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CONCRETE FOR REACTOR VESSELS

by

J. E. McDonald

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VICKSBURG, MISSISSIPPI

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FOREWORD

This paper was prepared for the Joint Mississippi-Louisiana Section Meeting, American Society of Civil Engineers, held at Gulfport, Mississippi, on 13-15 April 1972. The manuscript was reveiwed and cleared for presentation by the Oak Ridge National Laboratory and the Office, Chief of Engineers, U. S. Army.

The studies which provided the information and data discussed herein were conducted by the Concrete Division, U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, under the sponsorship of the U. S. Atomic Energy Commission.

Director of the WES during the preparation and publication of this paper was COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

CONCRETE FOR REACTOR VESSELS*

by

James E. McDonald**

Background

1. The economical production of nuclear power with the gas-cooled reactor concept requires a large nuclear core and high pressure; consequently, large thick-walled reactor vessels are required. The construction of such reactor pressure vessels with steel is extremely difficult; therefore, prestressed-concrete vessels were adopted as a substitute. The prestressed-concrete reactor vessel (PCRV) is ideal for this application since it appears that there is no limit to the pressure and vessel size other than the limitation of concrete strength.

2. Most PCRV's are of spherical or cylindrical configuration and are composite assemblies consisting of: (a) an inner gastight steel liner, (b) a concrete wall, and in the case of the cylindrical shape, (c) concrete ends, and (d) a suitable number of prestressing cables. The steel liner, which is about 1/2 to 1 in. thick, is anchored to the concrete wall so that the gas pressure forces are transmitted through its thickness directly to the concrete. In the case of a cylindrical design, the inside diameter may vary from 40 to 80 ft and the wall thickness may vary from 10 to 15 ft. The ends may be as thick as 20 ft or more.

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* Prepared for presentation at the Joint Mississippi-Louisiana Section Meeting, American Society of Civil Engineers, 13-15 April 1972, Gulfport, Miss. Based on investigations conducted for the U. S. Atomic Energy Commission.

** Supervisory Research Civil Engineer; Chief, Structures Section, Engineering Mechanics Branch, Concrete Division, U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss. 39180.

3. The use of prestressed concrete in construction of nuclear reactor pressure vessels is a departure from usual civil engineering practice, and, as would be expected, many unusual problems arise in the design and construction of such a vessel. In spite of the tremendous amount of research on the properties of concrete, information regarding certain properties of concrete under particular conditions is often insufficient. This appears to be especially true in the case of the use of prestressed concrete for reactor pressure vessels. One of the most important aspects in the design and safety evaluation of a PCRV is the time-dependent deformation behavior of concrete in the presence of varying temperature, moisture, and loading conditions. Consequently a basic research program formulated and directed by Oak Ridge National Laboratory for the purpose of developing and improving the technology of PCRV's in the United States included a sizeable effort directed toward investigating the time-dependent deformation behavior of concrete under conditions existing in a PCRV. Two of the projects included in this effort were a test of the moisture distribution in a PCRV wall and a multiaxial creep program, both performed at the Waterways Experiment Station (WES).

Moisture Migration in Concrete

4. Information regarding the nature of moisture movement and rate of moisture loss in a concrete pressure vessel wall subjected to a temperature gradient is of interest in view of the influence of these parameters on the properties of concrete. In an effort to evaluate these effects, an experimental study of moisture migration in a pie-shaped concrete specimen (fig. 1) representing the flow path or channel through a cylindrical wall of a PCRV was initiated. The test specimen selected was 9 ft in length

with cross-sectional dimensions of 2 by 2 ft on one end and 2 ft by 2 ft 8 in. on the other end. The specimen was sealed against moisture loss on the small end (interior) and along the lateral surfaces and exposed to the atmosphere on the other end (exterior). In addition, the lateral surfaces were heated and insulated to simulate conditions in a PCRV where uniaxial moisture and heat flow prevail.

5. After casting of the test specimen, the temperature distribution, shrinkage, and moisture distribution were monitored for approximately 17 months. After this initial testing, a temperature gradient of 80 F was applied to the specimen, and the above-mentioned measurements were continued for an additional test period of 1 year.

Test Specimen

6. The casting form for the moisture migration specimen with instrumentation, insulation, and moisture barrier in place is shown in fig. 2 immediately prior to casting. A concrete mixture proportioned with 3/4-in. maximum size crushed limestone aggregate to have a slump of 2 ± 1/2 in. and a compressive strength of 6000 psi at 28 days was used in casting the specimen. Upon completion of casting, the top was closed and moisture sealed to the remainder of the form.

Effects of Concrete Hydration

7. Temperature in the freshly placed concrete rose after casting (fig. 3), peaking at all stations between 29 and 98 hours after placement. The highest temperature recorded, near the midsection of the specimen, was 168 F, a rise of 93 F. After reaching the peak values, temperatures started falling at a very gradual rate (fig. 4), stabilizing near room temperature about 60 days after casting.

8. Moisture in the concrete, as indicated by the nuclear surface moisture gage, was fairly constant in all sections except the two ends, particularly the open end (fig. 5). Variations in total concrete strain (fig. 6) followed essentially the same trends as the temperature.

<u>Effects of a Temperature Gradient</u>

9. Strain, temperature, and moisture in the concrete were in essentially steady states prior to application of the temperature gradient of 80 F to the specimen (fig. 7) approximately 17 months after casting.

10. As expected, temperature increases in the early stages after application of heat were confined to that half of the specimen nearest the heat. After approximately 1 week, relatively uniform increases in temperature were noted throughout the specimen. The temperature gradient 1 year after application of heat was essentially the same as that shown at 21 days (fig. 8). Temperatures monitored by thermocouples at five different depths in each of three sections were fairly constant at different depths within a section. A temperature profile of the section nearest the heat indicated that the temperature differential between the interior and exterior of the specimen was within 1 F.

11. Variations in total concrete strain along the specimen's center line as a result of applying a temperature gradient are shown in fig. 9. The highest indicated total strain was about 340 millionths (expansion) at the station nearest the heat. From this maximum, indicated total strains decreased in a generally linear manner to less than 25 millionths near the open end. Correcting these strains for thermal effects, assuming a linear coefficient

of thermal expansion of 5.0 x 10^{-6}/F, changes in strain at each station during the 1-year test period were computed as shown in fig. 10. This indicates an expansion of approximately 20 millionths near the heated end with a generally linear decrease to a shrinkage of approximately 35 millionths near the open end.

12. Typical variations in concrete moisture at various stations along the top surface of the specimen as determined by a surface back-scatter nuclear gage are shown in fig. 11. Based on a linear regression analysis, all 10 stations, with the exception of No. 2, indicated small decreases in moisture content over the test period. These decreases ranged from 0.03 to 0.55 lb/cu ft and averaged 0.23 lb/cu ft. Station No. 2 indicated an increase in moisture content of 0.17 lb/cu ft. The indicated average change in concrete moisture content for all stations was a decrease of approximately 1.5 percent.

Discussion

13. The fairly uniform temperatures at different depths within a section and the relatively fast flow of heat toward the two cool faces of the specimen during cement hydration indicate the boundary conditions were sufficient to simulate the flow path through a cylindrical wall of a PCRV where uniaxial moisture and heat flow prevail.

14. Based on the results of this investigation, it appears that the magnitude of any changes in the specimen's strain and moisture state as a result of application of a temperature gradient was quite small. This indicates that the moisture movement and rate of moisture loss in a PCRV

wall subjected to a temperature gradient are such that these parameters should not affect the properties of concrete typical of that used in this investigation.

Multiaxial Creep of Concrete

15. The WES investigation was part of an overall investigation planned to provide information that could be used in predictions of vessel behavior for the many regimes of loading experienced under design and hypothetical accident conditions. This particular investigation is concerned with one strength (6000 psi at 28 days), three aggregate types (chert, limestone, and graywacke), one cement (type II), two types of specimens (as-cast and air-dried), two levels of temperature during test (73 and 150 F), and four types of loading (uniaxial, hydrostatic, biaxial, and triaxial).

