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FATIGUE TESTS OF DOWEL-SOCKET SYSTEMS

by
D. D. CHIANG

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GENERAL ATOMIC

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ABSTRACT

A test program was conducted to determine the fatigue behavior of LHTGR fuel element dowel/socket systems. Two dowel/socket systems, namely, a four-dowel system and a five-dowel system, were tested to failure under shear loads applied through a fatigue test apparatus to simulate repetitive loading during a seismic event.

The fatigue curves determined from a least-squares fit to the test data are as follows:

$$\begin{aligned}\log_e F \begin{pmatrix} N \\ 1b \end{pmatrix} &= \begin{pmatrix} 11.14923 \\ 9.65678 \end{pmatrix} - 0.026867 \log_e n \text{ (five dowels)} \\ \log_e F \begin{pmatrix} N \\ 1b \end{pmatrix} &= \begin{pmatrix} 10.64535 \\ 9.15290 \end{pmatrix} - 0.05255 \log_e n \text{ (four dowels)} ,\end{aligned}$$

where F is the alternating force level in newtons or pounds and
 n is the corresponding number of load cycles.

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1.0 SUMMARY

The fuel element dowel/socket system is designed to align coolant and control rod channels in adjacent HTGR fuel and reflector elements in a column. The dowel/socket system must survive an Operating Basis Earthquake and must maintain column alignment to allow control rod insertion and permit sufficient coolant flow to remove the reactor core decay heat during and after a Safe Shutdown Earthquake.

Dowel-socket systems consisting of four and five dowels were tested to failure under shear loads applied through a fatigue test apparatus to simulate repetitive loading during a seismic event. The four-dowel system represents the reference design for HTGR plants in low seismic zones. The five-dowel system is an alternate design for high-seismic zones. All of the specimens were fabricated from Great Lakes Carbon Company Grade H-451 graphite, the reference material for the large HTGR core.

Two specimens of each dowel system were tested for static strength. The average strength, stiffness, and deflection to failure are tabulated in Table 1-1. Fatigue tests were conducted on 11 specimens of the four-dowel system and 10 specimens of the five-dowel system, with the load varying approximately sinusoidally between equal values of force in opposite loading directions. Fatigue curves determined from a least-squares fit to the data are as follows:

$$\begin{aligned}\log_e F \begin{pmatrix} N \\ 1b \end{pmatrix} &= \begin{pmatrix} 11.14923 \\ 9.65678 \end{pmatrix} - 0.026867 \log_e n \text{ (five dowels)} \\ \log_e F \begin{pmatrix} N \\ 1b \end{pmatrix} &= \begin{pmatrix} 10.64535 \\ 9.15290 \end{pmatrix} - 0.05255 \log_e n \text{ (four dowels)} ,\end{aligned}$$

where F is the alternating force level in newtons or pounds and
 n is the corresponding number of load cycles.

TABLE 1-1
DOWEL SYSTEMS STATIC TEST RESULTS

No. of Dowels per System	Static Strength N (lb)	Dowel/Socket System Stiffness ^(a) N/mm (lb/in.)	Total Deflection to Failure mm (in.)
4	44,480 (10,000)	18,037 (103,000)	3.0 (0.12)
5	68,944 (15,500)	26,268 (150,000)	3.5 (0.14)

(a) The initial slope of load versus deflection curves is defined as the stiffness for the dowel/socket systems.

2.0 INTRODUCTION

The fuel element dowel/socket system is designed to maintain element alignment and survive an Operating Basis Earthquake. During and after a Safe Shutdown Earthquake the dowel/socket system must allow control rod insertion and permit sufficient coolant flow to remove the reactor core decay heat.

Recent seismic design load calculations and static strength tests of dowel/socket systems have shown that a four-dowel system will probably be adequate for HTGRs in low-seismic zones, while a five-dowel system may be required for some plant sites in high-seismic zones.

During a seismic event, the fuel elements will be subjected to repetitive impact against one another and with the side reflector. Consequently, the dowel/socket system will be subjected to cyclic loading. The fatigue strength can be expected to be significantly less than the one-cycle ultimate strength.

The objective of the test program was to determine the basic fatigue properties of both the four-dowel system and the five-dowel system such that their mechanical integrity under a seismic event can be evaluated.

The test program was conducted in two phases. The aim of the first phase of testing was to determine the static strength of the four-dowel and five-dowel systems with Great Lakes Carbon Company type H-451 graphite.

The aim of the second phase of the testing was to determine the fatigue life of both dowel systems. The fatigue tests were conducted at various force levels which were determined by the static ultimate strength for each dowel design. Each test was conducted to failure of the specimen.

