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GCFR 1/15-Scale PCRV Steam Generator Cavity Closure Model Test

W. G. Dodge
G. C. Robinson
J. P. Callahan

MASTER

OAK RIDGE NATIONAL LABORATORY
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CAVITY CLOSURE MODEL TEST

W. G. Dodge G. C. Robinson
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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
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CONTENTS

	<u>Page</u>
PREFACE	v
ACKNOWLEDGMENTS	vii
ABSTRACT	1
1. INTRODUCTION	2
2. PROTOTYPE DESCRIPTION	3
3. MODEL DESCRIPTION	6
3.1 Materials Simulation of Steel Components	7
3.2 Materials Simulation of Reinforced Concrete	14
4. TEST FACILITY	25
5. INSTRUMENTATION	27
5.1 Displacement Monitoring	27
5.2 Strain Monitoring	27
6. MODEL TEST	37
7. MODEL ANALYSIS	40
7.1 Material Constitutive Models	40
7.2 Boundary Conditions	43
7.3 Calculated Behavior of Model	44
8. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS	45
8.1 Displacement Results	45
8.2 Bonded Resistance Strain Gage Results	56
8.3 Embedded Strain Gages	66
9. CONCLUSIONS AND RECOMMENDATIONS	76
REFERENCES	77

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PREFACE

Model testing has traditionally been an important element in the design of complicated structures owing to the complexity of structural behavior and the deficiency of the existing analysis methods to determine structural response, especially overload response. Consequently, Section III, Division 2 of the ASME Boiler and Pressure Vessel Code which governs the design of prestressed concrete reactor vessels (PCRVs) has specific requirements for model tests.

The PCRV for the gas-cooled fast reactor (GCFR) is fairly unique with respect to its relatively high operating pressure and the requirement of a large penetration closure to provide access to the core cavity. It is therefore necessary to design, build, and test models of the PCRV and the two large closures for the steam generator cavities and the core cavity in order to demonstrate adequacy of the proposed designs.

The plan for the development of the PCRV for the GCFR was prepared by the General Atomic Company, which has the overall design responsibility. Oak Ridge National Laboratory is conducting the series of closure model tests, as outlined in the development plan. This work is supported by the Department of Energy under 189a No. 1350, *Pressure Vessel and Closure Studies*.

The closure testing program consists of a series of relatively small 1/15-scale models used to provide preliminary design information concerning structural response of the closure plug. Once the design has been finalized, tests will be conducted using larger and more elaborate 1/4-scale models to provide final design verification of both the plug and hold-down system. This report presents the results of the first of the series, the 1/15-scale steam generator cavity closure pressure test.

Since the 1/15-scale model tests are intended to serve as scoping studies, the number of models to be tested will depend upon the requirements of the designers. However, it is anticipated that more than one model of each of the two basic types of closures will be required. A separate report will be published for each test. In addition, the progress of the program is reported regularly in the ORNL Gas-Cooled Fast Reactor Program Progress Reports, the last of which was for the period Jan. 1, 1974, through June 30, 1975 (ORNL-5119).

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Although this test was neither complex nor expensive, the services and expertise required for its completion involved the cooperation and assistance of numerous people in the ORNL and Y-12 organizations. In particular, a special note of appreciation is made to T. M. Cate, H. D. Curtis, C. C. Hurtt, T. A. King, D. J. Naus, J. E. Smith, and W. J. Stelz-
man for the assistance rendered in materials property testing, development of instrumentation, fabrication and instrumentation of the model, and data acquisition.

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ABSTRACT

As a major participant in the Gas-Cooled Fast Reactor (GCFR) Development Program, the Oak Ridge National Laboratory has been assigned the tasks of planning and conducting structural response tests of the 300-MW(e) demonstration GCFR prestressed concrete reactor vessel closures. These studies are being conducted in close cooperation with General Atomic Co., which has the major design and development responsibility in the overall effort.

This report discusses the design, testing, analysis, and evaluation of the first test of this series (i.e., the 1/15-scale model of the steam generator cavity closure. The primary objective of this test was to demonstrate the design performance and ultimate load capacity of the closure. Although it had been desired also to obtain information on crack development and propagation and mode of failure of the composite structure, these objectives were not obtained because pressurization was stopped at 75.84 MPa (11,000 psig) prior to obtaining ultimate load. The decision to cease pressurization at this point was influenced by the fact that the load attained was nearly 7.5 times the design load [10.08 MPa (1462 psig)] and that the instrumentation revealed that inelastic action was in progress, and by the desire to prevent the test fixture hold-down mechanism from incurring damage that would preclude its usage on future tests. (Prior hydrostatic testing of the fixture had caused slight thread yielding, thus requiring minor modifications to the design of the fixture.)

Several pretest analyses were made to evaluate the effect of various design details and material parameters. These analyses were culminated by a nonlinear analysis using the finite-element code ADINA, which includes material constitutive models for representing the nonlinear stress-strain response of both steel and concrete components. A comparison of the strains and deformations indicated generally good to fair agreement between the analytical and experimental results; however, in some few instances agreement was rather poor. These poor comparisons are attributed to boundary conditions that were difficult to model and to inadequate constitutive equations for the concrete. Analytical results predicted that failure was imminent at the 75.84 MPa loading.

We recommend that, because of the demonstrated very high load capability of the plug, a modified thinner version be tested that can lead to substantial PCRV economies and that improved constitutive models be incorporated in the ADINA finite-element code to improve the analytical predictions.

1. INTRODUCTION

The Oak Ridge National Laboratory (ORNL) is conducting a series of structural model tests as part of the U.S. program to develop a 300-MW(e) gas-cooled fast reactor (GCFR) demonstration power plant. These studies are planned and conducted in close cooperation with the General Atomic Co.,¹ which is responsible for the design and development in the overall effort.

One of the tasks in the ORNL program entails the design, analysis, and testing of 1/15-scale models of the penetration closure plugs for the prestressed concrete reactor vessel (PCRVR). The principal objectives of the tests are to determine the structural response for normal operating pressures and for substantial overpressurization. The tests are also to provide reliable data for verification of analysis methods. This report describes testing and related analytical studies of the 1/15-scale steam generator cavity closure model, which is the first model of the series to be tested.