16. Concrete made with Tennessee limestone aggregate (3/4-in. maximum size) was chosen as the main mixture on the basis that it was representative of what might be used in a PCRV in most sections of the United States. Two other mixtures containing Alabama graywacke and chert, aggregate with elastic moduli lower and higher, respectively, than that of limestone, were used to provide information for comparison.

17. The as-cast specimens were sealed at casting and remained so throughout the tests. The resultant highly saturated concrete was representative of that in the interior of a mass of concrete such as a PCRV. After 7 days of wet curing, the air-dried specimens were allowed to dry in air at 73 F and 50 percent relative humidity for the

remainder of the 90-day period preceding testing. These specimens exhibited considerable moisture loss and were representative of concrete near the exterior of a PCRV. In addition, specimens cured in lime-saturated water at room temperature for the required period were tested for strength control.

18. The temperature levels during loading were selected as being representative of the limits of the range of concrete temperatures experienced in a nuclear reactor, 73 and 150 F corresponding to temperatures expected at the outer and inner surfaces, respectively, during normal operation.

19. Test specimens were loaded in uniaxial, biaxial, hydrostatic, and triaxial states of stress with both axial stress (σ_A) and radial confining stress (σ_R) ranging from 0 to 2400 psi.

Mixture Proportions

20. Three concrete mixtures were proportioned with type II portland cement and 3/4-in. maximum size aggregates whose moduli of elasticity ranged from 3.8 to 13.65 x 10^6 psi to have compressive strengths of 6000 psi at 28 days. The resultant concrete mixtures were designated high, main, and low modulus according to aggregate moduli.

Specimens

21. The 6- by 16-in. cylindrical creep and control specimens were cast horizontally in a steel mold that maintained parallelism of the 1-in. end plates which held the vibrating wire strain gages in place as shown in fig. 1[illegible]. After consolidation on a vibrating table, the specimens were troweled to complete the circular cross section, and then placed in a

100 percent hum'''-, \ rog") room. After 24 hours, all specimens weie stripped and the as-cast specimens were then coated with epoxy and returned to the fog room. The remaining cylinders were placed in lime-saturated water (limewater). Twenty-four hours later, as-cast specimens were given another coat of epoxy and were hermetically sealed with sheet copper and weighed.

22. After 7 days of limewater curing, the air-dried specimens were removed from the limewater and placed in a room at 50 percent relative humidity and 73 ± 3 F for the remainder of the 90-day period preceding testing. Prior to testing, the air-dried cylinders were coated with epoxy and hermetically sealed in copper sheet. Twenty-four hours later, the copper sheet was coated with epoxy and a rubber membrane was placed around the cylinders to protect them from the hydraulic oil.

23. In general, the test specimens were cured for 83 days as previously described, then placed in test rigs located in the proper environmental condition (73 or 150 F) for 7 days prior to loading. Appropriate loads were applied manually with a hydraulic hand pump. When the desired maximum load was attained, the vessel was switched to the manifold system (fig. 13) which maintained a constant load using an oil reservoir under regulated high-pressure gas.

24. Types and magnitude of loads and environmental conditions for the 66 creep specimens are shown in table 1. There were two specimens, one each as-cast and air-dried, associated with each test condition. Of the four control specimens per batch, two each were as-cast and air-dried. One control specimen of each type was maintained in each of the environmental conditions throughout the test period.

Experimental Results

25. Concrete compressive strengths at 28 and 90 days were determined for all concrete batches. In addition, compressive strengths at advanced ages were determined for concrete of the first three batches, and the results are presented in table 2.

26. Elastic strains due to the applied loads were determined by taking readings immediately prior to loading, after each load increment was added, and immediately after attaining maximum load. The air-dried uniaxial specimens loaded to 2400 psi at 73 F exhibited slightly higher strains (maximum of 26 millionths) at maximum load than companion as-cast specimens. Concrete moduli of elasticity determined using the average of these two maximum elastic strains were 6.38, 5.66, and 3.08×10^6 psi for the high, main, and low aggregate moduli of elasticity, respectively.

27. Creep strain-time relationships were determined for all loaded specimens by subtracting the elastic strain and control strain from the total strain for each gage. Typical results are shown in fig. 14-17. The results of these tests reveal that, for a given temperature and loading, the use of the three different aggregates gave axial creep strain values differing by a factor of 1.0 (chert):1.7 (limestone):3.1 (graywacke), which correlated generally with the reciprocal of the modulus of elasticity of the aggregate and, hence, the modulus of elasticity of the concrete, which were in the proportions of 1.0:1.3:3.6 and 1.0:1.1:2.1, respectively. Using the 150 F environment generally increased the creep,

with the overall increase averaging 86 percent. Axial creep strains also increased with load level and varied with the mode of loading. Taking an overall average for each mode, the higher axial creep strains were associated with the uniaxial loading followed by the triaxial loading in which strains were approximately 80 percent of those in the uniaxial mode. In the hydrostatic mode, average axial creep strains were approximately 35 percent of those in the uniaxial mode. The axial creep strains in the biaxial mode were tensile in nature, with a magnitude averaging slightly less than the hydrostatic strains or approximately 30 percent of those in the uniaxial mode.

Discussion

28. A comprehensive evaluation of the effects of aggregate moduli, moisture condition, testing temperature, and loading condition on the creep of concrete is currently being prepared and will be presented in a WES Technical Report. Nevertheless, the test results can be generally summarized as follows:

- a. It is possible to proportion concrete mixtures containing widely varying aggregate moduli with subsequent variations in concrete moduli to have similar compressive strengths.
- b. For the range of mixtures tested, it appears that creep of concrete is inversely proportional to the modulus of elasticity of the concrete.
- c. In general, air-dried specimens had creep strains equivalent to or slightly higher than as-cast specimens at a given temperature.
- d. Both as-cast and air-dried specimens tested at 150 F temperature exhibited higher creep strains than comparable specimens tested at 73 F temperature.

e. In uniaxially and biaxially loaded specimens at both temperatures, creep strains occurred in the direction perpendicular to the direction of the applied stress. Thus, a creep Poisson's effect apparently occurred.

Summary

29. Results indicate that the moisture movement and rate of moisture loss in a PCRV wall subjected to a temperature gradient are such that these parameters should not significantly affect the properties of concrete mixtures which are properly proportioned, mixed, and consolidated to obtain sound, dense concrete.

30. It appears that creep of concrete, for the range of conditions tested, is inversely proportional to the modulus of elasticity of the concrete, which is determined to a large extent by the modulus of elasticity of the aggregate. Hence, the selection of competent, high-modulus aggregates for PCRV concretes is of paramount concern. In addition, the significant increase in creep in a 150-F environment and the subsequent reduction in sustained modulus of elasticity of the concrete must be considered in predictions of vessel behavior over extended periods of time.