3.0 TEST ARRANGEMENT

The test arrangement with an exploded view of the test fixture is shown in Fig. 3-1. One-half of the test fixture was bolted to two fixed I-beams; the other half of the test fixture was connected to an actuator applying cyclic load in compression and tension. A load cell was connected between the test fixture and actuator to measure the cyclic load.

Each half of the test fixture contained a section of a fuel element about one-third as long as a fuel element. The applied load was transmitted between the sections through the dowel/socket system. The test fixture was designed to guide the fuel elements during testing so that the dowel/socket system was in pure shear loading.

Two LVDTs (Linear Variable Differential Transformers) were utilized in each test to monitor the movement of two fuel elements during the loading of the dowel/socket systems. Their locations are also shown in Fig. 3-1.

Fig. 3-1. Dowel fatigue test setup

4.0 TEST EQUIPMENT

The equipment used in the test program is listed in the following:

1.	Instrument	Function Generator
	Manufacturer	--
	Model Number	129CG
	Serial Number	--
	Calibration Period	--
	Range and Accuracy	--
2.	Instrument	Servo Contraller
	Manufacturer	Shore Western
	Model Number	SC1329C
	Serial Number	--
	Calibration Period	N/A
	Range and Accuracy	0 to 10-in. stroke; $\pm 5.0\%$ full scale
3.	Instrument	Recording Oscillograph
	Manufacturer	Midwestern Instruments, Inc.
	Model Number	M1603-F
	Serial Number	1553
	Calibration Period	Prior to use
	Range and Accuracy	0.070 to 170 in./second in 15
4.	Instrument	Buffer Supply
	Manufacturer	Sine Engineering Company
	Model Number	05-10347
	Serial Number	02
	Calibration Period	12 months
	Range and Accuracy	0 to 10 vdc, 0 to ± 15 vdc supply; $\pm 0.5\%$ of full scale
5.	Instrument	Buffer Supply
	Manufacturer	Sine Engineering Company
	Model Number	05-10347
	Serial Number	03
	Calibration Period	12 months
	Range and Accuracy	0 to 10 vdc, 0 to ± 15 vdc supply; $\pm 0.5\%$ of full scale.

6.	Instrument	Buffer Amplifier
	Manufacturer	Sine Engineering Company
	Model Number	05-10346
	Serial Number	02
	Calibration Period	12 months
	Range and Accuracy	DC to 5 KHz, 0 to 10 v; $\pm 0.5\%$ of full scale
7.	Instrument	Power Supply
	Manufacturer	Lambda Electronics Corp.
	Model Number	LXD-CC-152-R
	Serial Number	None
	Calibration Period	N/A
	Range and Accuracy	± 15 vdc @ 300 milliamperes; $\pm 0.5\%$
8.	Instrument	Valve
	Manufacturer	Moog Control
	Model Number	76-164
	Serial Number	888
	Calibration Period	--
	Range and Accuracy	--
9.	Instrument	Hydraulic Actuator
	Manufacturer	Shore Western
	Model Number	912-5.1-9-3-13
	Serial Number	94054
	Calibration Period	N/A
	Range and Accuracy	15,000 force pounds; ± 4.5 in.
10.	Instrument	Interface Load Cell
	Manufacturer	--
	Model Number	1220-AF
	Serial Number	28-90
	Calibration Period	N/A
	Range and Accuracy	50,000 pounds
11.	Instrument	Linear Variable Differential Transformer
	Manufacturer	G. L. Collins Corporation
	Model Number	SS108
	Serial Number	164307
	Calibration Period	N/A
	Range and Accuracy	--
12.	Instrument	Linear Variable Differential Transformer
	Manufacturer	G. L. Collins Corporation
	Model Number	SS-208
	Serial Number	155111
	Calibration Period	Six months
	Range and Accuracy	0 to ± 4 in.

13. Instrument	Digital Multimeter
Manufacturer	Dana Labs
Model Number	2000
Serial Number	4990
Calibration Period	Six months
Range and Accuracy	0 to 1000 vac or vdc, 0 to 2 amperes

5.0 INSTRUMENTATION AND CALIBRATION

The instrumentation utilized for the performance of this test program is schematically shown in Fig. 5-1. The load system consisted of a hydraulic actuator whose internal pressure and flow were adjusted by a servo amplifier and servo valve configuration. The servo amplifier was utilized in a load feedback mode which controlled a fixed value of load to the dowel/socket system as adjusted by the command signal input. The hydraulic pressure test system utilized to provide the force required to shear the dowel systems is schematically shown in Fig. 5-2. Figure 5-3 shows how the displacement was measured during each test.