2. PROTOTYPE DESCRIPTION

The vertical cross-sectional view of the PCRV for the 300-MW(e) GCFR demonstration plant, shown in Fig. 2.1, indicates the relative size, location, and principal features of both the reactor and the steam generator cavity closures. The design maximum cavity pressure is 10.08 MPa (1462 psig). The steam generator cavity closure plug, shown in Fig. 2.2, is a composite structure made of concrete and steel. The concrete is confined on the inner, outer, and bottom surfaces by a relatively thin steel liner, and ring forgings are attached to the top of both inner and outer wall liners. The function of the rather massive forging attached to the outer liner is to transfer the resulting pressure loads from the plug to the adjacent axial prestressing tendons of the PCRV. This transfer is accomplished by means of a series of circumferentially spaced two-force members called toggles. The toggles are inclined at an angle of 25° from the vertical and induce a radial compression to the ring forging; thus, together with the lateral pressure of the coolant, they contribute to a circumferential prestress effect on the plug that remains directly proportional to the pressure loading induced by the reactor coolant. The helium circulator is supported by the heavy-walled cylindrical steel component attached to the bottom of the inner liner. Since the plug shown in Fig. 2.2 was intended only for testing in the primary or toggle hold-down mode, the secondary hold-down system shown near the bottom of the closures in Fig. 2.1 was not included. Attached to the inside of the outer liner of the plug is a built-up steel structure consisting of a continuous conical ring that is supported by the series of vertical gussets shown in view A-A of Fig. 2.2. This assembly, which is called a shear console, is designed to provide for transfer of shearing loads from the concrete to the outer liner. A much smaller rectangular cross-section steel ring performs a similar function at the inner liner of the plug.

Fig. 2.1. Vertical cross section of the PCRV for the 300-MW(e) GCFR demonstration power plant.

Fig. 2.2. Plan and vertical sections of the prototype steam generator cavity closure plug selected for the 1/15-scale model test.

3. MODEL DESCRIPTION

Figure 3.1 shows a cross section of the model positioned ready for testing in the steel test fixture which is distinguished by cross-hatching. The model represents a linear scaling of all physical features of the prototype shown in Fig. 2.2. The primary difference between the prototype and model is in the restraint provided by their associated hold-down systems. The ball bearing support system shown in Fig. 3.1 was selected to

Fig. 3.1. Cross section of the 1/15-scale steam generator cavity closure plug model positioned for testing in the test fixture.

provide sufficient strength to preclude premature failure during the overpressurization phase of the test. However, this system does not necessarily produce the same radial component of load on the outer ring forging as the toggle system. In particular, the pressure acting along the outer wall of the plug tends to deflect the forging inwardly, while the ball bearing support system places a restraint on this deformation that does not exist with the toggle system of the prototype. Thus, less radial compression is probably produced on the model forging than would be produced using the toggle system of the prototype. Detailed analysis indicates that, due to the massiveness of the forging, this effect is rather small and does not significantly affect the results of this test.

The following sections describe the procedures used for accurate simulation in the model of the mechanical properties of the various component parts of the prototype.

3.1 Materials Simulation of Steel Components

The steel materials for the prototype plugs, consisting of ASTM A508 class 1 forgings, ASTM A537 class 1 plate, and ASTM A615 grade 60 reinforcing bars, are relatively common low-alloy steels but are not available in small lots. Consequently, a severe economic penalty would have been experienced in attempting to employ a one-to-one correspondence of steel materials between the prototype and model. We therefore elected to utilize available low-carbon steels and apply various heat treatments, as required, to effect simulation of the proper stress-strain curves. It was assumed that the stress-strain curves of the model and prototype steel components could be considered reasonably matched if correspondence were maintained up to about 1% strain.

Figure 3.2 shows the top plan and a vertical section of the 1/15-scale model of the steam generator closure plug. Also shown are material category designations A through G, which are used in Table 3.1 to provide the correspondence between prototype and model steel materials and the heat treatment, if any, found necessary for simulation.

As noted in Table 3.1, material category A, the ASTM A36 plate material for the outer ring forging of the model requires no heat treatment

Fig. 3.2. Plan and vertical section of the 1/15-scale model of the 300-MW(e) GCFR-PCRVR steam generator cavity closure plug.

Table 3.1. Correspondence between prototype and model steel materials

Material category ^a	Prototype material	Model material	Model material heat treatment
A	A-508 class 1	A36	None
B	A-537 class 1	A106 grade C	Austenitize 1 hr at 871°C, hold 1 hr, water quench, temper at 540°C, hold 1 hr, air cool
C	A-537 class 1	A106 grade C	Austenitize 1 hr at 870°C, hold 1 hr, water quench
D	A-537 class 1	A533 grade B class 1	<i>b</i>
E	A-537 class 1	A533 grade B class 1	<i>b</i>
F	A-508 class 1	A533 grade B class 1	<i>b</i>
G	A-615 grade 60	AISI 1010	14 AWG wire anneal 2 hr in argon at 565.5°C, air cool 18 AWG wire anneal 2 hr in argon at 574°C, air cool

^aMaterial categories are shown on Fig. 3.4.

^bMaterials for these categories were obtained from the ORNL Heavy-Section Steel Technology Program and had been previously austenitized, quenched, tempered, and characterized by mechanical testing.²

to simulate the prototype ASTM A508 class 1 forging material. Figure 3.3 shows the room temperature yield and ultimate strengths of the model material compared to the prototype properties, while Fig. 3.4 shows a similar comparison of the total elongation and reduction of area.

Categories D, E, and F of Table 3.1 utilized ASTM A533, grade B, class 1 plate obtained from the ORNL Heavy-Section Steel Technology (HSST) Program^{2,3} to simulate the ASTM A537 class 1 plate for the bottom liner, circulator support, and shear console, and ASTM A508 class 1 forging for the inner ring. Table 3.2 provides representative room-temperature tensile properties of the various HSST plates corresponding to the model

Fig. 3.3. Variation of room-temperature tensile properties of ASTM A36 plate used to simulate ASTM A508 class 1 forging in 1/15-scale model of GCFR-PCRVR closure plug.

