region 17 (page 1 of 6)

Fig. 5-3. Axial strain distribution and side face bow in FSV core region 17 (page 2 of 6)

(d) AXIAL LEVEL 7

Fig. 5-3. Axial strain distribution and side face bow in FSV core region 17 (page 4 of 6)

Fig. 5-3. Axial strain distribution and side face bow in FSV core region 17 (page 5 of 6)

Fig. 5-3. Axial strain distribution and side face bow in FSV core region 17 (page 6 of 6)

Fig. 5-4. Differences in measured and calculated axial strain for FSV segment 1 fuel elements

Fig. 5-5. Differences in measured and calculated radial strain for FSV segment 1 fuel elements

Fig. 5-6. Calculated bow vs measured bow for FSV segment 1 fuel elements

Fig. 5-7. Comparison of axial strains observed in FSV segment 1 fuel elements with the design curves for irradiation-induced dimensional change of H-327 graphite in the axial orientation

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Fig. 7-1. Dark stain on side face D of element 17.02.F.08 (Mosaic 1 of 4)

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Fig. 7-2. Dark stain on side face D of element 17.02.F.08 (Mosaic 2 of 4)

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Fig. 7-3. Dark stain on side face D of element 17.02.F.08 (Mosaic 3 of 4)

Fig. 7-4. Dark stain on side face D of element 17.02.F.08 (mosaic 4 of 4)

Fig. 7-5. Rub marks on face F of element 17.04.F.09

Fig. 7-6. Interface mark on side face A of element 17.01.F.07

Fig. 7-7. Soot deposits on bottom side face E of element 17.03.F.05

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Fig. 7-8. Scratch on side face C of element 17.06.F.05 (Mosaic 1 of 4)

Fig. 7-9. Scratch on side face C of element 17.06.F.05 (Mosaic 2 of 4)

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Fig. 7-10. Scratch on side face C of element 17.06.F.05 (Mosaic 3 of 4)

Fig. 7-11. Scratch on side face C of element 17.06.F.05 (Mosaic 4 of 4)

Fig. 7-12. Fingerprints on bottom side face B of element 17.01.F.07

Fig. 7-13. Large chip on bottom chamfer on side face F of element 17.04.F.06 (apparent white surface is glare from robot lighting)

Fig. 7-14. Debris on dowel of element 17.04.F.07

Fig. 7-15. Circle around fuel handling hole on top surface of element 17.07.F.07

Fig. 7-16. Painted H on top surface of element 17.02.F.06