The load cell utilized in the test program was calibrated prior to testing. A known value of force was applied in tension and compression to the load cell. The electrical output versus load application was recorded as shown in Figs. 5-4 and 5-5. Evaluation of the calibration data obtained verified that the sensitivity of the load cell transducer specified by the manufacturer was in fact correct.

Prior to initiating the test program and periodically during the test program, the LVDTs utilized for measuring displacement were calibrated. Calibration consisted of placing spacers of known dimensions between the LVDT shaft and the LVDT body and measuring the output voltage of the LVDT instrument. The LVDT calibration data were incorporated in the galvanometer oscillograph data obtained prior to the initiation of each test.

Fig. 5-1. Dowel/socket load instrumentation test system

Fig. 5-2. Dowel/socket load test system

NOTE: ONE CHANNEL SHOWN FOR PURPOSES OF CLARITY

Fig. 5-3. Dowel/socket displacement measurement test instrumentation

Fig. 5-4. Load cell calibration curve

INSTRON: AETL ID #G3110E GA LOAD CELL (20,000 POUNDS MAXIMUM) AETL ID #G3115E

Fig. 5-5. Load cell calibration curve (against Instron machine)

6.0 TEST SPECIMEN

The test specimens subjected to static and fatigue tests were 8-in. or 6-in.-long sections of full-scale control fuel elements. They were machined by Great Lakes Carbon Company to the specification of Drawings 021075, 021074 and 018866 as shown in Figs. 6-1 through 6-3.

The mechanical properties of the test specimens are tabulated in Table 6-1.

The test specimen utilized in each test is listed in Table 8-1.

HOLE DATA			
SYMBOL	DIAMETER	LENGTH FROM DATUM B	QUANTITY
	.828 $\pm .003$	THROUGH	32
	.719 $\pm .003$	THROUGH	10
	.625 $\pm .003$	7.55 $\pm .06$	56
	.625 $\pm .003$	6.23 $\pm .06$	24

NOTES:
 1 DIMENSIONS PER ANSI-Y14.5.
 MATERIAL: ISOTROPIC GRAPHITE PER
 GA SPEC 900739 GRADE A.

Fig. 6-2. Test specimen (drawing 021074)

▲ TYPICAL THERMAL STABILITY
 ▲ TYPICAL DEEP HOLD TOLERANCE:
 (C) A G D 02 D 78

Technical drawing of a bolt and nut assembly. The bolt is labeled "1/2-16 UN-2B" and the nut is labeled "A 5/16-18 UN-2B". The drawing shows the bolt passing through a plate with a hole, and the nut being tightened on the other side. Dimensions are given for the bolt length and the plate thickness.

SECTION 10-10
SCALE 1/2"

HOLE DATA		QUANTITY
SYMBOL	DIAMETER INCHES	LENGTH INCHES
.875 - .001 1/2	THROUGH
.719 - .003 1/4	THROUGH
.685 - .001 1/8	THROUGH
.626 - .001 3/16	THROUGH

ESTIMATED WT: 34.85.

DVS-NON-DELIVERABLE

Fig. 6-3. Test Specimen (drawing 018866)

2 MATERIAL: ISOTROPIC GRAPHITE PER
GA SPEC 900739 GRADE A.

HOLE DATA			
SYMBOL	DIAMETER	LENGTH FROM DATUM "A"	QUANTITY
	.820 $\pm .003$	THROUGH	32
	.719 $\pm .003$	THROUGH	10
	.625 $\pm .001$	5.17 $\pm .06$	24
	.625 $\pm .003$	THROUGH	24

Fig. 6-1. Test specimen (drawing 021075)

TABLE 6-1
H-451 GRAPHITE TEST ELEMENTS

GLCC Lot No.	GLCC Fur. No.	GLCC Graphitization No.	GLCC Log. No.	Density ^(a) (g/cm ³)	V (ppm)	Ash (ppm)	Axial Tensile ^(b) Strength (psi)	Axial Tensile ^(c) Strength (psi)	Comments
							1st	2nd	
424	44	5698-C	17	1.71	592	--	2050	--	--
426	77	6003-C	100	1.72	23	--	1900	--	Burned
426	77	6003-C	104	1.73	37	--	2065	1941	Burned
426	77	6003-C	110	1.75	31	--	2410	--	Cracked
426	77	6003-C	116	1.70	158	0.8	1830	--	Burned
426	77	6003-C	130	1.71	44	--	1475	--	Burned
--	--	--	167	--	--	--	--	--	--
426	77	6003-C	174	1.73	151	0.5	--	(1812)	Burned
426	77	6003-C	180	1.73	24	--	2355	--	Burned
426	77	6003-C	196	1.71	28	--	1465	--	Burned
426	77	6003-C	203	1.72	29	--	2010	--	--
427	77	6003-C	220	1.74	61	0.6	1550	1506	Burned

(a) Measured on whole log.

