Conf- 730532--1

Talk to be presented as a seminar to the Department of Engineering Science, Mechanics, and Aerospace Engineering, University of Florida, May 25, 1973

DEVELOPMENT OF HIGH-TEMPERATURE STRUCTURAL DESIGN METHODS FOR LIQUID-METAL FAST-BREEDER REACTOR SYSTEM COMPONENTS*

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Abstract

A brief description of liquid-metal fast-breeder reactor systems will be given along with some attendant structural design problems associated with inelastic material behavior. Central features of the ORNL program to develop applicable structural design methods will be outlined, including considerations of material deformation and failure. Activities to develop constitutive equations applicable to elastic-plastic and creep behavior will be discussed and currently recommended methods described. Some basic features of inelastic behavior of pertinent materials (particularly type 304 stainless steel) will be illustrated, along with the role they play in the development of constitutive equations. A number of elevated temperature structural tests will be described, and selected comparisons of test results with analysis predictions will be presented.

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

OUTLINE

C. Time-Dependent (Creep) Behavior

1.	Typical creep behavior	SLIDE 22
2.	Creep laws	SLIDE 23
3.	Variable load creep	SLIDE 24
4.	Variable load predictions	SLIDE 25 SLIDE 26
5.	Equation-of-state approach	SLIDE 27
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7.	Variable load conditions	SLIDE 29
8.	Multiaxial stress	SLIDE 30 SLIDE 31 SLIDE 32 SLIDE 33
9.	Cyclic creep rules	SLIDE 34
10.	Cyclic creep test	SLIDE 35
11.	Relaxation test	SLIDE 36 SLIDE 37

D. Creep-Plasticity Interactions

1.	Soaking effects on stress-strain	SLIDE 38
2.	Relaxation effects on stress-strain	SLIDE 39
3.	Creep effects on stress-strain	SLIDE 40
4.	Plastic loading effects on creep	SLIDE 41

E. Structural Tests

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2.	Beam test facility	SLIDE 43
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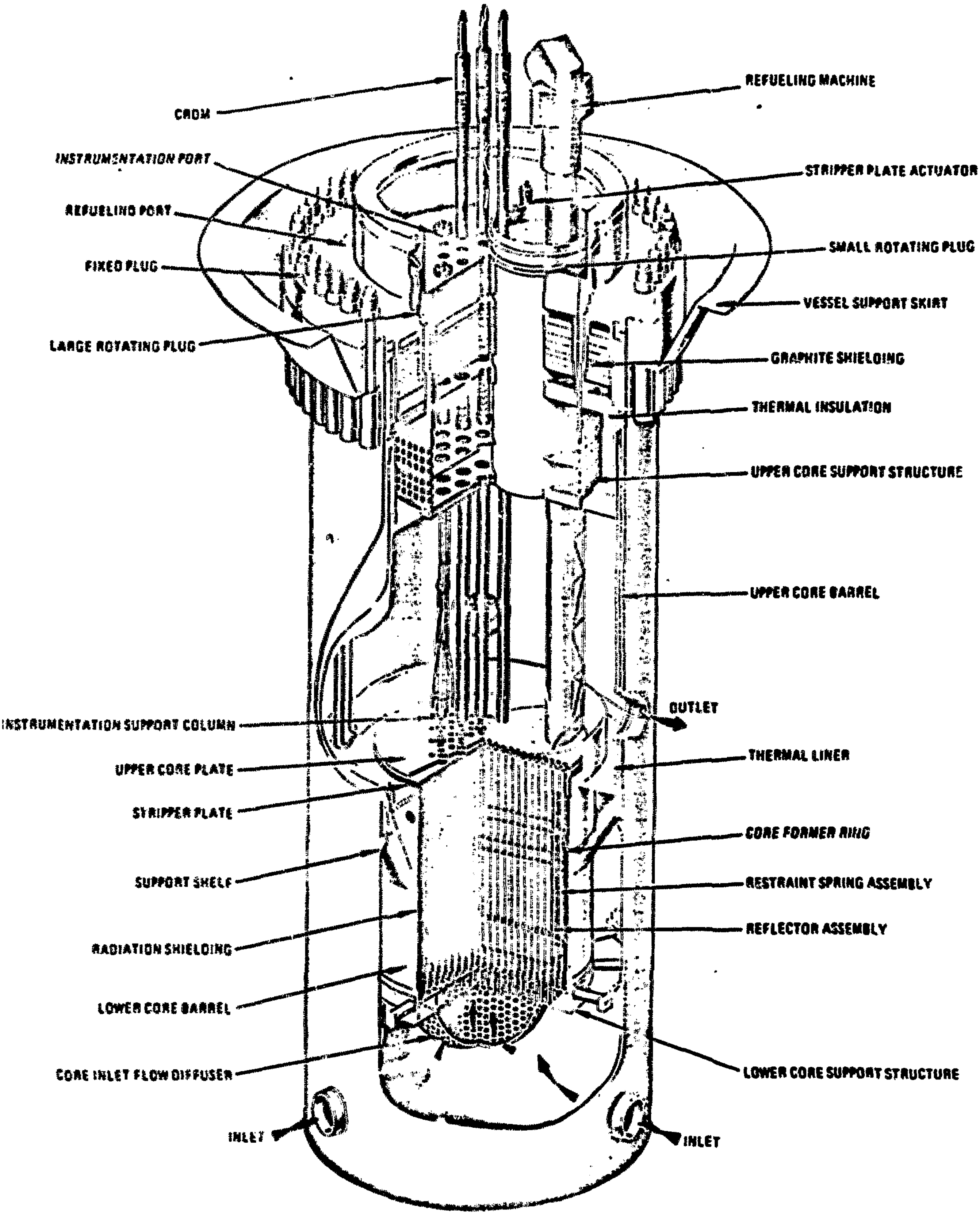
F. Research and Development Needs — SLIDE 48

G. Conclusions: Constitutive equations currently in use are based on small deformation theory and the postulate that the total strain tensor can be decomposed into time-independent components and time-dependent components. On the basis of available data, these equations are capable of representing essential features of inelastic behaviors to be expected under service conditions. However, in-depth studies are needed of the inelastic behavior of materials under general nonradial loading programs, including possible creep-plasticity interactions. An integral tie must exist between experimentation and theory development.