Table 1

Creep Test Conditions

Batch No.	Concrete Modulus	Type of Loading	Temp F	Load, psi σ_A	Load, psi σ_R
I	High	Uniaxial	150	600	0
		Uniaxial	150	2400	0
		Uniaxial	73	2400	0
		Uniaxial	73	600	0
II	Main	Uniaxial	150	600	0
		Uniaxial	150	2400	0
		Uniaxial	73	600	0
		Uniaxial	73	2400	0
III	Low	Uniaxial	150	2400	0
		Hydrostatic	150	2400	2400
		Uniaxial	73	2400	0
		Hydrostatic	73	2400	2400
IV	High	Hydrostatic	150	2400	2400
		Hydrostatic	73	600	600
		Hydrostatic	73	2400	2400
V	Main	Biaxial	150	0	600
		Hydrostatic	150	2400	2400
		Biaxial	73	0	600
		Hydrostatic	73	600	600
		Hydrostatic	73	2400	2400
VI	Main	Biaxial	150	0	2400
		Triaxial	150	2400	600
		Triaxial	73	2400	600
		Biaxial	73	0	2400
VII	High	Biaxial	150	0	2400
		Biaxial	150	0	600
		Triaxial	150	2400	600
		Triaxial	73	2400	600
VIII	Low	Uniaxial	150	600	0
		Biaxial	150	0	2400
		Biaxial	150	0	600
		Triaxial	150	2400	600
		Triaxial	73	2400	600

Table 2

Compressive Strength Test Results

Age, days	Type of Curing	Compressive Strengths, psi					
		High Modulus		Main Modulus		Low Modulus	
		73 F	150 F	73 F	150 F	73 F	150 F
28	S	6690	--	6600	--	6320	--
	D	6970	--	7320	--	6700	--
90	S	7890	--	7480	--	7160	--
	D	8010	--	8110	--	7570	--
183	S	7480	8,660	8590	8560	8370	8690
	D	9250	8,880	8590	7890	8220	7990
365	S	8160	10,010	9110	9430	9350	8200
	D	8840	8,410	8660	8380	8530	8710
455	S	8160	9,855	9140	8690	9350	9250
	D	9480	9,030	8980	8380	8345	9295

S = As-cast
D = Air-dried

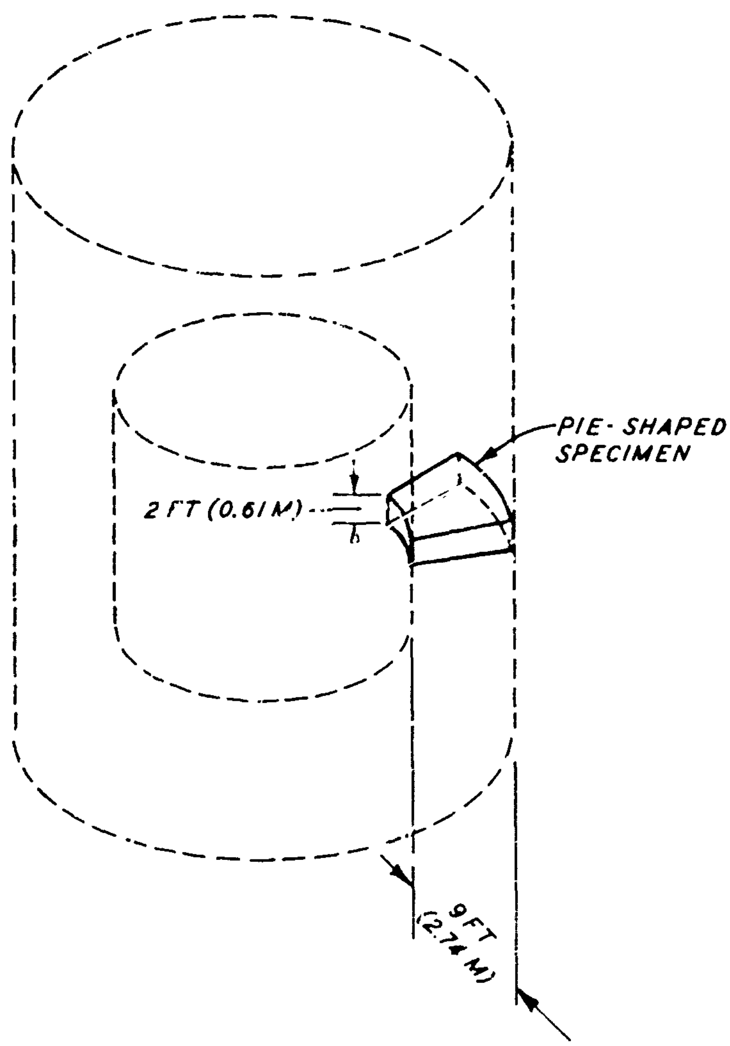

Fig. 1. Simulated location of specimen in vessel

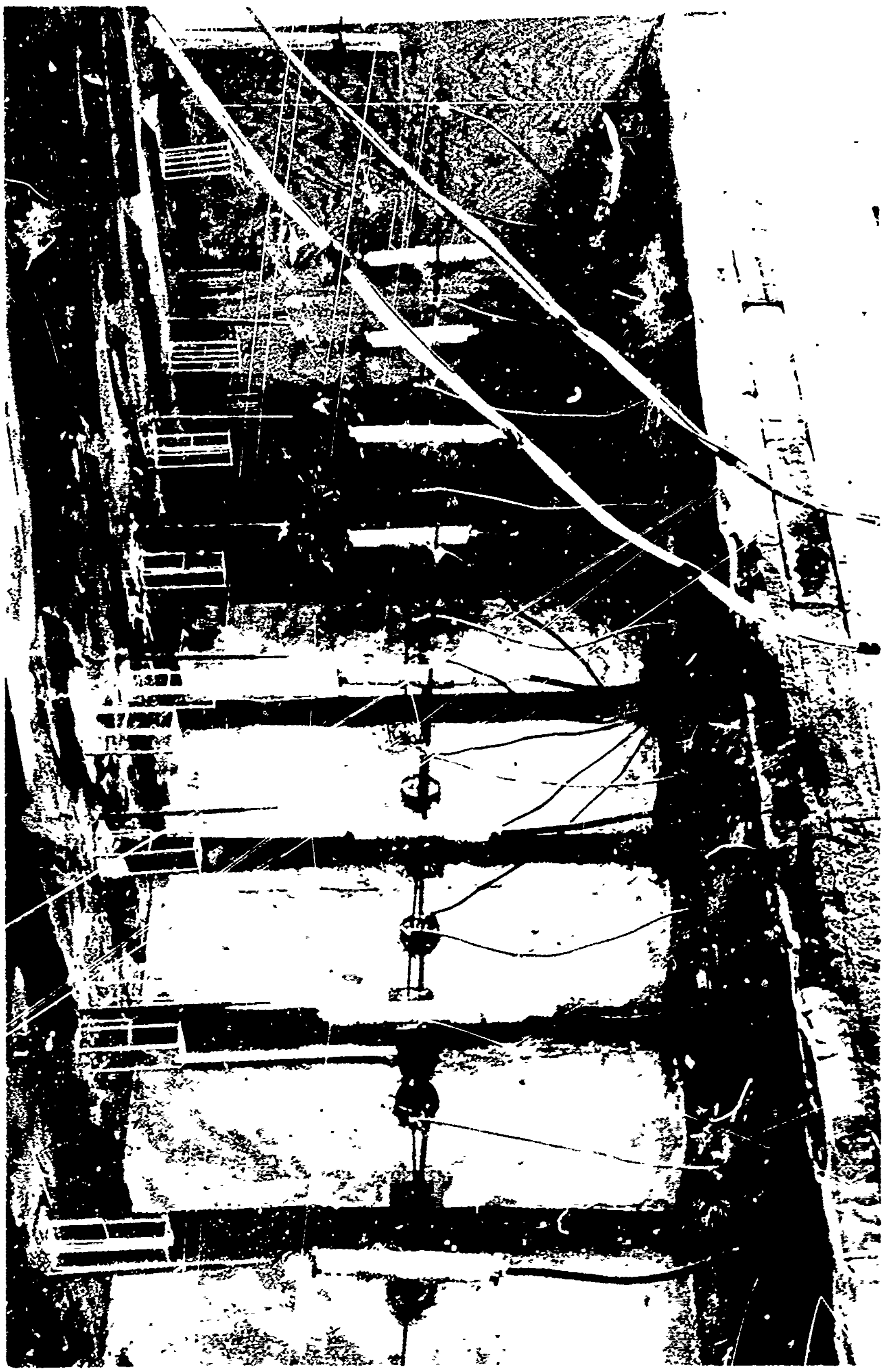

Fig. 2. Embedded instrumentation for moisture migration studies - view from closed end