Table 3.2. Room-temperature tensile properties of material used to simulate material categories D, E, and F of 1/15-scale steam generator cavity closure plug model

Item	Prototype material simulated	HSST plate identification ^a	HSST test direction ^b	Strength properties		Ultimate tensile [MPa (ksi)]	Total elongation ^c (%)	Reduction in area (%)
				Upper yield [MPa (ksi)]	Lower yield [MPa (ksi)]			
Category D ^d	A537 cl 1	02E	R	475.1 (68.9)	470.9 (68.3)	615.7 (89.3)	24.4	54.3
			W		481.3 (69.8)	619.8 (89.9)	16.7	32.0
			T	488.2 (70.8)	457.7 (69.0)	627.4 (91.0)	23.5	53.9
Category E ^e	A537 cl 1	03E	R	454.4 (65.9)	453.0 (65.7)	611.6 (88.6)	22.5	55.5
			W	455.1 (66.0)	446.1 (64.7)	610.9 (88.6)	21.0	50.0
		01M4	F	408.9 (59.3)	402.7 (58.4)	548.1 (79.5)	32.0	69.5
			W	415.8 (60.3)	399.9 (58.0)	546.8 (79.3)	29.0	63.0
Category F ^f	A508 cl 1	03E	F	454.4 (65.9)	453.0 (65.7)	611.7 (88.7)	22.5	55.5
			W	455.1 (66.0)	446.1 (64.7)	610.9 (88.6)	21.0	50.0
ASTM A508 class 1					240 ^g (35.0)	485-655 (70-95)	20 ^g	38 ^g
ASTM A537 class 1					345 ^g (50)	485-620 (70-90)	22.0 ^g	

^aModel material taken from midthickness section of HSST plates 01, 02, and 03 from the identified plate sections. Tensile strength characterizations of these HSST plates are given in Refs. 1 and 2.

^bR orientation is tensile axis in primary rolling direction; W orientation is tensile axis perpendicular to primary rolling direction and parallel to plate surface (width direction); T orientation is tensile axis perpendicular to plate surface (thickness direction).

^cTotal elongation in standard 0.505-in.-diam 2-in. gage-length specimen.

^dCategory D, bottom liner, aligned in plane (major dimension) with HSST plate RW direction; category D, circulator support, aligned with axial direction corresponding to HSST plate T direction.

^eCategory E, gussets and cone, aligned in plane (major dimensions) with HSST plate RW direction.

^fCategory F, inner ring forging, aligned in plane (major dimensions) with HSST plate RW direction.

^gMinimum values.

Fig. 3.4. Variation of room-temperature ductility of ASTM A36 plate to simulate A508 class 1 forging in the fabrication of 1/15-scale model components of the GCFR-PCRVR closures.

material categories and also lists the ASTM requirements for the prototype. Except for the yield strength of model category F material, which is somewhat high, the simulation was quite good.

ASTM A106 grade C pipe was used to simulate the ASTM A537 class 1 plate of the outer and inner liners (categories B and C of Table 3.1). Both the 10- and 4-in. pipes were austenitized and quenched to increase their yield and ultimate strengths, while the 10-in. pipe also required a tempering treatment. Yield and ultimate strengths of these piping materials as a function of heat treatment steps are given in Fig. 3.5 and compared with the desired prototype values. Comparisons of the achieved reduction of area and elongation as a function of heat treatment steps and requisite prototype value (none specified for reduction of area) are given in Fig. 3.6.

All weld seams on the prototype were designed as radiographable, full-penetration welds. The small size of the model required that careful consideration be given to the weld details employed in the model compared to those of the prototype. All welds in the model, except intermittent welds joining the cone to the gussets in the shear console, were

Fig. 3.5. Variation of room-temperature tensile properties of ASTM A106 grade C pipe heat treated to simulate ASTM A537 class 1 plate in 1/15-scale model of GCFR-PCRv closure plug.

Fig. 3.6. Variation of room-temperature elongation and ductility of ASTM A106 grade C pipe heat treated to simulate ASTM A537 class 1 plate in the fabrication of 1/15-scale model components of the GCFR-PCRVR closures.

full-penetration type and were done in accordance with Union Carbide Procedure UCN W-106 and inspected by liquid-penetrant testing per Union Carbide Procedure UCN W-51. The filler material employed, Rayco 1/16-in.-diam wire conforming to E70S-3, was selected to match the yield strength of the components simulating ASTM A537 class 1 plate material.

3.2 Materials Simulation of Reinforced Concrete

Sixteen trial microconcrete mixes having various water-to-cement ratios were examined in order to select a material having the mechanical

properties specified in Table 3.3. The mixes utilized a crushed limestone aggregate screened to pass a No. 8 standard sieve and to be retained on a No. 50 sieve. The compressive strength and modulus of elasticity of the trial mixes at 118 to 148 days age is presented in Fig. 3.7 as a function of water-to-cement ratio. The Poisson's ratio determined by these tests varied from 0.22 to 0.26.

Table 3.3. Requisite prototype concrete properties

Item	Specified value
Minimum compressive strength at 60 days age, MPa (psi)	44.82 (6500)
Modulus of elasticity at 60 days age, MPa (psi)	2.925×10^4 to 4.482×10^4 (4.5×10^6 to 6.5×10^6)
Poisson's ratio	0.15 to 0.25

Mix No. 2 provided the best representation of the prototype concrete and except, for plasticizer added to increase workability, was the mix used to cast the model. The model and 12 companion control specimens, 10.2 cm diam $\times$ 20.3 cm long (4 in. diam $\times$ 8 in. long) were cast on Dec. 1, 1976. Three of these, tested at 29 days age, yielded an average compressive strength of 51.02 MPa (7.40 ksi) and an average elastic modulus of 34,474 MPa (5000 ksi). Three instrumented specimens tested at 37 days age yielded an average compressive strength of 55.16 MPa (8.0 ksi) and an average elastic modulus of 33,095 MPa (4800 ksi). The remaining six cylinders were tested without being instrumented with strain gages. These specimens had an average compressive strength of 51.71 MPa (7.5 ksi) at an age of 37 days. The slightly higher strength of the instrumented specimens is thought to be due to the two days of drying required for instrumenting the specimens.

The procedures used to simulate the tensile and bond properties of the ASTM A615 rebar of the prototype, material category G of Table 3.1, were developed at the University of Illinois⁴ and Cornell University.⁵

Fig. 3.7. Compressive strength and modulus vs water-to-cement ratio - trial concrete mixes for 1/15-scale GCFR-PCR closure plugs.