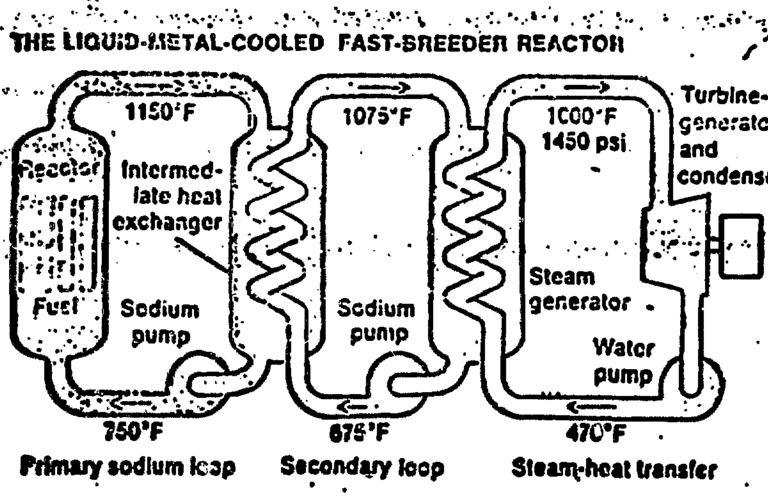
ORNL-DWG 73-2402



REACTOR (UNDER-THE-PLUG REFUELING)
WESTINGHOUSE LMFBR DEMONSTRATION PLANT

SLIDE 1

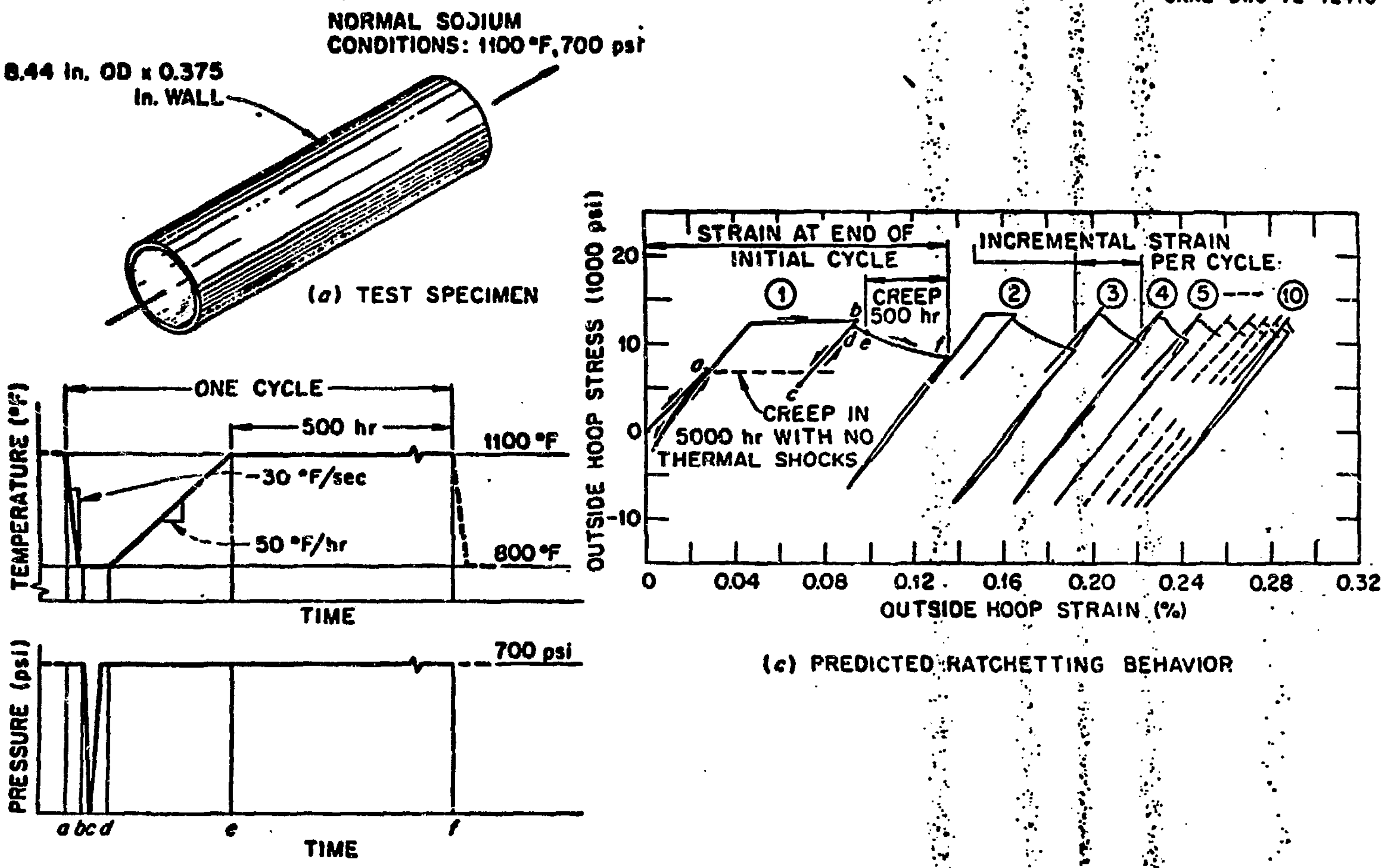
M+C
LM 518



SLIDE 2

SLIDE 3

ORNL-DWG 72-12416

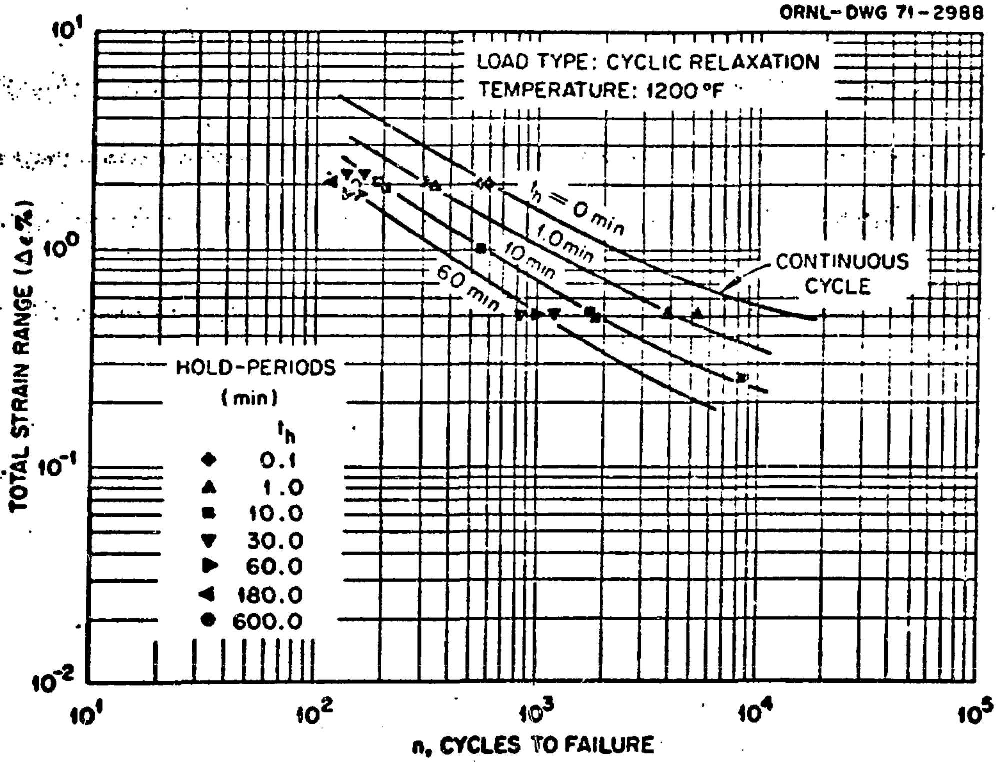


(a) TEST SPECIMEN

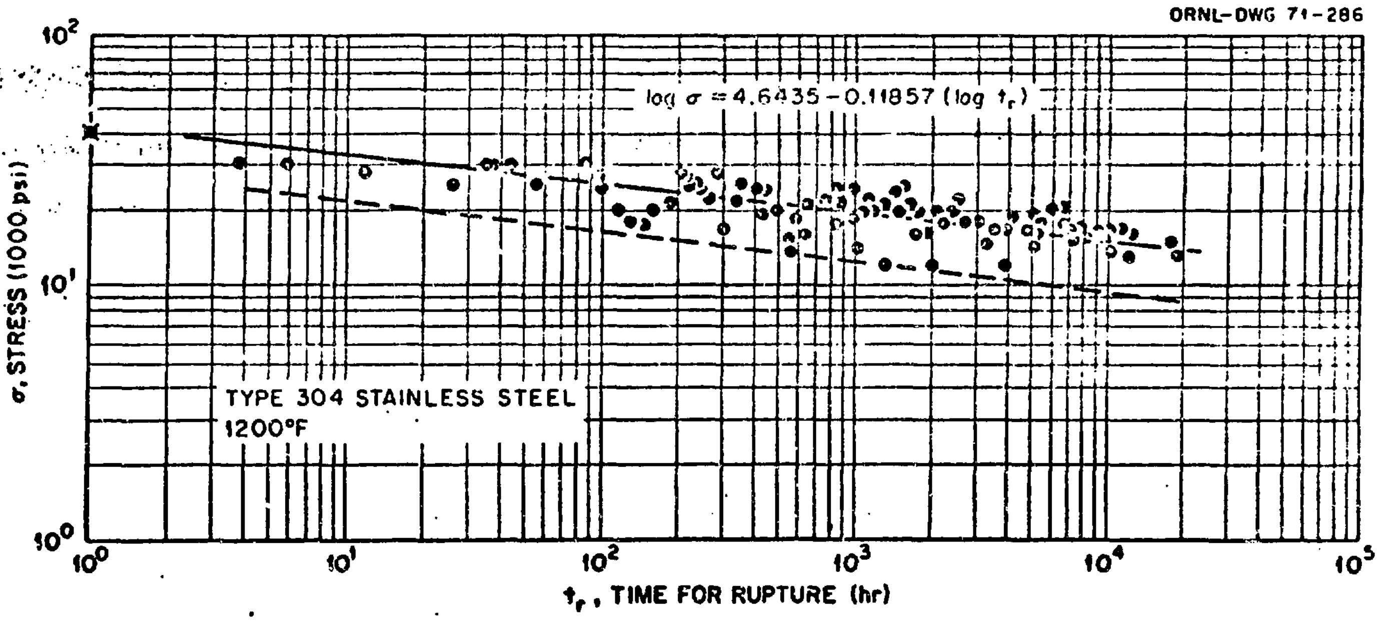
(b) TEMPERATURE–PRESSURE HISTOGRAMS

(c) PREDICTED RATCHETTING BEHAVIOR

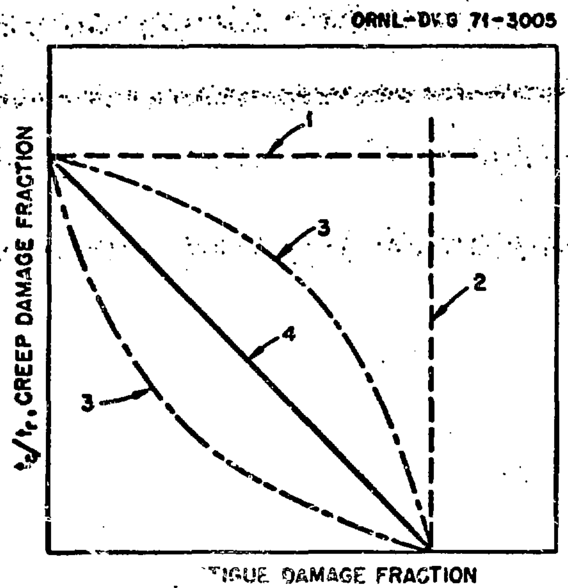
Pipe Thermal Ratchetting Tests



ORNL-DWG 71-2988
LOAD TYPE: CYCLIC RELAXATION
TEMPERATURE: 1200 °F
t_h = 0 min
1.0 min
10 min
60 min
CONTINUOUS CYCLE
HOLD-PERIODS (min)
t_h
0.1
1.0
10.0
30.0
60.0
180.0
600.0
TOTAL STRAIN RANGE (Δε %)
n, CYCLES TO FAILURE


ORNL-DWG 71-286
log σ = 4.6435 − 0.11857 (log t_r)
σ, STRESS (1000 psi)
TYPE 304 STAINLESS STEEL
1200°F
t_r, TIME FOR RUPTURE (hr)
10^0
10^1
10^2
10^3
10^4
10^5