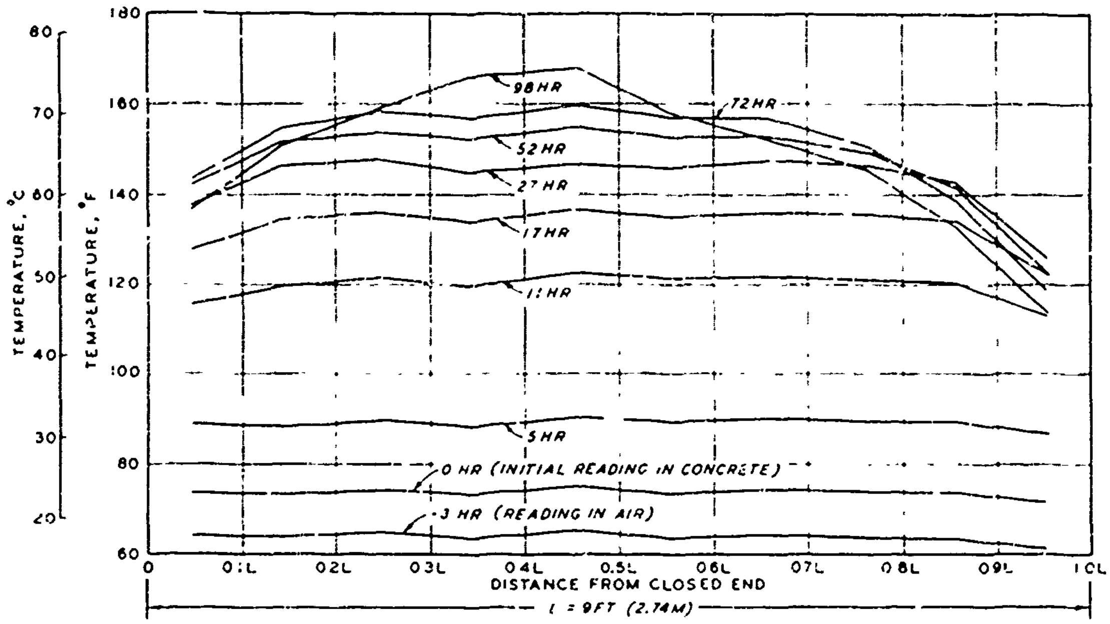

Fig. 3. Temperature rise

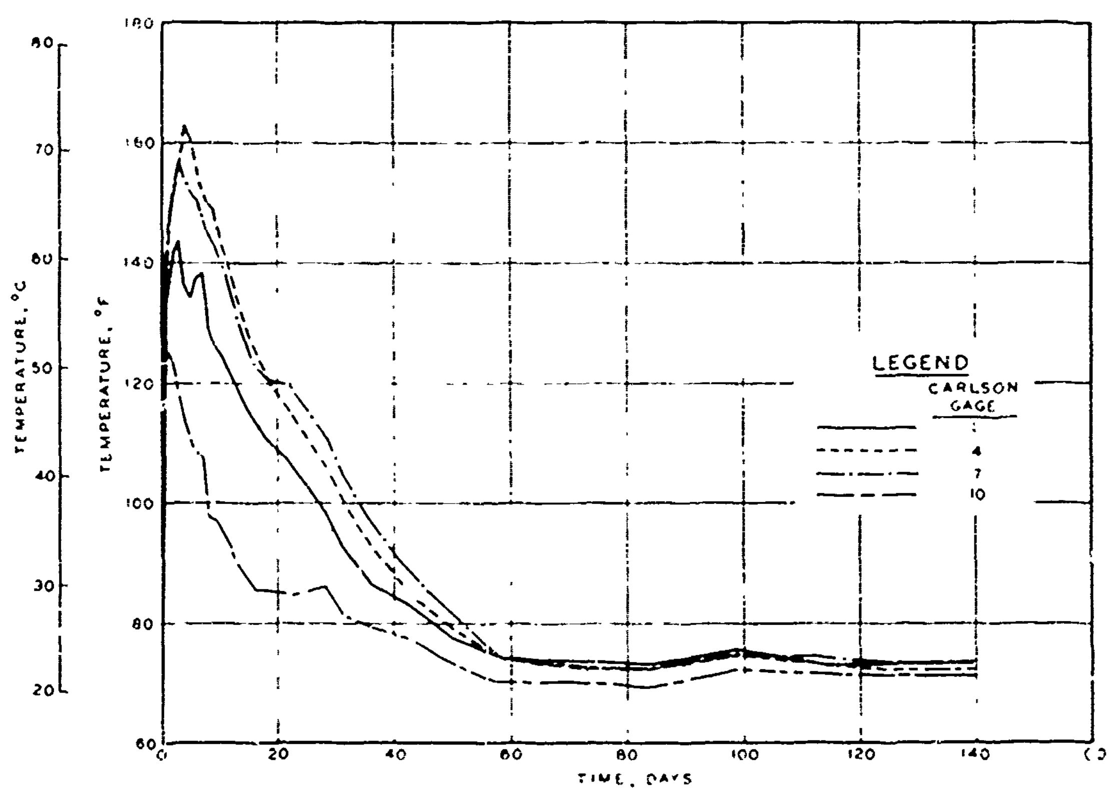

Fig. [illegible]. Temperature versus time

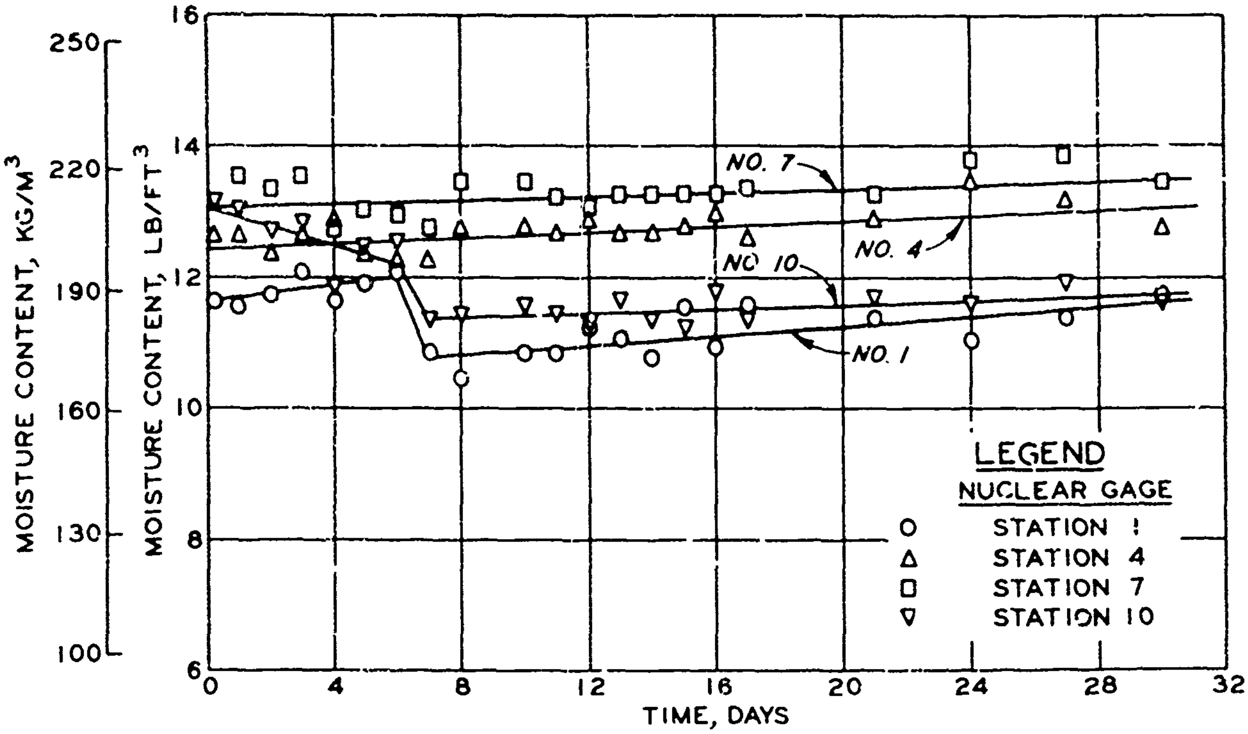

Fig. 5. Moisture content versus tim

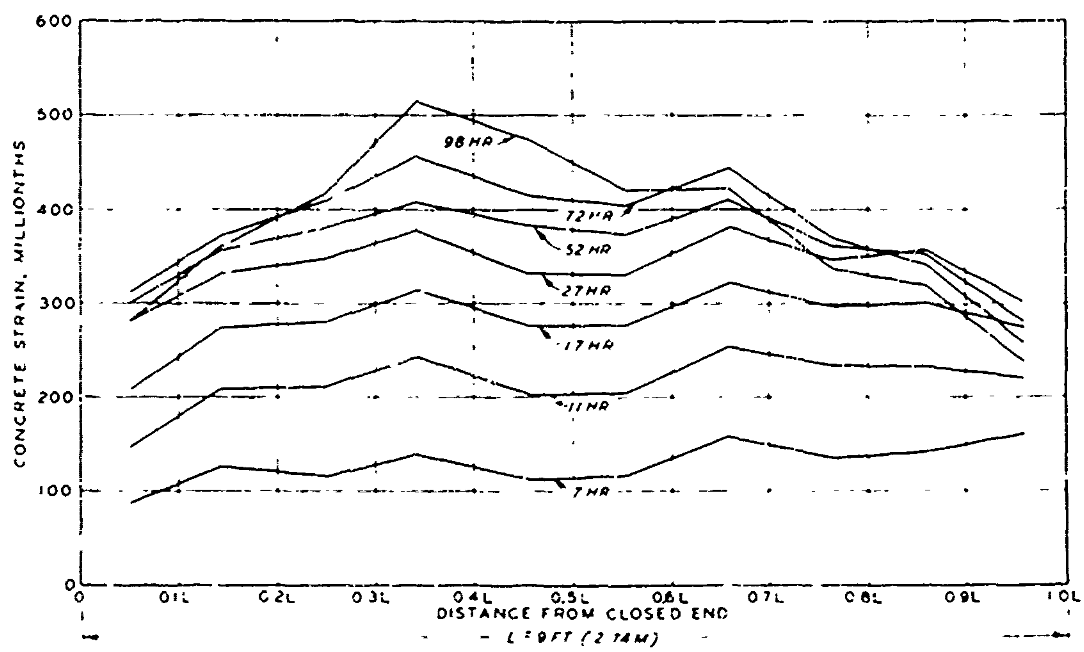

Fig. 6. Indicated strain distrib.