(b) Single test ~6 in. from end at center of log.

(c) Specimen glued at break and retested.

NOTE: Burned means oxidized on surface but still usable for machined elements.

7.0 TEST PROCEDURE

All tests were performed at room ambient conditions consisting of a temperature of $70^{\circ} \pm 20^{\circ}\text{F}$, a relative humidity of less than 95%, and a barometric pressure of 29.92 ± 2.0 in. of mercury absolute.

The procedure to install the test specimen into the test fixture was as follows:

Part I

1. Attach lifting angle to box assembly (021036-001) with (2) 3/8-16 bolts (021047-001). Use bolt holes in top of box closest to stiffener. Place box in test rig. Center box under load cell front to back on scribed line on top side of box base and side to side between box sides. Maintain this position within ± 0.06 inches. Attach box to test rig using existing (8) 0.56-in.-diameter holes. Remove lifting angle.
2. Install back clamp (021042-001) inside of box assembly with (2) 3/8-16 x 2-in. bolts using 0.45-in. clearance in back of box. These bolts shall not extend through back clamp (flush). Install (3) 3/8-16 x 1-in. bolts with jamb nuts in threaded holes in back of box; run bolts through back approximately 1/4 in.
3. Install (2) side clamps (021040-001) inside box assembly with (2) (each side) 3/8-16 x 2-in. bolts using 0.50-in. x 0.87-in. slots. Side clamps shall face each other toward center of box. Bottom out bolts in side clamps. Install 3/8-16 x 1-in. bolts with jamb nuts in threaded holes flush with inside of box.

4. Install top clamp (021039-001) on inside (top) of box assembly with (1) 3/8-16 x 3-in. bolt using (1) 0.43 clearance hole. This bolt shall not extend through top clamp (flush). Install (4) 3/8-16 bolts (021047-001) with jamb nuts in threaded holes in top of box; run bolts through top approximately 1 in.
5. Install bottom spacer (021044-001 or 022454-001) inside bottom of box assembly with (2) 3/8-16 x 2-3/4-in. or 2-1/4-in. bolts and 3/8 flat washers and lock washers in 3/8-16 threaded holes in bottom of box.

Part II

1. Place graphite test block in box assembly with dowels facing out, and align front face with scribe line on bottom plate of box assembly. Center (test block) between box assembly side plates.
2. Clamp test block in box assembly with top clamp by tightening (4) 3/8-16 adjusting bolts. Lock in place with (4) 3/8-16 jamb nuts.
3. Clamp test block in box assembly with (2) side clamps by tightening (2) (each side) 3/8-16 adjusting bolts. Lock in place with (2) (each side) jamb nuts.
4. Clamp test block in box assembly with back clamp by tightening (3) 3/8-16 adjusting bolts. Lock in place with (3) 3/8-16 jamb nuts.
5. Check to ensure that test block is in proper alignment with box assembly and test rig and that all clamping surfaces are in full contact.

Part III

1. Attach lifting angle to box assembly (021037-001) with (2) 3/8-16 bolts (021047-001). Use threaded holes in top of box farthest from stiffener.

2. Prior to installation in the test rig, install the following parts as described in Part I: 021039-001, 021040-001, 021041-001 and 021042-001.
3. Place graphite test block in box assembly with dowel sockets facing open end of box. Push test block fully into box until dowel protrudes through back clamp and (dowels) contact back of box.
4. Temporarily clamp test block in box assembly with top clamp (021039-001).
5. Place this assembly (box with test block) in test rig and align with box assembly (and test block) already in test rig with their respective dowels and sockets. This can be done by aligning box assemblies vertically with (2) 0.62-in.-thick shims between bottoms of boxes.
6. Release top clamp temporarily.

Part IV

1. Install guide blocks 021045-001/-002 on bottom plate of box assembly (021036-001) first and then guide blocks on top plate. Note: guide blocks are marked (A, B, C, D respectively) for a specific location on box assembly. Use 3/8-16 x 5-in. bolts and lock washers.
2. Push test block forward to engage dowels on mating test block. This may be done by pushing on 3/8-16 retaining bolts in back of back clamp.
3. Clamp test block with back clamp. Refer to Part II, step 4. Clamp.
4. Clamp test block with top clamp. Refer to Part II, step 2.
5. Clamp test block with side clamps. Refer to Part II, step 3. Check to ensure proper alignment. Refer to Part II, step 5. Faces of test blocks shall be in full contact.

Install the plates (021046-001) with (8) (each side) 3/8-16 x 1.5-in.-
bolts, 3/8 flat washers, and lock washers.