SLIDE 5



ONLY, $\alpha = 0$

NLY, $\beta = 0$

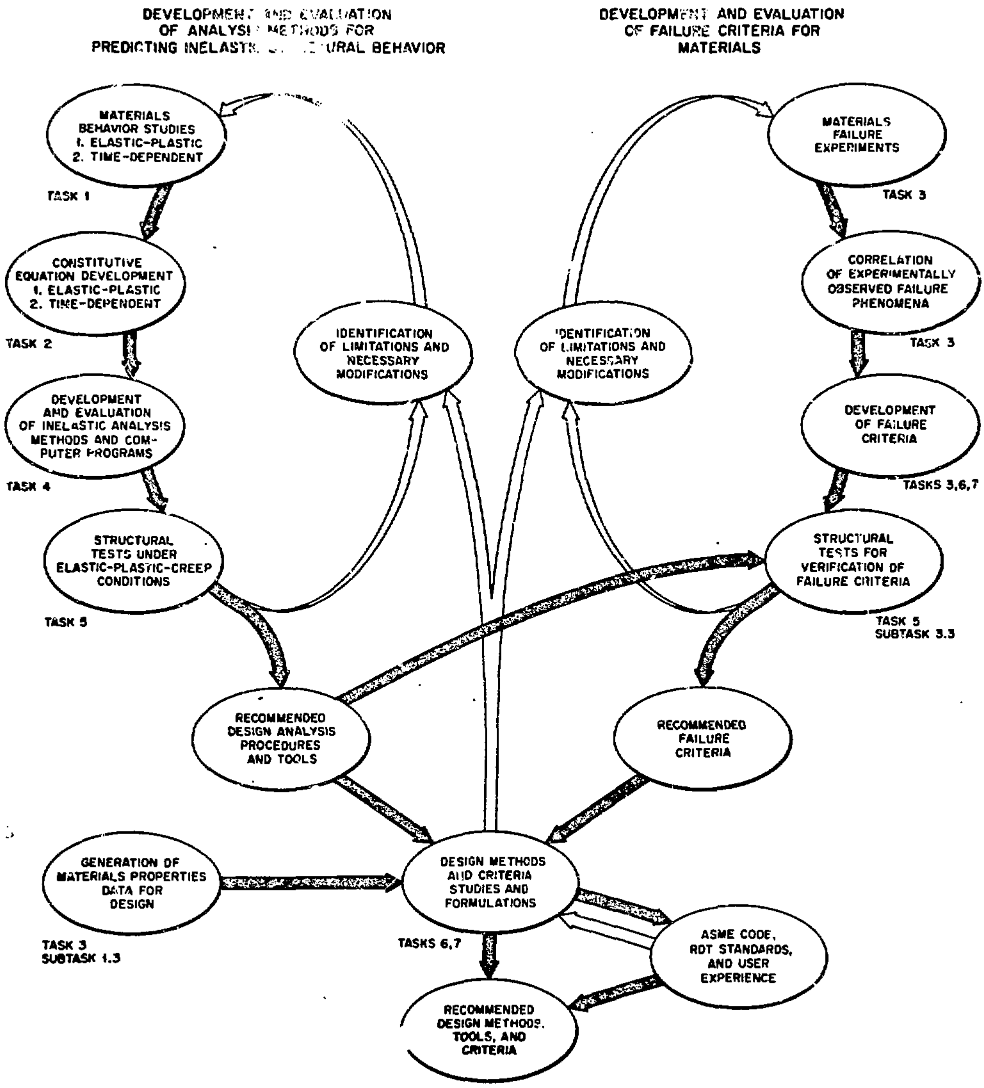
3. NO FATIGUE

INTER

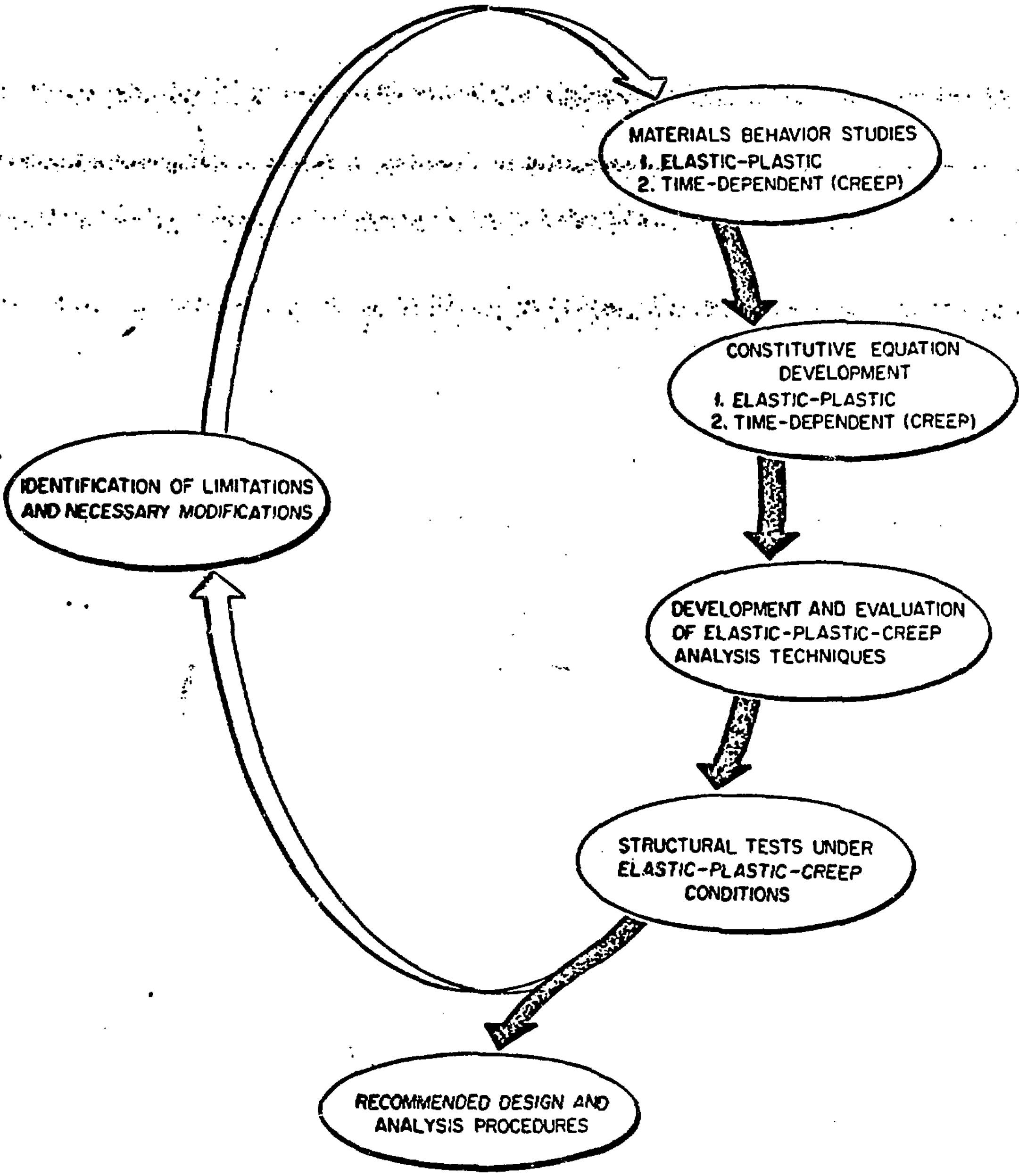
UE

SLIDE 6

ORNL-DWG 73-2406

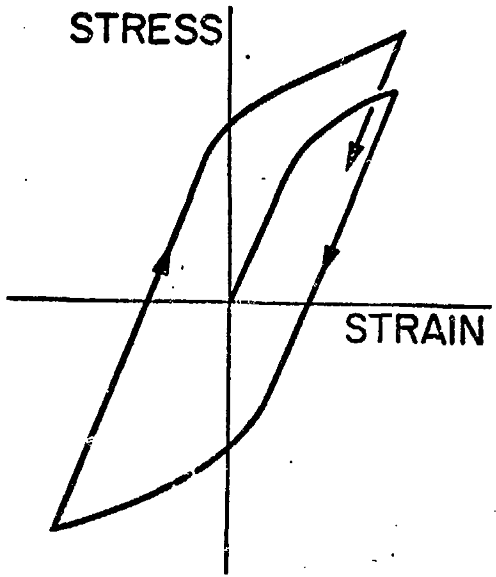


ORNL-DWG 71-3411



Coordinated Effort to Develop and Evaluate Analytical Methods.