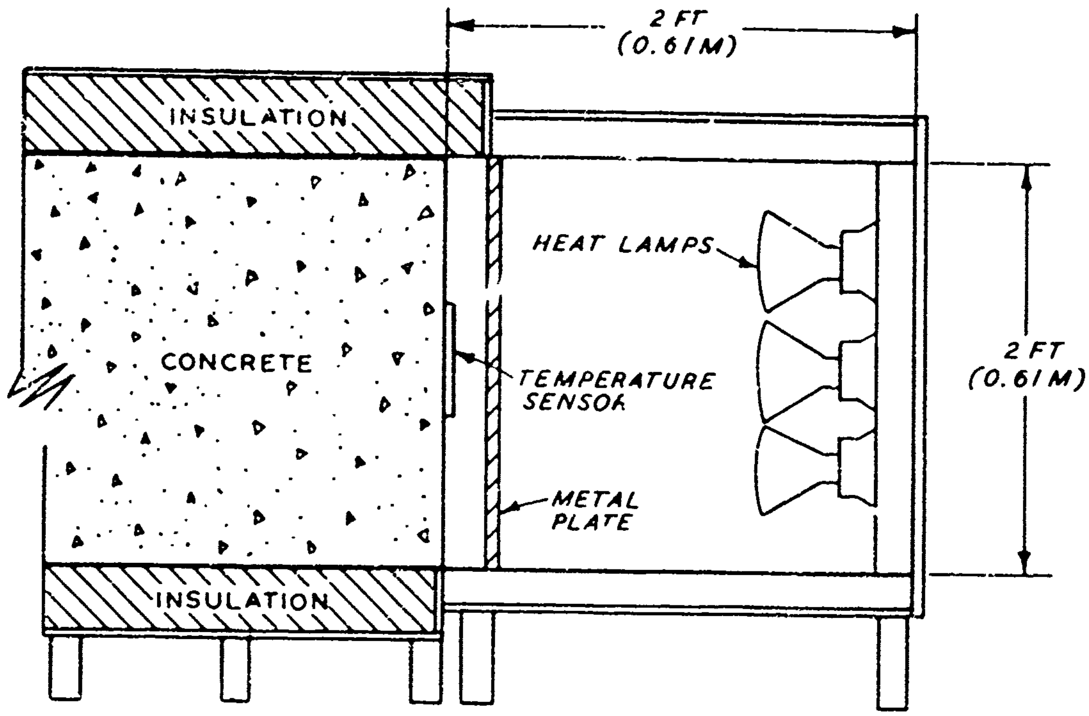

Fig. 7. Heating arrangement

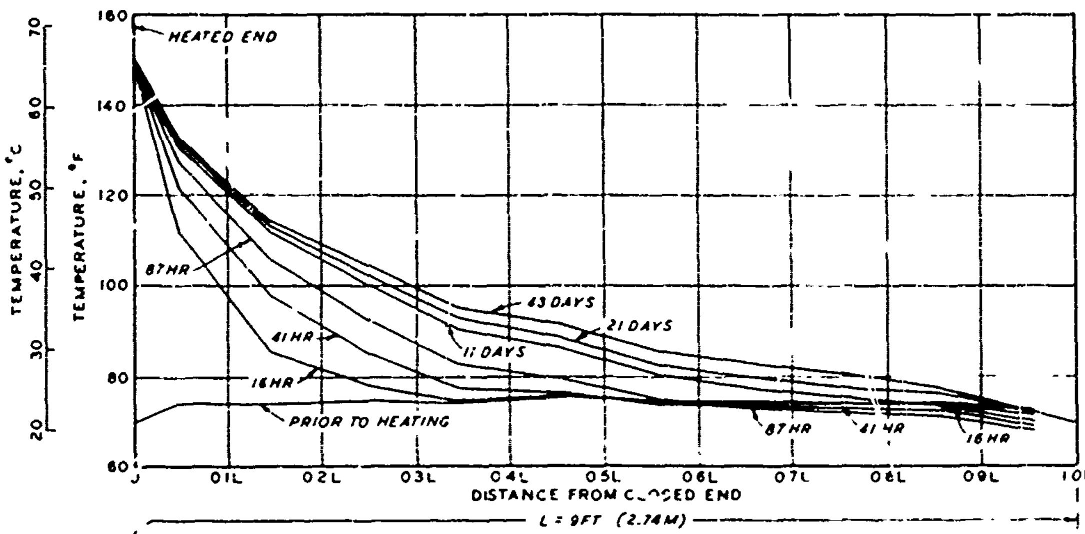

Fig. 8. Temperature variation along ℄ of specimen after heating

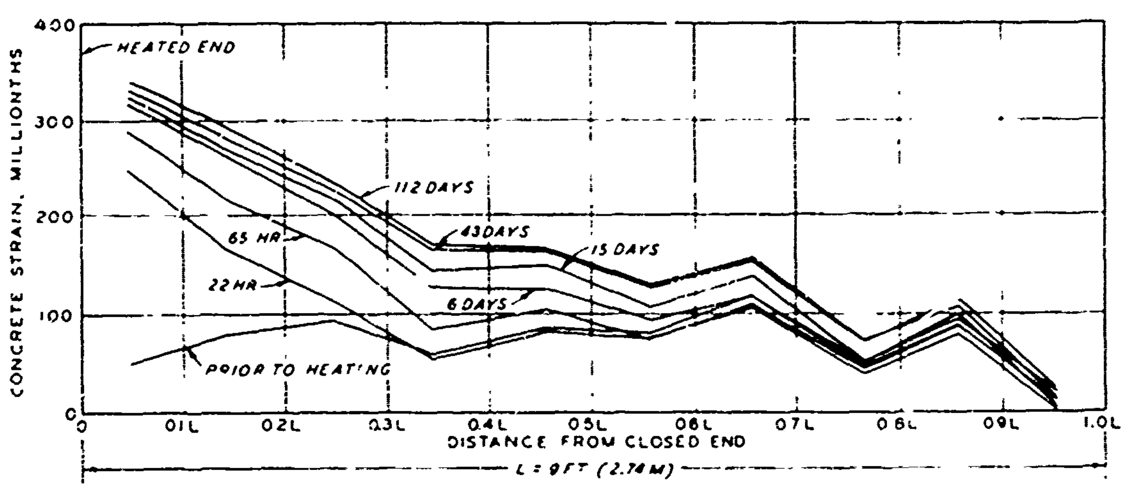

Fig. 9. Indicated strain distribution after heating