Bright basic AISI 1010 wire No. 14 AWG (2.45 mm diam) and No. 18 AWG (1.27 mm diam) were used to simulate the No. 10 and No. 6 rebar, respectively. This wire was deformed using the University of Illinois knurling machine shown in Fig. 3.8 and then heat treated by annealing to obtain the yield strength specified for ASTM A615 rebar. Figure 3.9 shows the deformed appearance of the knurled wire. Table 3.4 provides a comparison between the required deformation dimensions for ASTM A615 rebar and that achieved by the knurling process. All requirements are equaled or surpassed except, in some cases, the deformation height specified for the No. 10 AWG wire.

Fig. 3.8. University of Illinois knurling machine used to deform wire for simulation of rebar.

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Fig. 3.9. Wire deformed by University of Illinois knurling machine, large-diameter No. 14 AWG wire, small-diameter No. 18 AWG wire.

Table 3.4. Simulation of rebar deformation requirements for 1/15-scale model GCFR-PCRVR steam generator closure plug

Prototype bar designation	Model wire designation	Scaled prototype bar diam (mm)	Model wire diam (mm)	Scaled ^a prototype bar deformation spacing, max (mm)	Model wire deformation spacing (mm)	Scaled prototype deformation height, min (mm)	Model wire deformation height (mm)
No. 6	No. 18 AWG	1.27	1.23	0.9	0.64-0.76	0.063	0.076-0.127
No. 10	No. 14 AWG	2.15	2.06	1.51	0.64-0.76	0.108	0.076-0.127

^aDimensions given have been scaled 1/15 from the ASTM A615 requirement.

Figure 3.10 shows the upper yield strength of the No. 14 and No. 18 AWG wires as received and as subjected to trial tempering treatments at various temperatures. The required properties to simulate the prototype rebar are 414 MPa (60 ksi) yield strength, 621 MPa (90 ksi) ultimate tensile strength, and 7% elongation for a 203-mm gage length. The desired yield strength lies in a zone which is extremely sensitive to the heat treatment temperature. Figures 3.11 and 3.12 show the target tempering temperatures chosen to achieve the proper upper and lower yield strengths, respectively, for these wires. Both deformed and undeformed wires were used in the trial tests, and the deformation operation had no appreciable effect on the tensile results. Table 3.5 presents the tensile values

Table 3.5. Tensile properties of knurled and heat treated wire for simulating rebar in 1/15-scale steam generator cavity closure plug model

Sample No.	0.2% yield [MPa (ksi)]	Strength ^a		Ultimate [MPa (ksi)]	Total elongation ^b (%)
		Upper yield [MPa (ksi)]	Lower yield [MPa (ksi)]		
No. 18 AWG ^c					
1		481.3 (69.8)	459.2 (66.6)	459.2 (66.6)	3.2
2		504.0 (73.1)		462.6 (67.1)	3.2
3		507.5 (73.6)	485.4 (70.4)	496.4 (72.0)	2.8
4		511.6 (74.2)	485.4 (70.4)	499.9 (72.5)	2.8
5		544.7 (79.0)	504.0 (73.1)		3.3
Average		509.5 (73.9)	483.3 (70.1)	486.0 (70.5)	3.1
No. 14 AWG ^d					
1	397.1 (57.6)			442.6 (64.2)	17
2		419.9 (60.9)	410.9 (59.6)	446.8 (64.8)	20
3		370.9 (53.8)	355.8 (51.6)	410.9 (59.6)	33
4			342.7 (49.7)	397.8 (57.7)	42
5		357.8 (51.9)	348.2 (50.5)	397.1 (57.6)	45
Average		382.7 (55.5)	370.9 (53.8)	419.2 (60.8)	31

^a Testing machine crosshead speed was 0.50 mm/min (0.020 in./min).

^b Gage length was 50.8 mm (2 in.).

^c 1.23-mm (0.0485-in.) average diameter wire tempered 2 hr at 574°C (1065°F) 2 hr and air cooled.

^d 2.06-mm (0.081-in.) average diameter wire tempered 2 hr at 566°C (1050°F) 2 hr and air cooled.

Fig. 3.10. Effect of tempering temperature on yield strength of bright basic wire to simulate ASTM A615 grade 60 rebar in 1/15-scale model of GCFR-PCRv closure plug.

Fig. 3.11. Target tempering temperatures for upper yield strength of bright basic wire used to simulate ASTM A615 grade 60 rebar in 1/15-scale model of GCFR-PCRv closure plugs.

Fig. 3.12. Target tempering temperatures for lower yield strength of bright basic wire to simulate ASTM A615 grade 60 rebar in 1/15-scale model of GCFR-PCRv closure plugs.

actually achieved on the wire used to simulate the model rebar. The yield strength values of the No. 14 AWG wire are somewhat low and in neither case was it possible to simulate the ultimate strength of the ASTM A615 rebar. However, as previously noted, it had been assumed that model failure would ensue prior to any appreciable work hardening of steel components, so that matching of the yield strengths rather than ultimate strengths was adopted as the primary criterion.

4. TEST FACILITY

The facility and equipment employed in the test of the 1/15-scale models is shown schematically in Fig. 4.1. The facility is capable of providing pressurization to 276 MPa (40 ksi). The upper surface of the model can be observed visually by a periscope and a remote viewing video camera and monitor. Photographs of the top surface of the model were taken periodically through the periscope using a 35-mm camera, and a tape recording was made of the video signal.

The model test fixture, shown in Fig. 3.1, was designed to permit pressure testing of all 1/15-scale closure models. The vessel was fabricated from a modified HY-100 forging procured from the National Forge Co. and machined in the Oak Ridge Y-12 Plant Machine Shop. The test model is secured in the vessel by a single piece threaded bushing assembly, shown in Fig. 3.1, and sealing is accomplished by elastomeric O-ring seals. The original design employed a shear ring which was split into two halves to facilitate insertion and was held in position by a threaded bushing. During hydrostatic testing to 172 MPa (25 ksi), the bushing sustained thread upsetting which made disassembly difficult. Consequently, the more rigid single piece composite design shown in Fig. 3.1 was adopted.

Penetrations were provided in the vessel to permit pressurization and to provide entry of up to 24 (three-wire) channels of instrumentation. The beam gage plug assembly at the bottom of the vessel cavity, shown in Fig. 3.1, serves as a mounting block for six beam gages to monitor vertical movement of the bottom face of the plug and also as ballast to reduce the total potential energy of the hydraulic fluid contained within the vessel.