ORNL-DWG 71-3416

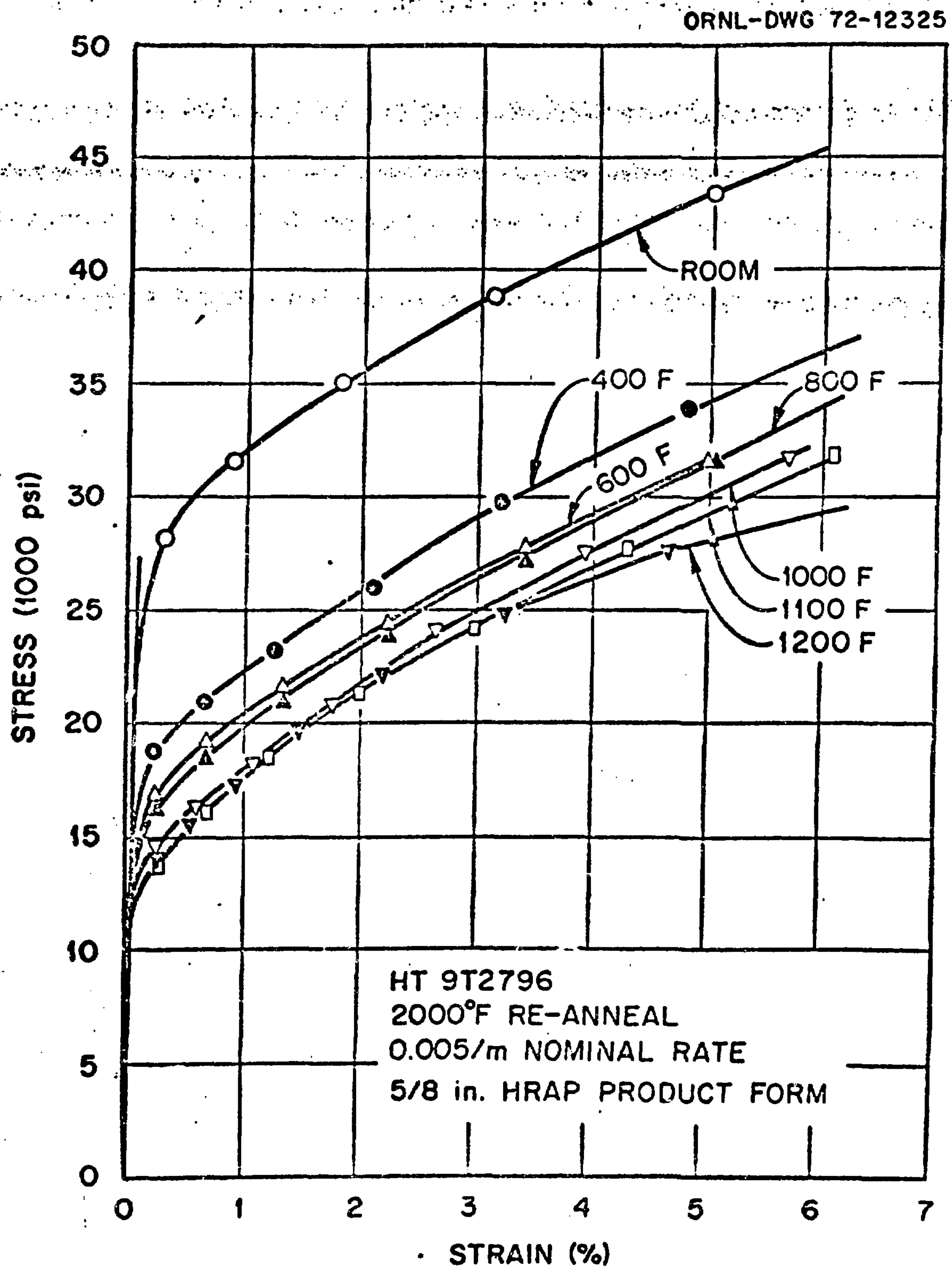


UNIAXIAL CYCLIC STRESS-STRAIN CURVE FOR A WORK HARDENING MATERIAL

TO DESCRIBE TIME-INDEPENDENT ELASTIC-PLASTIC BEHAVIOR REQUIRES:

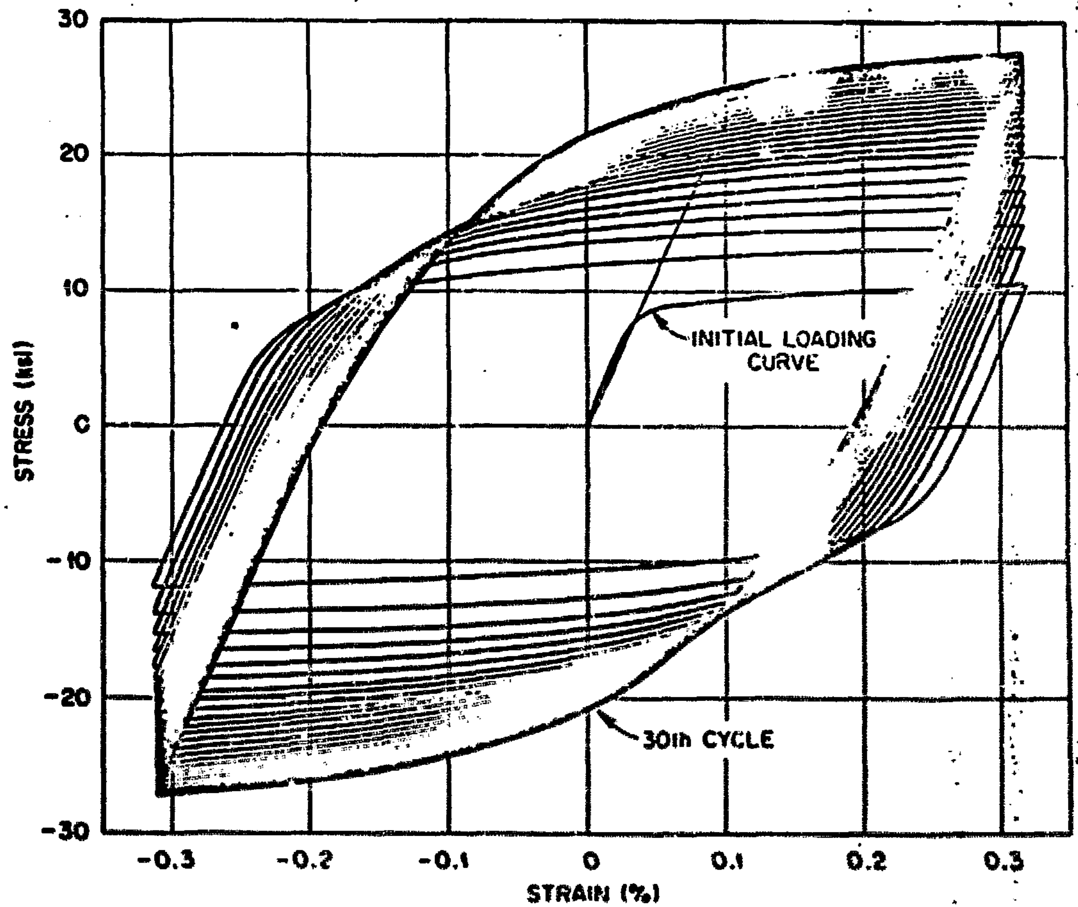
1. YIELD CRITERIA
2. FLOW RULE
3. HARDENING LAW

SLIDE 9


ORNL-DWG 72-12325
STRESS (1000 psi)
STRAIN (%)
ROOM
400 F
600 F
800 F
1000 F
1100 F
1200 F
HT 9T2796
2000°F RE-ANNEAL
0.005/m NOMINAL RATE
5/8 in. HRAP PRODUCT FORM
50
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7