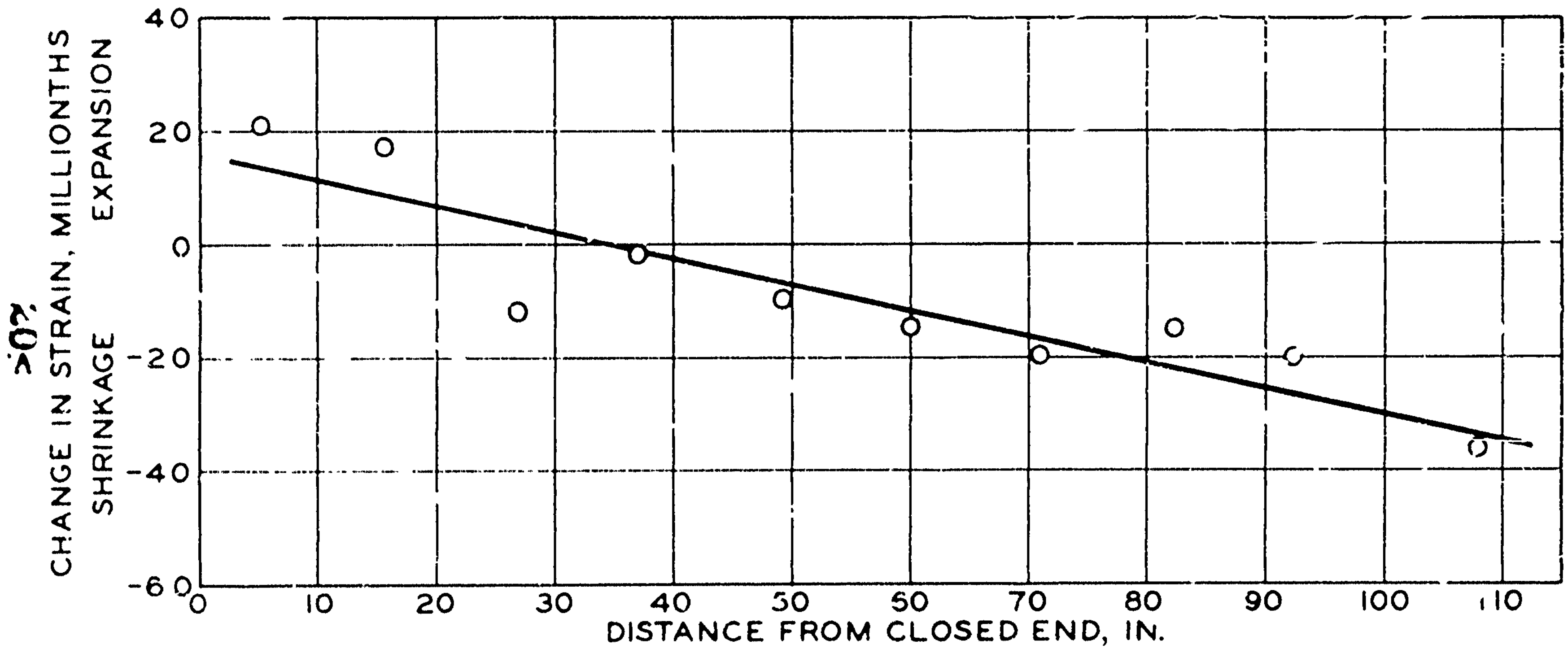

Fig. 10. Corrected strain variation along centerline of specimen

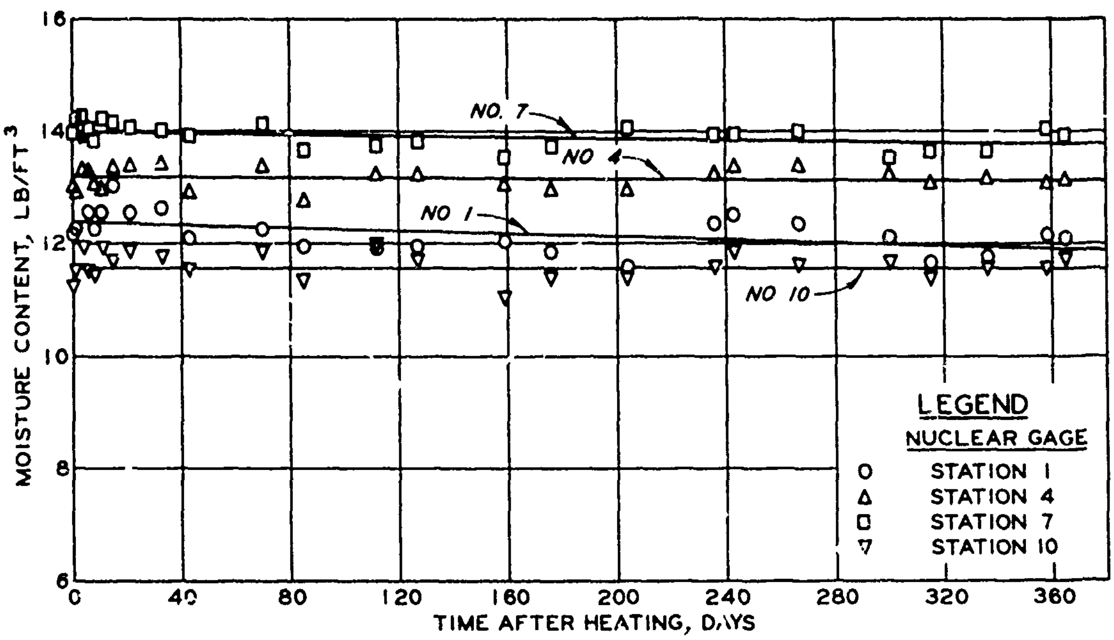

Fig. 11. Moisture content versus time

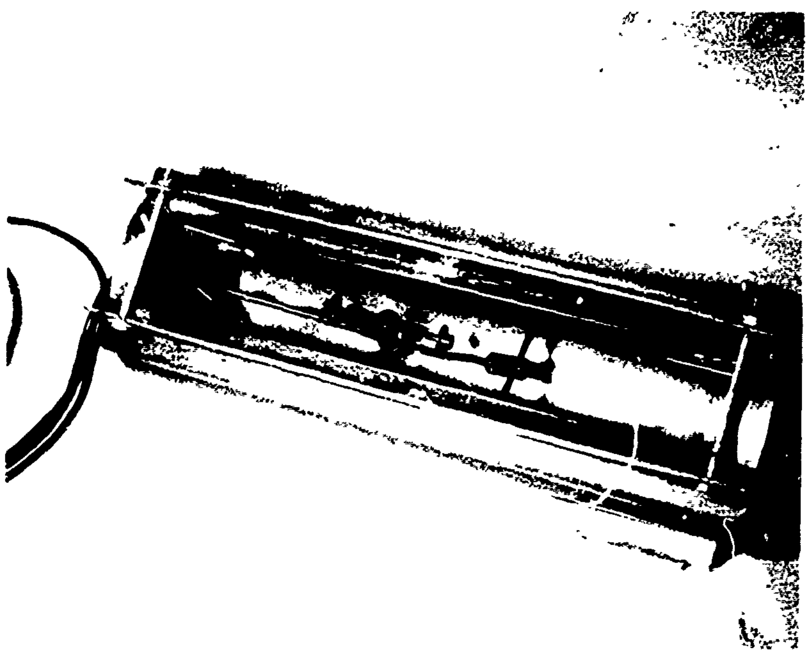