Fig. 4.1. Test setup for 1/15-scale closure plug models.

5. INSTRUMENTATION

5.1 Displacement Monitoring

The monitoring of model displacements was accomplished by gages located as shown in Fig. 5.1. The six beam gages, designated X1 through X6, were specially fabricated units. Two commercial foil-type electrical resistance strain gages were bonded on each side of phosphor bronze cantilever spring and wired to form 240- Ω half bridges. The cantilever spring was preloaded during installation of the model by a pin bearing on the model bottom surface.

Displacement gages X7 through X9 were commercial DCDTs (direct-current displacement transducers) mounted on a bridge assembly at the top of the model. Displacement gage X10, a commercial DCDT, was mounted horizontally on the bridge assembly to measure the radial movement of a contact point on a post tackwelded to the outer ring forging. The contact point of this gage is located approximately 19 mm (3/4 in.) above the top surface of the outer ring forging, and thus its radial movement can be produced by both radial displacement and rotation of the forging.

Displacement gages X11 through X16 were specially fabricated curved-beam clip gages that were mounted to posts tack welded to the model inner and outer ring forgings. A full bridge complement of strain gages was bonded at midpoint of each brass beam. Due to the attachment location of these gages, approximately 8 mm (5/16 in.) above the top surface of the model, the radial displacements monitored can be made up of both radial translation and rotation of the ring forging.

5.2 Strain Monitoring

Figures 5.2 and 5.3 show the location of strain gages mounted on the steel components of the model. Foil-type electrical resistance strain gages were bonded to the model using high-strength epoxy cement. The strain gages shown in Fig. 5.3 and their leads were subjected to hydraulic pressure; therefore the wires were directed through the Autoclave lead-through fittings located in the bottom of the test fixture vessel. Based

DISPLACEMENT GAGE NO.	ORIENTATION	SURFACE REGISTERED OR PLANE OF MEASUREMENT	TYPE	RADIAL POSITION FROM VESSEL CL (cm)	INITIAL SPAN OF HORIZONTAL GAGES (cm)
X1	VERTICAL	MODEL BOTTOM	BEAM	11.75	—
X2				9.78	—
X3				7.81	—
X4				11.75	—
X5				9.78	—
X6				7.81	—
X7	HORIZONTAL	MODEL TOP	TRANS-TEK 352-000	10.95	—
X8				8.09	—
X9			TRANS-TEK 351-000 CLIP	5.32	—
X10				—	10.41
X11				—	9.91
X12				—	9.91
X13				—	3.56
X14				—	3.56
X15				—	3.56
X16				—	3.56

Fig. 5.1. Location of displacement gages on 1/15-scale model of steam generator cavity closure plug.

Fig. 5.2. Location of surface-mounted strain gages on 1/15-scale steam generator cavity closure plug model (not exposed to hydraulic pressure).

Fig. 5.3. Location of surface-mounted strain gages on 1/15-scale steam generator cavity closure plug model (subjected to hydraulic pressure).

on the results of previous tests (Ref. 6), it was anticipated that the apparent strain due to the pressurization effect would not cause more than 5% deviation from the true strain.

Figure 5.4 shows the location of two strain gage arrays embedded in the concrete of the model. Figure 5.5 shows a perspective view of the arrays and principal dimensions, and Fig. 5.6 shows fabrication details of the encapsulated strain gage assemblies. Several encapsulating materials, including a Cerroalloy, were evaluated, but none proved comparable to epoxy when subjected to an ad-hoc water environment validation test devised to demonstrate sealing capability.

Figure 5.7 shows a view of the model with all instrumentation except clip gages attached and a partially completed companion model that was stripped to illustrate the rebar. A duplicate set of components was built to provide assurance that one model could be fabricated which would meet the close tolerances required to provide an accurate representation of the prototype within the prescribed time schedule. Figure 5.8 is a partial view of the top surface of the model that shows the upper embedded strain gage array prior to concrete casting.

A 206.8-MPa (30,000-psig) capacity pressure cell was connected to the pressurization line, and the signal was fed in conjunction with signals from DCDT deflection gages X7 through X10 to two 2-channel X-Y-Y plotters. In addition, two axially oriented strain gages were placed on the inside and outside surfaces of the 11.4-cm (4.5-in.) wall section of the test vessel to monitor the relative movement of the upper and lower anchor positions of the displacement gages during pressurization. All displacement gages and strain gages other than X7 through X10 were monitored by a single commercial data-acquisition system.

All the special displacement gages, X1 through X6 and X11 through X16, were calibrated prior to installation in the test fixture. However, when the test fixture was filled with hydraulic oil, large responses were recorded by gages X1 through X6. Since these cantilever-beam-type gages depended upon predeflection during insertion of the model, the subsequent movement tended to reduce the deflection measuring capability of these gages. It was possible to check displacement gages X7 through X10 after

Fig. 5.4. Location of embedded strain gages in 1/15-scale steam generator cavity closure plug model.

Fig. 5.5. Perspective view of embedded strain gage array for use in 1/15-scale steam generator cavity closure plug model.

installation for proper response on the X-Y-Y recorders by insertion of feeler gages between the tips and stops. The axially oriented gage of the lower embedment gage array, No. 28, was the only gage found inoperable prior to conducting the pressure test of the model.

Fig. 5.6. Fabrication details of typical epoxy encapsulated strain gage used in 1/15-scale steam generator cavity closure plug model.

Fig. 5.7. Partially instrumented 1/15-scale steam generator cavity closure plug model with companion components.

Fig. 5.8. Top surface view of 1/15-scale steam generator cavity closure plug model showing top embedded strain gage array.

6. MODEL TEST

The model was subjected to 10 pressurization cycles to 10.08 MPa (1462 psig). After each cycle the pressure was reduced to 2.07 MPa (300 psig); data were recorded for cycles 1, 2, 5, and 10. The final testing phase consisted of continuing to pressurize in steps until the ultimate capacity of the plug was achieved; however, the test was stopped at 75.84 MPa (11,000 psig), which was approximately 7.5 times the design pressure of the prototype. Although the ultimate capacity had not been reached at this pressure, displacement gages X7 through X10 were exhibiting significant nonlinearities and several gages on the steel components inferred that significant yielding had occurred. Figure 6.1 is a view of the model after removal from the test fixture, and Fig. 6.2 shows a view of the 0 to 180° cross section of the model after sectioning. Neither visual cracking nor gross distortion is evident. Localized voids can be seen in the concrete underneath the inner and outer ring forgings, and minor porosity is also evident throughout the structure. However, good embedment is evident at the top embedment strain gages and at the shear console. The only detectable sign of distress in the model was a banding on the slanted surface of the outer ring forging contact surface. The absence of such banding during the pretest examination infers that it was possibly Lüders bands produced by plastic deformation of the steel.