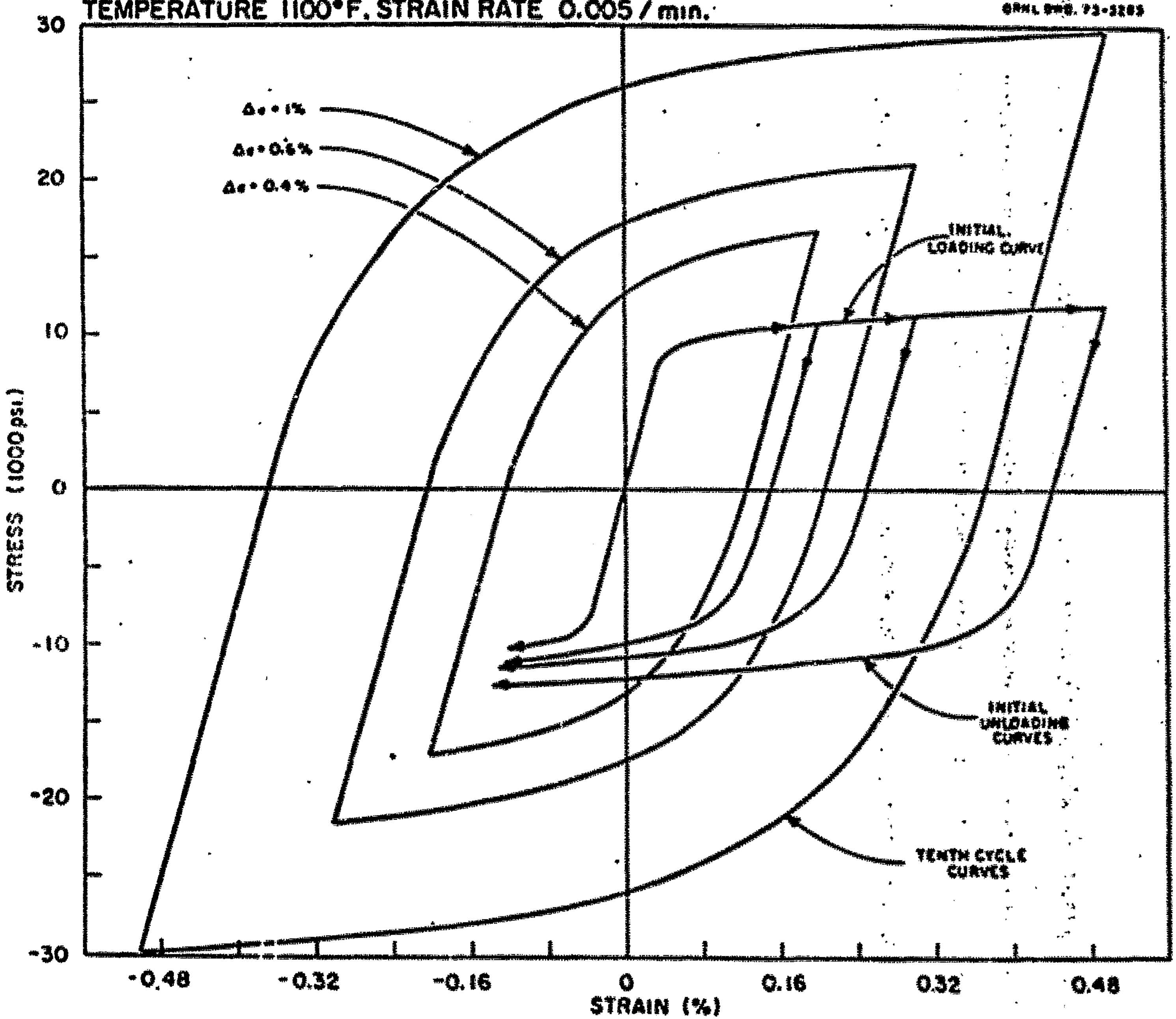
ORNL-DWG 73-2814

TYPE 304 STAINLESS STEEL, ANNEALED
(HEAT 9T2796)
TEMPERATURE: 1100°F
STRAIN RATE: 0.005/min

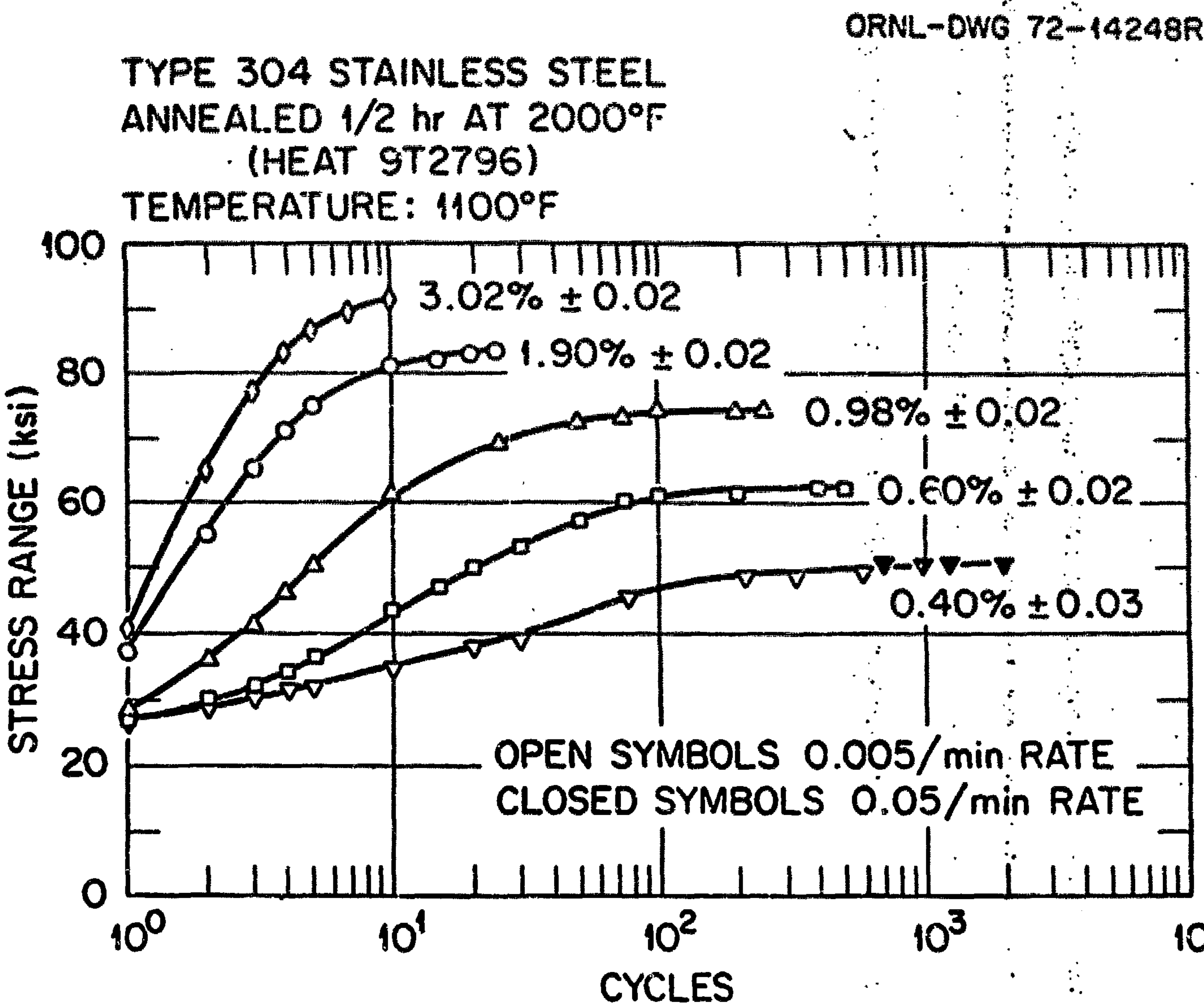


SLIDE 11

TYPE 304 STAINLESS STEEL, ANNEALED
(HEAT 9T2796)
TEMPERATURE 1100°F, STRAIN RATE 0.005 / min.