For disassembly reverse steps outlined in Parts III and IV. Note:
The plates may be easily removed by using tapped holes provided and
using 3/8-16 bolts as jacking screws.

8.0 TEST RESULTS

The test program was conducted in two phases of testing. The first phase was to determine the ultimate static strength of the four-dowel and five-dowel systems with type H-451 graphite. The second phase of testing was to conduct fatigue tests on both dowel systems. All of the tests were conducted in the orientation expected to be the weakest as shown in Fig. 8-1 to arrive at a conservative evaluation of the strength of the dowel/socket systems.

8.1 Static Load Test

Two tests each were conducted on the four-dowel system and the five-dowel system. For each test, the compression load was applied at the rate of 0.05 in./minute to the dowel/socket system until major cracking and large displacements were observed on the oscillograph records. The test results are as follows:

Dowel System	Ultimate Load	
	Newtons	(Pounds)
4	47,594	(10,700)
	44,121	(9,920)
5	68,944	(15,500)
	70,056	(15,750)

During each test, the movement of both test fuel elements was monitored by two LVDTs. The difference of the LVDTs was the deflection of the dowel/socket system under loading. Figures 8-2 through 8-5 show the load versus deflection curves of the four static tests conducted on the four- and five-dowel systems.

Technical drawing of a hexagonal plate with various dimensions and features. The drawing includes a top view of the hexagonal plate and a side view of a corner. Key dimensions and features are labeled:

- Top View Dimensions:**
 - Overall width: 3.715
 - Overall height: 4.696
 - Top edge chamfer: 30° TYP
 - Top edge chamfer width: 4.068 TYP
 - Bottom edge chamfer: 30° TYP
 - Bottom edge chamfer width: 2.712 TYP
 - Bottom edge chamfer width: 2.895 ± .001 DIA
- Side View Dimensions:**
 - Top edge chamfer: 30° TYP
 - Top edge chamfer width: 1.787 ± .001 TYP
 - Top edge chamfer width: 1.906 ± .003 TYP
 - Top edge chamfer width: .062 MAX TYP
 - Top edge chamfer width: .08 TYP
 - Top edge chamfer width: 1.11 TYP
- Surface Features:**
 - Top surface: 3.715
 - Bottom surface: 4.696
 - Top surface: 2.712 TYP
 - Bottom surface: 2.895 ± .001 DIA
 - Top surface: 1.787 ± .001 TYP
 - Top surface: 1.906 ± .003 TYP
 - Top surface: .062 MAX TYP
 - Top surface: .08 TYP
 - Top surface: 1.11 TYP
- Surface Text:**
 - Top surface: 3.715
 - Bottom surface: 4.696
 - Top surface: 2.712 TYP
 - Bottom surface: 2.895 ± .001 DIA
 - Top surface: 1.787 ± .001 TYP
 - Top surface: 1.906 ± .003 TYP
 - Top surface: .062 MAX TYP
 - Top surface: .08 TYP
 - Top surface: 1.11 TYP

Fig. 8-1. Test orientation of four- and five-dowel system in the fatigue tests

Fig. 8-2. Test result of S4-1 four-dowel system load versus deflection curve

Fig. 8-3. Test result of S4-2 four-dowel system load versus deflection curve

Fig. 8-4. Test results of S5-1 five-dowel system load versus deflection curve

Fig. 8-5. Test result of S5-2 five-dowel system load versus deflection curve

After the completion of each test, the fuel elements were examined and photographed (see Figs. 8-6 through 8-9). The common failure mode was the cracking of the two bottom dowels and the sidewall underneath them. For the five-dowel system, an additional cracking of the central dowel was observed.

8.2 Fatigue Test

A total of 11 tests were conducted on the four-dowel system and 10 tests on the five-dowel system. For each test, the load application was sinusoidal in nature. The input command signal of tension and compression loading was gradually increased until the specified load level was obtained. The load level for each test was chosen from the test results of the static load tests both for the four-dowel and the five-dowel systems.

During the application of compression and tension loading, the displacement of both test fuel elements was monitored by two LVDTs and permanently recorded on a galvanometer oscillograph. The typical traces of recorded data are shown in Fig. 8-10. The failure of the fatigue test was determined to occur when the test fuel elements exhibited very large displacements and major cracks were observed. Fig. 8-11 shows the traces of load cell and LVDTs from a typical fatigue test at the time when failure occurred. The test results for the fatigue tests of the four-dowel and five-dowel systems are tabulated in Table 8-1.

The rate of cycling of loads for each test was adjusted depending on the number of cycles the dowel/socket system being tested could stand. The cycling rate for the first 50 cycles was approximately 2 to 4 cycles per minute. For additional cycles beyond the first 50, the cycling rate was between 8 to 10 cycles per minute.