Fig. 6.1. View of 1/15-scale steam generator cavity closure plug model following pressurization to 72.84 MPa.

Fig. 6.2. View of sawed section of 1/15-scale steam generator cavity closure model following pressurization to 75.84 MPa.

7. MODEL ANALYSIS

The primary purpose of the 1/15-scale model test of the steam generator cavity closure plug was to experimentally determine the ultimate capacity and mode of failure; however, the instrumentation was installed to provide data for evaluating the accuracy of analytical methods in predicting the response of such structures. A series of analyses, beginning with linear elastic and elastic-plastic analyses, was performed to evaluate the effect of various design details and material parameters. These analyses were culminated by a nonlinear analysis using the finite-element code ADINA,⁷ which contains material constitutive models for representing the nonlinear stress-strain response of both steel and concrete components.

The finite-element model used for the nonlinear analysis is shown in Fig. 7.1. Axisymmetric solid finite elements were used to represent all aspects of the design with the exception of the embedded reinforcement, which was modeled using two-force truss members. Because the ADINA code does not provide the capability of embedding reinforcing within elements, it was necessary to model the structure such that the solid element boundaries coincided with the location of the reinforcing members lying in vertical planes while the node positions must coincide with the location of circumferential reinforcement. The analytical representation of the model that was developed within these constraints consisted of 247 nodes, 68 elastic-plastic steel elements, 97 concrete elements, and 79 truss elements. Seven elastic elements were used to represent the gusset plates connecting the conical plate of the shear console to the outer wall. Since the region of the model containing the gusset plates is not truly axisymmetric, it was necessary to use "smeared" material properties in order to achieve an adequate representation of the force-displacement response of this region.

7.1 Material Constitutive Models

A bilinear kinematic hardening material model (material model 9 in the code) was used to represent the stress-strain response of the elastic-

Fig. 7.1. Finite-element model used for nonlinear analysis of 1/15-scale steam generator cavity closure model.

plastic steel elements, shown shaded in Fig. 7.1. A yield point of 220.6 MPa (32 ksi) was used to represent the inner and outer ring forging material; 482.6 MPa (70 ksi) was used for the inner wall material; and 517.1 MPa (75 ksi) was used for the remaining steel components. An initial elastic modulus of 206,800 MPa (30,000 ksi), a Poisson's ratio of 0.28, and a hardening modulus of 6895 MPa (1000 ksi) was used for all steel components.

The constitutive model used to represent the concrete response is rather complicated and only its essential features will be discussed in this report; a more detailed discussion can be found in Ref. 8. In this model, the uniaxial stress-strain response is defined by the initial tangent modulus and the stress and strain corresponding to uniaxial compressive failure. An equivalent multiaxial Young's modulus is obtained at each solution increment as a weighted average of the tangent modulus obtained from the uniaxial stress-strain curve by assuming each principal stress acts independently. Tension and compression failure is determined using the failure surface proposed by Khan and Saugy,⁹ while the post-failure condition is modeled by modifying the material properties at the element integration points. For tensile cracking the stiffness normal to the crack is reduced, while for crushing the stiffness in all directions is set equal to zero. The failure surface is defined by specifying the uniaxial tensile and compressive strengths of the concrete and the compressive strain at the ultimate compressive strength. A post-failure normal and shear stiffness reduction factor may also be specified. For the analysis of the plug model, the uniaxial tensile and compressive strengths were specified at 5.52 MPa (800 psi) and 55.16 MPa (8.0 ksi), respectively, while the compressive strain at failure was specified as 2.5 mm/m (0.0025 in./in.). An initial modulus of 41,370 MPa (6000 ksi) and a Poisson's ratio of 0.24 were specified. The normal and shear stiffness reduction factor was specified as 0.2.

There are two basic problems associated with the concrete constitutive model contained in the ADINA code that introduce discrepancies between predicted and observed results; both are related to the effect of triaxial compression on the stress-strain response of concrete. Concrete

is more ductile under triaxial compression than under uniaxial compression and can achieve significantly higher strains prior to failure. Since the stress-strain relation for multiaxial states of stress is based on uniaxial response, the material model is too stiff under triaxial compressive loading; that is, at a given strain level the stresses are overestimated. For many cases this can result in a premature prediction of compressive failure. The second problem arises after compressive failure has been indicated. As stated earlier, in the post-compressive failure condition the stiffness in all directions is set to zero; thus the material is not able to sustain a hydrostatic state of stress after compressive failure occurs. This is obviously not a correct analytical model for confined concrete under triaxial compressive loading, which is a condition of common occurrence in the experimental model. The effect of the above-mentioned discrepancies will become evident in the comparison of the analytical and experimental results.

7.2 Boundary Conditions

The simulation of the constraint provided by the ball support system and the seal assembly at the base of the circulator support presented difficulty. The reaction forces produced by both systems are nonlinear functions of deformation and are strongly influenced by fit-up tolerances. For small values of the radial displacement of the outer ring forging, the ball assembly should act much like the toggle system of the prototype; however, for larger radial deformations the system will act more like a pinned restraint. The restraint condition for the seal assembly at the base of the circulator support is even more poorly defined, being something between a completely free and fully clamped condition. Since it was not possible to fully resolve these questions of restraint, the most conservative condition was assumed for each case. The ball support system was represented by a two-force truss member with a line of action of 25° from vertical, thus duplicating the restraint condition of the prototype. The base of the circulator support was assumed to be free of restraint.