Fig. 12. Mold for creep and control specimens with vibrating wire strain gages in place

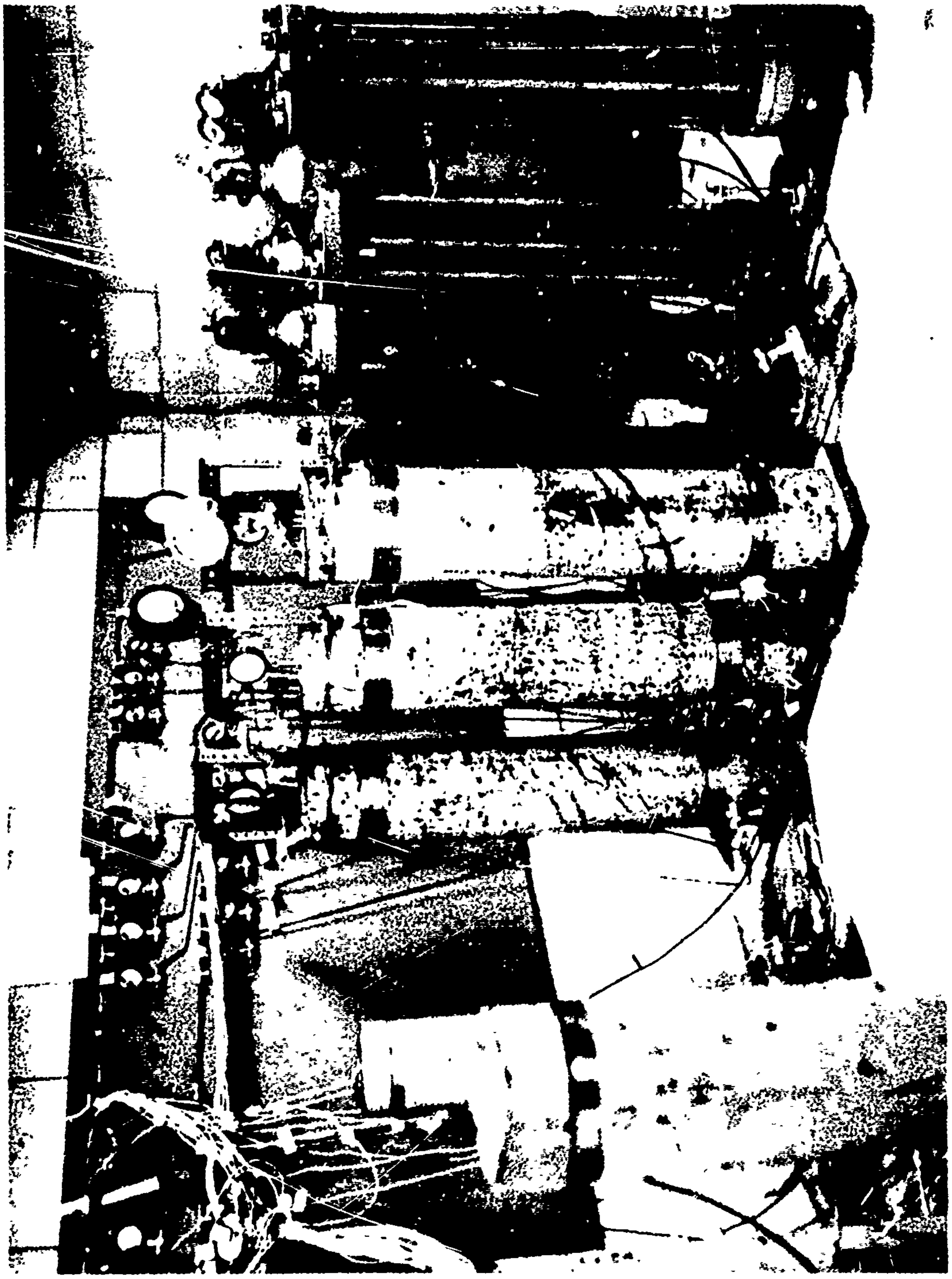

Fig. 13. Multiaxial creep test rigs, 73 F

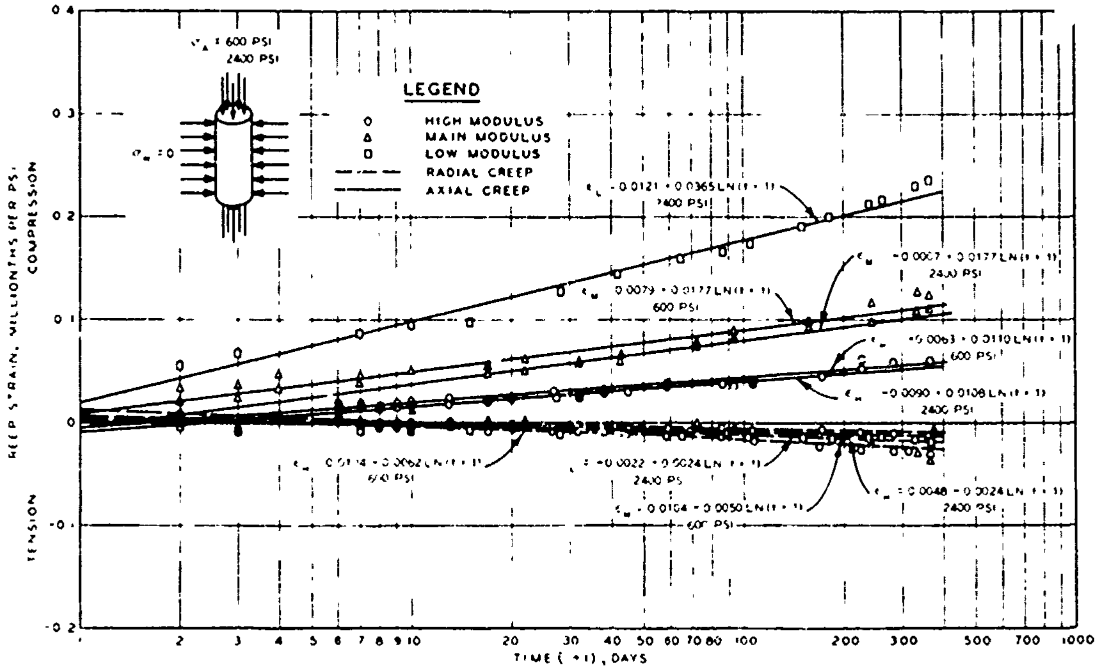

Fig. 14. Creep strain-time relations for uniaxial loaded as-cast specimens at 73 F