During each test, the deflection of the elements tested was monitored by two LVDTs for each load cycle. The amplitude of deflection increased as the number of load cycles increased. The difference between the deflection at the beginning of the test and that at the termination of the test was measured and tabulated for each test under the column of deflection drift in Table 8-1.

Fig. 8-6. Test S4-1 - four-dowel static test, maximum load 47,594 N

Fig. 8-7. Test S4-2 - four-dowel static test, maximum load 44,129 N

Fig. 8-8. Test S5-1 - five-dowel static test, maximum load 68,944 N

Fig. 8-9. Test S5-2 - five-dowel static test, maximum load 70,055 N

Fig. 8-10. Typical traces of recorded information in the fatigue test

Fig. 8-11. Typical traces recorded in the fatigue test when fatigue occurred

TABLE 8-1
TEST RESULTS OF THE DOWEL/SOCKET SYSTEM FATIGUE TEST

Test No.	Dowel System	Dowel/Socket Element Identification Number		Number of Load Cycles to Failure	Tension & Compression Load Level Newtons (lb)	Deflection Drift mm (in.)
		Dowel Side	Socket Side			
F4-1	4	424/17 C	426/220 A	20	35,584 (8,000)	--
F4-5	4	426/220 A	424/17 C	13	40,032 (9,000)	0.254 (0.01)
F4-6	4	426/100 B	426/203 D	>1,000	31,136 (7,000)	0.457 (0.018)
F4-7	4	426/203 D	426/100 B	23	33,360 (7,500)	0.406 (0.015)
F4-8	4	426/167 A	426/174 B	5	37,808 (8,500)	0.559 (0.022)
F4-9	4	426/174 B	426/167 A	2	40,032 (9,000)	--
F4-10	4	426/220 A	426/220 B	3	35,584 (8,000)	--
F4-11	4	426/220 B	426/220 A	>1,000	33,360 (7,500)	0.533 (0.021)
F4-12	4	426/100 A	426/174 B	700	31,136 (7,000)	0.787 (0.031)
F4-13	4	426/174 B	426/100 A	>1,000	26,688 (6,000)	0.762 (0.03)
F4-14	4	426/203 C	424/17 A	4	35,584 (8,000)	--
F5-1	5	426/130 B	426/180 A	>1,000	53,376 (12,000)	0.5596 (0.022)
F5-2	5	426/180 A	426/130 B	49	62,272 (14,000)	0.203 (0.008)
F5-3	5	424/17 B	426/104 B	>1,000	44,480 (10,000)	0.635 (0.025)
F5-4	5	426/104 B	424/17 B	>1,000	48,928 (11,000)	0.279 (0.011)
F5-5	5	426/196 A	426/104 A	>1,000	53,376 (12,000)	0.559 (0.022)
F5-6	5	426/104 A	426/196 A	630	57,824 (13,000)	0.940 (0.037)
F5-7	5	426/203 B	426/220 C	190	60,048 (13,500)	0.406 (0.016)
F5-8	5	426/220 C	426/203 B	216	62,272 (14,000)	0.965 (0.038)
F5-9	5	426/104 C	426/104 C	17	64,496 (14,500)	0.432 (0.017)
F5-10	5	426/174 C	426/104 C	114	60,048 (13,500)	0.965 (0.038)

After the completion of each test, the fuel elements were examined and photographed. They are shown in Figs. 8-12 through 8-32. The failure mode from the fatigue tests was quite similar to that displayed in static tests; i.e., the cracking of the two bottom dowels and the sidewall underneath them. In addition to the above-referenced failure, the central dowel of the five-dowel system was broken and sheared off in a 45-degree cone.

For some of the tests, the cycling was terminated after 1000 tension and compression load applications. This limit was chosen because of the fact that the dowel/socket system would not experience over 100 loading cycles in a seismic event.

A least-squares fit computer code was utilized to fit the test data into straight lines on a log-log scale. The results showed the fatigue life for the dowel/socket system to be described mathematically by

$$\log_e F = 11.14923 - 0.026867 \log_e n$$

for the five-dowel system, and

$$\log_e F = 10.64535 - 0.05255 \log_e n$$

for the four-dowel system,

where F is the alternating force level in Newtons and
 n is the corresponding number of cycles.

To calculate the load in pounds of force, use 9.65678 instead of 11.14923 in the first equation and 9.15290 instead of 10.64535 in the second equation.

The fatigue curves and the test results together with their 95% confidence limits for both four- and five-dowel systems are plotted in Fig. 8-33.