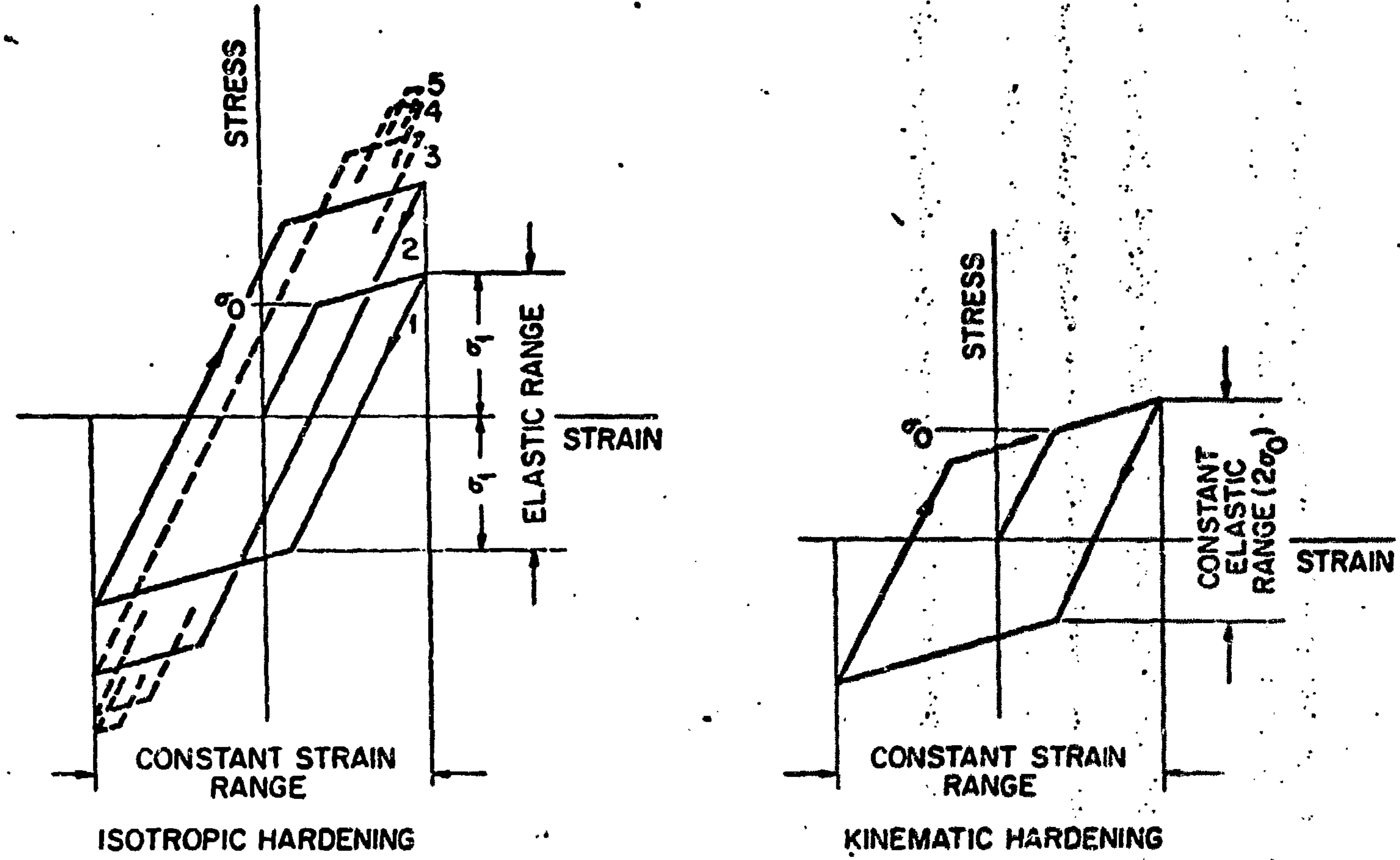


SLIDE 12


ORNL-DWG 72-14248R
TYPE 304 STAINLESS STEEL
ANNEALED 1/2 hr AT 2000°F
(HEAT 9T2796)
TEMPERATURE: 1100°F
3.02% ± 0.02
1.90% ± 0.02
0.98% ± 0.02
0.60% ± 0.02
0.40% ± 0.03
OPEN SYMBOLS 0.005/min RATE
CLOSED SYMBOLS 0.05/min RATE
STRESS RANGE (ksi)
CYCLES
100
80
60
40
20
0
10^0
10^1
10^2
10^3
10^4