7.3 Calculated Behavior of Model

In the analysis, the model was subjected to a monotonic increasing pressure applied in 30 increments up to a final value of 75.8 MPa (11 ksi). The first indication of distress occurred at 20.7 MPa (3 ksi) and took the form of minor concrete tensile cracks on the upper surface near the outer ring forging. As the pressure increased, this cracking spread across the upper face but did not penetrate below the first row of elements. At a pressure of 41.4 MPa (6 ksi), plastic yielding began at the intersection of the upper ring forging and the outer wall. This zone of plastic yielding spread slowly inward and upward as the pressure increased. By the time the pressure reached 55.2 MPa (8 ksi), approximately half of the outer ring forging had experienced plastic yielding, and significant yielding had occurred in the circulator support and in the inner wall liner at its intersection with the circulator support.

At a pressure of 58.0 MPa (8.5 ksi), crushing occurred in the concrete adjacent to the outer ring forging. When this occurred, the material stiffness for these elements were set to zero, and they no longer provided restraint for the outer ring forging. Thus, plastic yielding occurred throughout the forging. By the time the pressure had reached 62.0 MPa (9 ksi), the plastic yielding of the inner wall liner, which began at the circulator support, had progressed until the total inner wall was undergoing plastic deformation. At 68.9 MPa (10 ksi), crushing began in the concrete adjacent to the upper portion of the inner wall liner and yielding occurred in the outer wall liner adjacent to the outer ring forging. By the time the pressure had reached 72.4 MPa (10.5 ksi), the outer wall liner between the outer ring forging and the shear console gusset plate had undergone plastic deformation.

At the maximum pressure level of 75.8 MPa (11 ksi), all steel components except the portion of the outer wall liner between the shear console and the bottom liner had undergone plastic deformation and the greater portion of the concrete above the shear console was either cracked or crushed. Thus, at this pressure, the analysis indicated that the closure plug was very near its ultimate pressure capacity.

8. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

A limited number of displacement and strain transducers were incorporated into the test model to provide qualitative data for evaluating the accuracy of the analytical predictions. The type and location of transducers used are discussed in Section 5. In examining the experimental results, it is important to recognize that space limitations imposed by the small size of the model presented problems that could have adverse effects on the accuracy of the measurements. Consequently, in examining the comparisons between the analytical and experimental results, attention will be directed to trends of a more global nature.

8.1 Displacement Results

Displacements were measured by the 16 separate transducers described in Section 5. For each transducer there existed, in general, at least one other transducer whose position differed only in its angular position. Thus, in most cases, duplicate measurements were available for comparison with the axisymmetric analytical results. In order to provide a uniform basis for comparison of vertical displacements, it was necessary to adjust the analytical results to account for the vertical rigid body motion of the model due to seating of the hold-down assembly. This was accomplished by the addition of a constant factor to the calculated vertical displacements where the constant was chosen so as to force agreement between the calculated and measured vertical displacements of the upper ring forging (gage position X7). No adjustments were necessary for the comparison of radial displacements.

The vertical displacements of the outer ring forging (gage X7), the top face of the concrete (gage X8), and the inner ring forging (gage X9) are shown in Figs. 8.1 to 8.3, respectively. The agreement between experiment and analysis for gage positions X8 and X9 is quite good. No analytical results are shown for gage position X7 as these results were forced to agree with experiment. The vertical displacements of the bottom liner at radial positions of 11.75, 9.78, and 7.81 cm (4.63, 3.85, and 3.07 in.) are shown in Figs. 8.4 to 8.6, respectively. The agreement

Fig. 8.1. Vertical displacement of the outer ring forging (gage X7).

Fig. 8.2. Vertical displacement of the top face of the concrete (gage X8).

Fig. 8.3. Vertical displacement of the inner ring forging (gage X9).

Fig. 8.4. Vertical displacement at the bottom liner at a radial position of 11.75 cm (4.63 in.) (gages X1 and X4). Displacement offset at 0 pressure results from previous 10 cycles.

Fig. 8.5. Vertical displacement of the bottom liner at a radial position of 9.78 cm (3.85 in.) (gages X2 and X5). Displacement offset at 0 pressure results from previous 10 cycles.

Fig. 8.6. Vertical displacement of the bottom liner at a radial position of 7.81 cm (3.07 in.) (gages X3 and X6). Displacement offset at 0 pressure results from previous 10 cycles.

between experiment and analysis is not as good for these results as it was for the upper surface of the model. In particular, the analytical results indicate a greater stiffness for the model than was demonstrated by the experimental values. The vertical rise seen in the experimental results at the higher levels of internal pressure was the result of the actual displacement exceeding the available gage travel.

The radial displacements of the inner and outer ring forgings and the relative radial displacements of the two are shown in Figs. 8.7 to 8.9, respectively. Both the analytical and the experimental results (gages X11 and X12) indicate very small radial displacements at the inner ring forging. The agreement between the analytical and experimental radial displacements at the outer ring forging are not nearly so consistent. There are two primary reasons for this discrepancy: (1) inconsistency in modeling the effect of the hold-down system and (2) improper modeling of the post-failure condition in the concrete constitutive model. The measurement point for transducer X10 is approximately 19 mm (3/4 in.) above the top surface of the forging, and thus its radial movement is produced by both the radial displacement and the rotation of the forging. The stiffness of the forging due to radial displacement is quite large, while the rotation of the forging is strongly dependent on the line of action of the restraining force produced by the hold-down system. Both types of deformation produce components of displacement at the measurement point that are of the same order of magnitude; thus, without accurate modeling of the restraint condition for the hold-down system, it is not possible to achieve accurate analytical predictions of the displacement results shown in Fig. 8.8. Also, rather high compressive stresses exist along the interface between the forging and the concrete. When the calculated stresses in the concrete elements that are adjacent to the forging exceed the compressive failure strength, their stiffness is set to zero and they no longer offer restraint to the deformation of the forging. This situation occurs at approximately 55 MPa (8 ksi) internal pressure and accounts for the abrupt change in the predicted load deflection curves shown in Figs. 8.8 and 8.9. It should be noted that the clip used to measure the relative displacements of the inner and outer ring forgings, Fig. 8.9, are not significantly affected by the rotation of the outer

Fig. 8.7. Radial displacement of the inner ring forging (gages X11 and X12).

Fig. 8.8. Inward radial displacement of the outer ring forging (gage X10).

Fig. 8.9. Radial displacement of outer ring forging relative to the inner ring forging (gages X13, X14, X15, and X16). Displacement offset at 0 pressure results from previous 10 cycles.

ring forging; thus, the major deviation between experimental and analytical results occurs after the crushing strength of the concrete is exceeded in the analytical calculations.