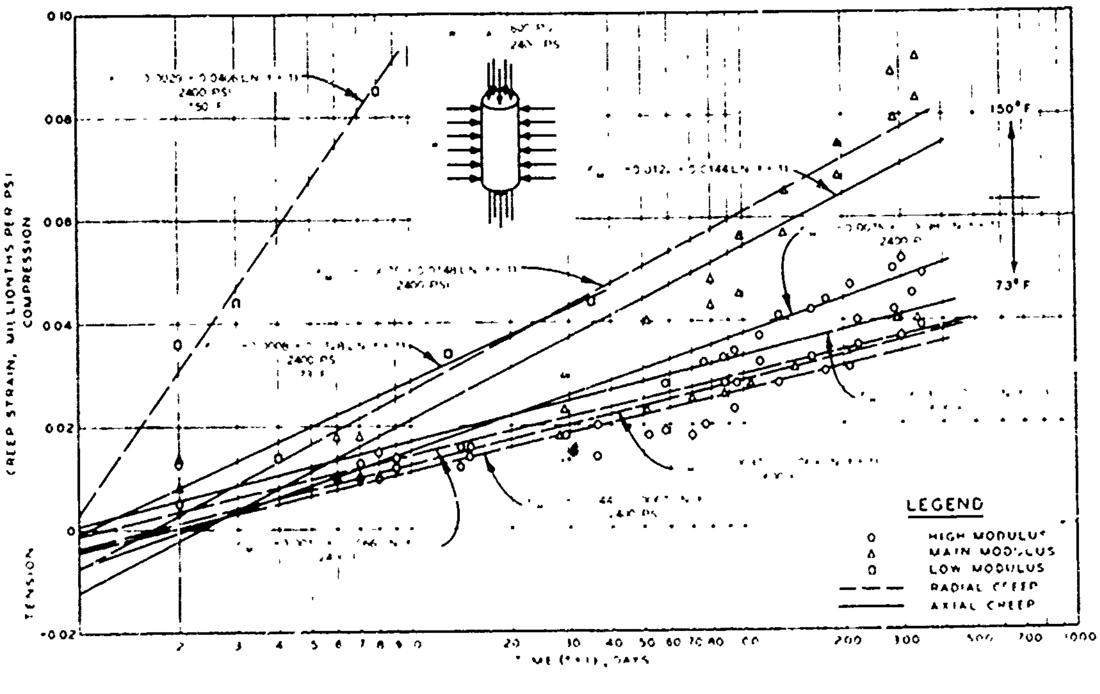

Fig. 15. Creep strain-time relations for hydrostatically loaded air-dried specimens at 73 and 150 F

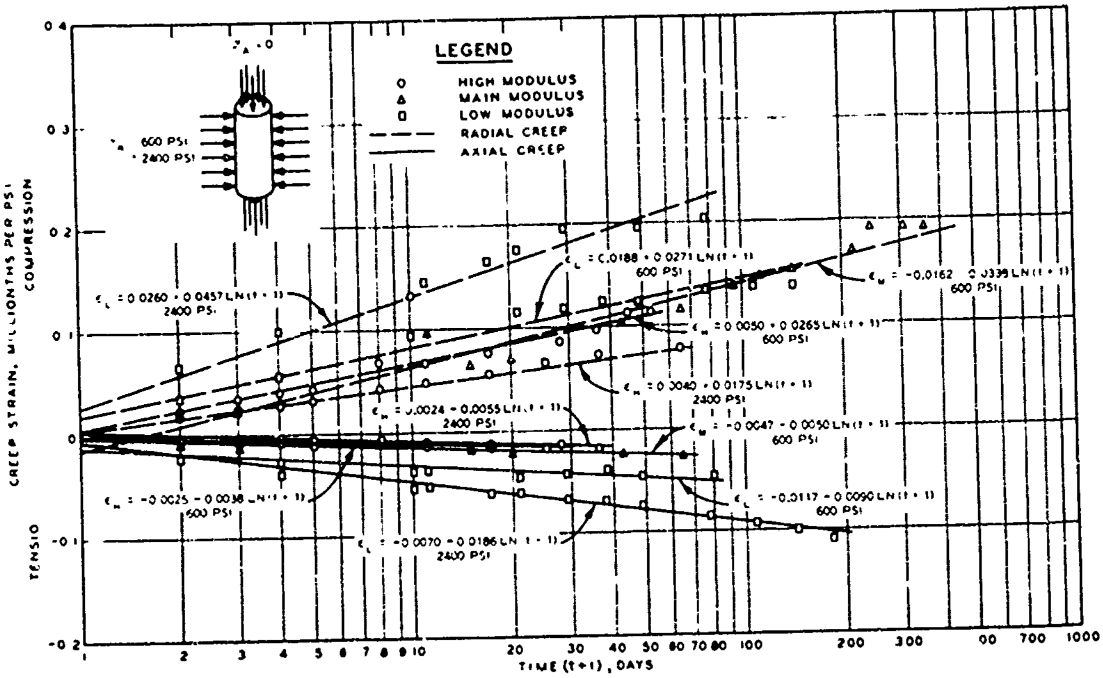

Fig. 16. Creep strain-time relations for biaxially loaded air-dried specimens at 150 F

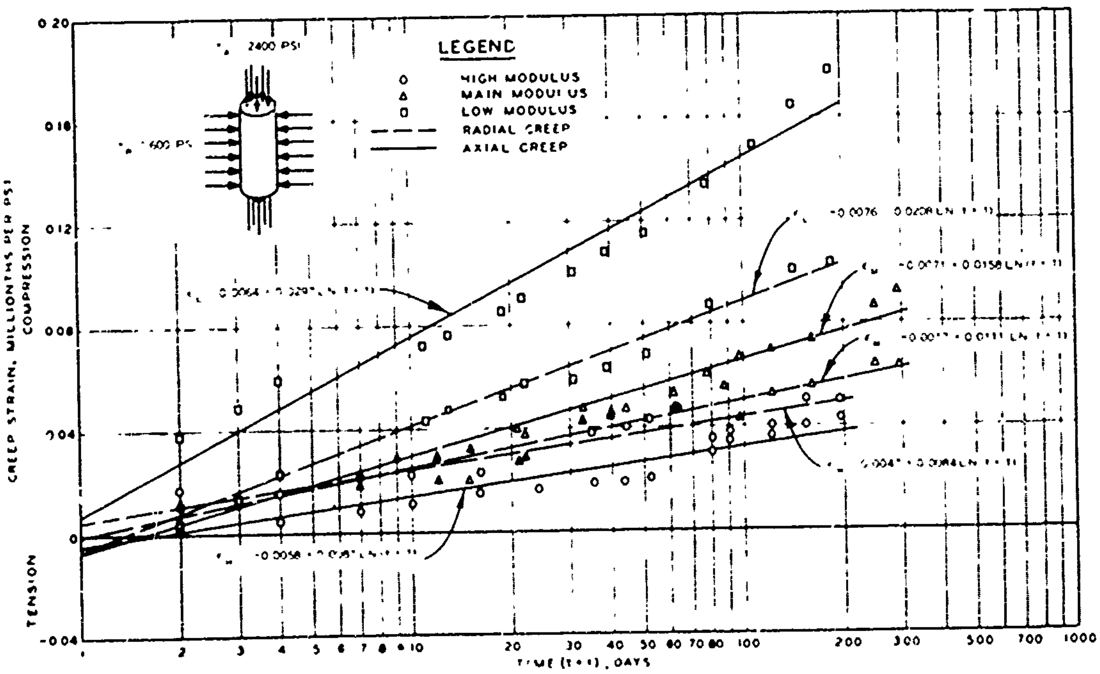

Fig. 17. Creep strain-time relations for triaxially loaded as-cast specimens at 73 F