Fig. 8-12. Test F4-1 - four-dowel fatigue test. Force level: $\pm 35,584$ N.
Number of cycles to failure: 20

Fig. 8-13. Test S4-5 - four-dowel fatigue test. Force level: $\pm 40,032$ N.
Number of cycles to failure: 13

Fig. 8-14. Test F4-6 - four-dowel fatigue test. Force level $\pm 31,136$ N. No failure was observed after 1000 cycles. A static load-to-failure test was then conducted. The maximum load was 44,169 N.

Fig. 8-15. Test F4-7 - four-dowel fatigue. Force level $\pm 33,360$ N. Number of cycles to failure: 23

Fig. 8-16. Test F4-8 - four-dowel fatigue test. Force level: $\pm 37,808$ N. Number of cycles to failure: 5. The bottom two dowels were completely cracked.

Fig. 8-17. Test F4-9 - four-dowel fatigue test. Force level: $\pm 40,032$ N. Number of cycles to failure: 2. The bottom two dowels completely cracked.

Fig. 8-18. Test F4-10 - four-dowel fatigue test. Force level: $\pm 35,584$ N. Number of cycles to failure: 3. The bottom two dowels completely cracked.

Fig. 8-19. Test F4-11 - four-dowel fatigue test. Force level: $\pm 33,360$ N. No failure was observed after 1000 cycles. The after-test inspection showed cracks in the bottom dowel.

Fig. 8-20. Test F4-12 - four-dowel fatigue test. Force level: $\pm 31,136$ N.
Number of cycles to failure: 700

Fig. 8-21. Test F4-13 - four-dowel fatigue test. Force level: $\pm 26,688$ N.
No failure was observed after 1000 cycles. The after-test inspection showed cracks in the bottom dowels.

Fig. 8-22. Test F4-14 - four-dowel fatigue test. Force level: $\pm 35,584$ N.
Number of cycles to failure: 4

Fig. 8-23. Test F5-1 - five-dowel fatigue test. Force level: $\pm 53,376$ N. No failure was observed after 1000 cycles. The after-test inspection found cracks in the central and bottom two dowels. The central dowel was twisted off during after-inspection and left in the socket hole for this photograph.

Fig. 8-24. Test F5-2 - five-dowel fatigue test. Force level: $\pm 62,272$ N. Number of cycles to failure: 49

Fig. 8-25. Test F5-3 - five-dowel fatigue test. Force level: $\pm 44,480$ N. No failure was observed after 1000 cycles. A static load-to-failure test was then conducted. The maximum load was 66,720 N.

Fig. 8-26. Test F5-4 - five-dowel fatigue test. Force level: $\pm 48,928$ N. No failure was observed after 1000 cycles. The after-test inspection found cracks in the central and bottom two dowels. The central dowel was twisted off during after test inspection and left in the socket hole for this photograph.

Fig. 8-27. Test F5-5 - five-dowel fatigue test. Force level: $\pm 53,376$ N. No failure was observed after 1000 cycles. A static load-to-failure was then conducted. The maximum load was 69,389 N.

Fig. 8-28. Test F5-6 - five-dowel fatigue test. Force level: $\pm 57,824$ N. Number of cycles to failure: 630

Fig. 8-29. Test F5-7 - five-dowel fatigue test. Force level: $\pm 60,048$ N.
Number of cycles to failure: 190

Fig. 8-30. Test F5-8 - five-dowel fatigue test. Force level: $\pm 62,272$ N.
Number of cycles to failure: 216

Fig. 8-33. Fatigue curves for four- and five-dowel systems

9.0 DISCUSSION

Table 9-1 compares the dowel/socket system static test results of type H-451 graphite with the recent test results of type H-327 graphite (Ref. 2).

TABLE 9-1
DOWEL/SOCKET SYSTEM STATIC TEST RESULTS

Type of Graphite	Static Strength - Newtons (Pounds)	
	4-dowel system	5-dowel system
H-327	26,700 (6,000)	44,500 (10,000)
H-451	44,500 (10,000)	69,000 (15,500)

The dowel/socket system strength was increased by more than 50% by changing the fuel element material from type H-327 graphite to type H-451 graphite.

For type H-327 graphite, the failure mode of the dowel/socket system was the local crushing of ligaments between the edge of the element and the two dowels opposite the reserve shutdown hole (the lower pair in Figs. 8-6 through 8-9 and 8-13 through 8-32).

The failure mode for H-451 graphite was the cracking of these dowels as well as the failure of the adjacent sidewall. The following table lists the measured tensile strength (Refs. 1, 2) for both types of graphite at two different locations.