8.2 Bonded Resistance Strain Gage Results

Resistance strain gages were bonded to the outer ring forging, inner and outer liners, and circulator support ring (Figs. 5.2 and 5.3). The comparison between the analytical and experimental results for the outer ring forging is shown in Figs. 8.10 and 8.11. The poor agreement between the two results is thought to be due to the inability to model accurately the restraint condition of the hold-down assembly. The effect of the highly nonlinear response of the hold-down assembly is evident in the experimental strain values. The effect of the crushing of the concrete adjacent to the forging predicted by the analysis is evident in the abrupt change in the pressure-strain curve that occurs at approximately 55 MPa (8 ksi).

The strains on the upper portion of the outer liner are shown in Figs. 8.12 to 8.14. As can be seen from Figs. 8.12 and 8.13, the experimental values of the circumferential strain on both the inside and outside surface are larger than those predicted by analysis. Since the magnitude of the circumferential strain is directly proportional to the radial displacement at the gage location, it follows that the analytical model is stiffer than the actual structure. This is consistent with the fact that for triaxial states of stress the concrete constitutive model used in the ADINA code is inherently too stiff. This same effect is the probable explanation for the fact that the onset of yielding evident in the plot of the axial strain, Fig. 8.14, occurred at a higher pressure for the analytical model than for the actual structure. This same effect can be seen in the comparison of the analytical and experimental strains on the lower portion of both the inner and outer liners, Figs. 8.15 to 8.18. Thus the comparison of the strains on the liner consistently indicate that the analytical constitutive model for the concrete is too stiff and thus the predicted strain levels in the steel liner are too low.

Fig. 8.10. Circumferential strain on the outer ring forging (gage G3). Strain offset at 0 pressure results from previous 10 cycles.

Fig. 8.11. Axial strain on the outer ring forging (gage G2). Strain offset at 0 pressure results from previous 10 cycles.

ORNL-DWG-77-19786

Fig. 8.12: Circumferential strain on the inside surface of the upper portion of the outer liner. (gage G1). Strain offset at 0 pressure results from previous 10 cycles.

ORNL-DWG 77-19787

Fig. 8.13. Circumferential strain on the outside surface of the upper portion of the outer liner (gages G5 and G7).

Fig. 8.14. Axial strain on the outside surface of the upper portion of the outer liner (gages G4 and G6). Strain offset at 0 pressure results from previous 10 cycles.

ORNL-DWG 77-19789

Fig. 8.15. Circumferential strain on the lower portion of the outer liner (gages G9 and G11).

ORNL-DWG 77-19790

Fig. 8.16. Axial strain on the lower portion of the outer liner (gages G8 and G10).

Fig. 8.17. Circumferential strain on the lower portion of the inner liner (gages G17 and G19).

ORNL-DWG 77-19792

Fig. 8.18. Axial strain on the lower portion of the inner liner (gages G16 and G18).

The strains for gages located on the circulator support are shown in Figs. 8.19 to 8.22. Comparisons between analytical and experimental values of the circumferential strain on the inside and outside surfaces are shown in Figs. 8.19 and 8.20. The fact that the experimental strain values are consistently higher than the calculated values implies that the radial deflections in the actual structure are larger than the calculated values. This is probably due to the fact that perfect bonding is assumed between the concrete and the liner in the analytical model, and hence the model can sustain a higher moment loading at the circulator support-liner intersection than the actual structure. This conclusion is consistent with the results obtained for the axial strains shown in Figs. 8.21 and 8.22. As can be seen in these figures, the calculated strain values are more tensile on the outside and more compressive on the inside than the corresponding experimental values. This implies that the bending moment is larger in the analytical model than in the actual structure. It should also be noted that a significant portion of the discrepancies between the analytical and experimental results obtained for the circulator support could be due to inexact modeling of the boundary conditions at the bottom seal interface.

8.3 Embedded Strain Gages

Especially constructed embedment gages were installed in the upper and lower portions of the plug (see Fig. 5.4). The results of comparisons between the analytical and experimental results are shown in Figs. 8.23 to 8.27. As can be seen in the comparison of circumferential strains of both the top and bottom gage locations (Figs. 8.24 and 8.26, respectively), and the axial strain at the top location (Fig. 8.23, the axial embedded gage at the bottom location was inoperable), the experimental strains were consistently larger than the values predicted by the analysis. This result again concurs with the hypothesis that the analytical constitutive model for the concrete is too stiff under the existing stress conditions. The reason that consistent agreement was obtained for the radial strains at the top gage location (Fig. 8.25) but not at the lower location (Fig. 8.27) is not understood at this time.

Fig. 8.19. Circumferential strain on the inside surface of the circulator support (gages G21 and G23).

Fig. 8.20. Circumferential strain on the outside surface of the circulator support (gages G13 and G15).

Fig. 8.21. Axial strain on the inside surface of the circulator support (gages G20 and G22).

ORNL-DWG 77-19796

Fig. 8.22. Axial strain on the outside surface of the circulator support (gages G12 and G19).

ORNL-DWG 77-19797

Fig. 8.23. Axial strain at the location of the upper embedment gage (gage G24).

ORNL-DWG 77-19798

Fig. 8.24. Circumferential strain at the location of the upper embedment gage (gage G26).

ORNL-DWG 77-19799

Fig. 8.25. Radial strain at the location of the upper embedment gage (gage G27).

ORNL-DWG 77-19800

Fig. 8.26. Circumferential strain at the location of the lower-embedment gage (gage G30).

Fig. 8.27. Radial strain at the location of the lower embedment gage (gage G31).

9. CONCLUSIONS AND RECOMMENDATIONS

This test demonstrated the capability of the PCRV steam generator cavity closure plug for the 300-MW(e) gas-cooled fast reactor to sustain substantial overpressure without exhibiting any signs of structural distress. Detailed comparisons of experimental and analytical results indicate that improved constitutive equations for concrete are needed to provide better agreement between calculated and experimental values; however, the comparisons provide verification of the capability of the ADINA finite-element code to provide a conservative analysis of this type of structure.

It was thus concluded from the test that the current closure plug is substantially overdesigned. Therefore, we recommend that the present design be modified to eliminate the excess conservatism and a second model be built and tested. The cost of conducting the follow-up test should be relatively small since the test fixture and a duplicate set of parts for the original model are available.

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