TABLE 9-2
TENSILE STRENGTH OF TYPE H-327 AND TYPE H-451 GRAPHITE

Location in the log	Tensile Strength	
	H-451 Graphite $\frac{MN}{m^2}$ (PSI)	H-327 Graphite $\frac{MN}{m^2}$ (PSI)
END CENTER AXIAL Direction	15.52 $\pm$ 2.69 (2251 $\pm$ 391)	15.03 $\pm$ 3.0 (2180 $\pm$ 435)
END EDGE AXIAL Direction	18.03 $\pm$ 2.09 (2615 $\pm$ 303)	16.51 $\pm$ 3.31 (2395 $\pm$ 480)
END CENTER RADIAL Direction	13.93 $\pm$ 2.65 (2020 $\pm$ 385)	9.31 $\pm$ 1.86 (1350 $\pm$ 270)
END EDGE RADIAL Direction	15.17 $\pm$ 2.28 (2200 $\pm$ 331)	9.31 $\pm$ 1.86 (1350 $\pm$ 270)

The higher tensile strength of type H-451 graphite compared to that of type H-327 graphite in the radial direction appears to account for the 50% increase in dowel/socket system strength. The failure of dowels observed in tests with H-451 graphite appears to be a result of the fact that H-451 graphite is only slightly stronger than H-327 graphite in the axial direction.

The initial slopes of the static stress-strain curves defined the stiffness of the dowel/socket systems. This is an important input parameter in the analytical prediction of dowel loads during a seismic event. Table 9-3 lists the stiffness of the dowel/socket systems for both types of graphite.

TABLE 9-3
TEST RESULTS OF DOWEL/SOCKET SYSTEMS STIFFNESS

Type of Graphite	Dowel/Socket System Stiffness		Total Deflection to Failure	
	4-dowel system N/mm (lb/in.)	5-dowel system N/mm (lb/in.)	4-dowel system N/mm (lb/in.)	5-dowel system N/mm (lb/in.)
H-327	8,800 (50,000)	14,900 (85,000)	4.3 (0.17)	5.1 (0.2)
H-451	18,000 (103,000)	26,300 (150,000)	3.0 (0.12)	3.5 (0.14)

The greater stiffness measured in the present tests with H-451 graphite is due in part to the approximately 50% higher elastic modulus of H-451 graphite in the radial direction. Better instrumentation may also be a factor since two LVDTs were used in the present test program to monitor the deflection of both fuel elements. The difference of the two LVDT readings was used as a measure of the deflection of the dowel/socket systems under loading. In the previous tests of type H-327 graphite dowel/socket systems only one LVDT was used to record the relative displacement of the two halves of the test fixture. The movement of the dowel side fuel element was ignored. More accurate monitoring of the movement of the fuel elements under loading accounted for part of the apparent increase in stiffness and reduction in deflection to failure of the H-451 graphite dowel/socket system compared to previous results with H-327 graphite.

During fatigue testing of tests F4-11, F4-12, F5-3, F5-4 and F5-5 (see Table 8-1), the tests were stopped after the application of tension and compression loads for approximately 100 cycles. The fuel elements being tested were examined. The bottom two dowels of the four-dowel system and the bottom two dowels and the central dowel of the five-dowel system were found to have cracks in them. The test elements were put back in the test fixture and load cycle testing continued.

All but test number F4-12 went through over 1000 cycles and without major cracking or increase in deflection. Test number F4-12 failed at 700 load cycles.

All the rest of the fatigue testing was conducted at loading levels higher than those in the tests examined after 100 cycles. This indicates that for all the fatigue tests conducted, initial cracks in the dowels probably occurred in the first few cycles of tension and compression load application. As the load cycles went on the cracks in the dowels propagated and after several load cycles led to major failure. This phenomenon was observed from the readings of two LVDTs used in each test to monitor the movement of the fuel elements under dowel/socket system constant cyclic loading. The deflections of the LVDTs were at constant amplitude at the beginning of the load cycling. The deflections increased as the number of load cycles increased. The difference between the deflection immediately before the failure and the deflection at the beginning of test is tabulated in Table 8-1.

The maximum increase in deflection recorded in any test was 0.053 in. Comparing this with the 0.828-in. size of the coolant hole, we see that deflection prior to failure will not cause any problem with coolant flow blockage.

The function of the dowel/socket system is to align the fuel elements in a column. The existence of the cracks in the dowels does not affect the function of the dowel/socket system. So long as the cracks do not propagate and the dowels can still withstand the loading, the dowel/socket system is capable of performing its design function to maintain the coolant hole alignment in a column.

10.0 REFERENCES

1. Johnson, W. R., and G. B. Engle, "Properties of Unirradiated Fuel Element Graphites H-451 and TS-1240," USERDA Report GA-A13752, General Atomic, January 31, 1976.
2. Price, R. J., "Mechanical Properties of Graphite for High-Temperature Gas-Cooled Reactors: A Review," USERDA Report GA-A13524, General Atomic, September 22, 1975.