SLIDE 13

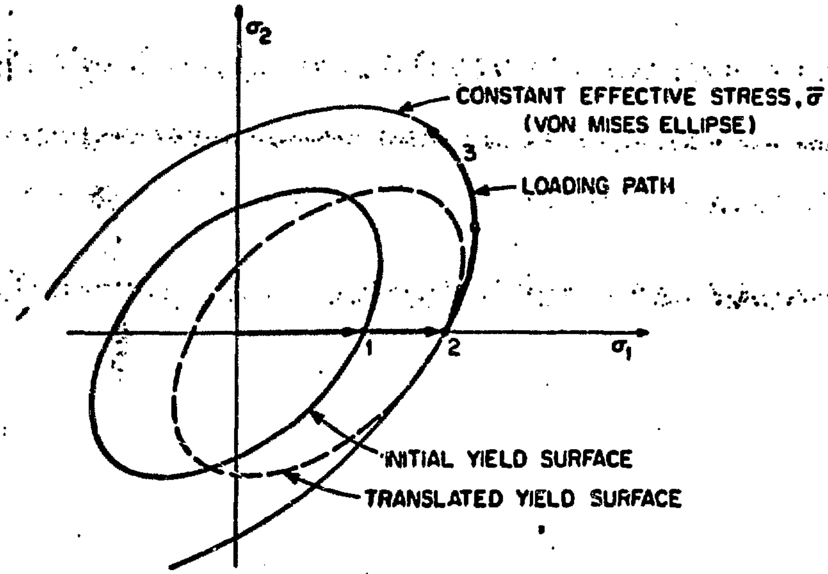
ORNL-DWG 71-3417



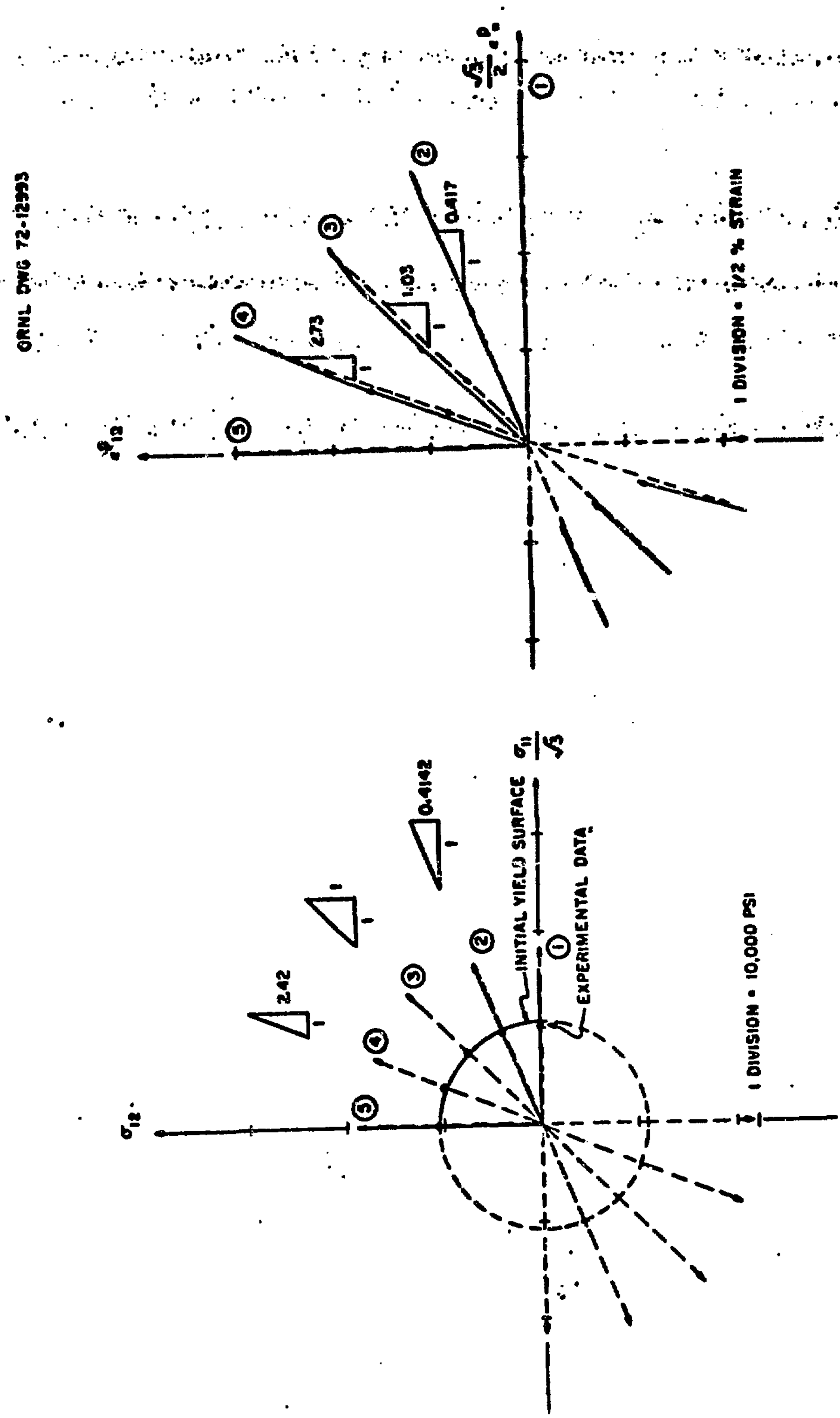
Uniaxial Elastic-Plastic Stress-Strain Behavior Predicted by Hardening Laws (Bilinear Representation Used for Simplicity).

SLIDE 14

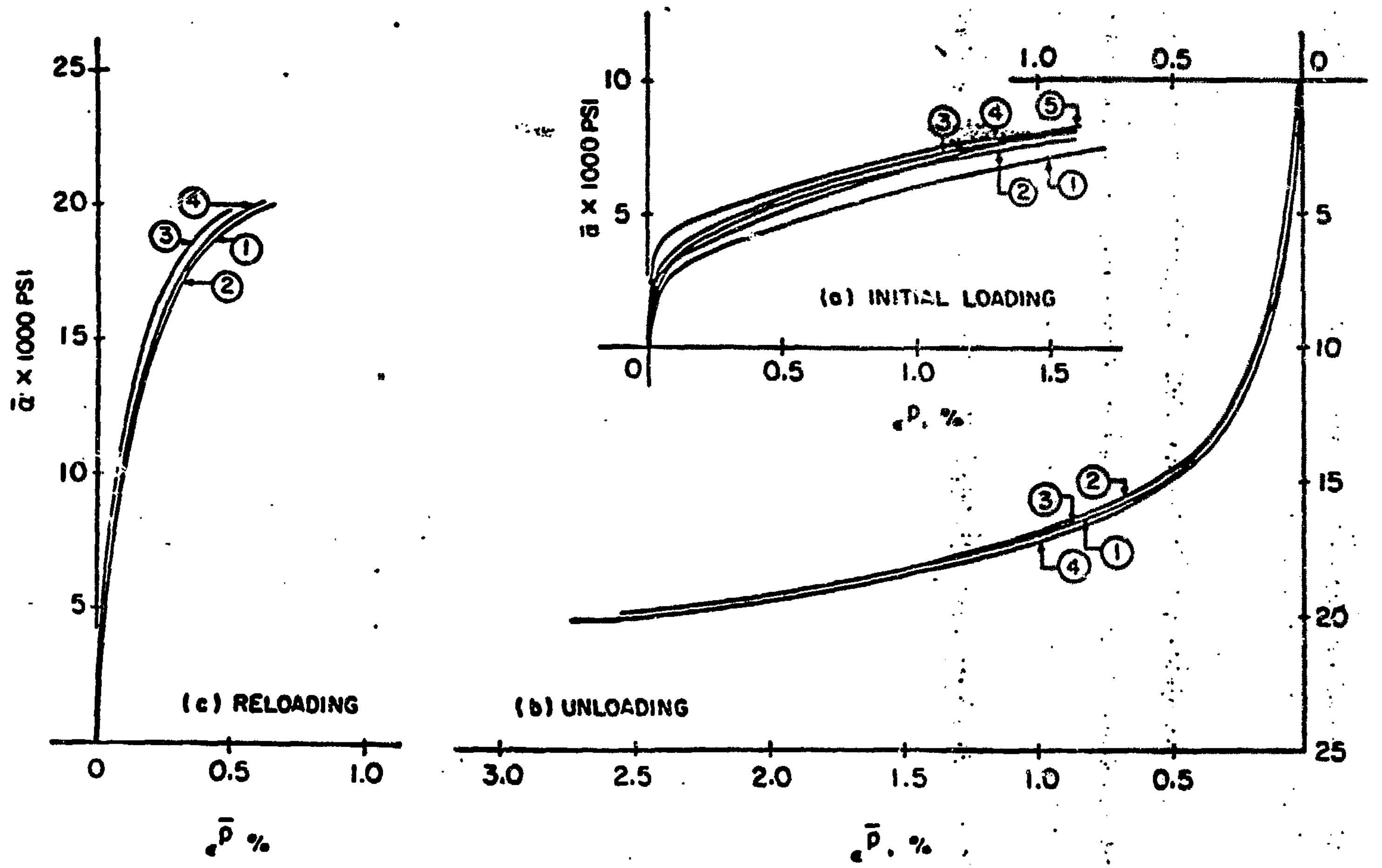
ORNL-DWG 72-4442



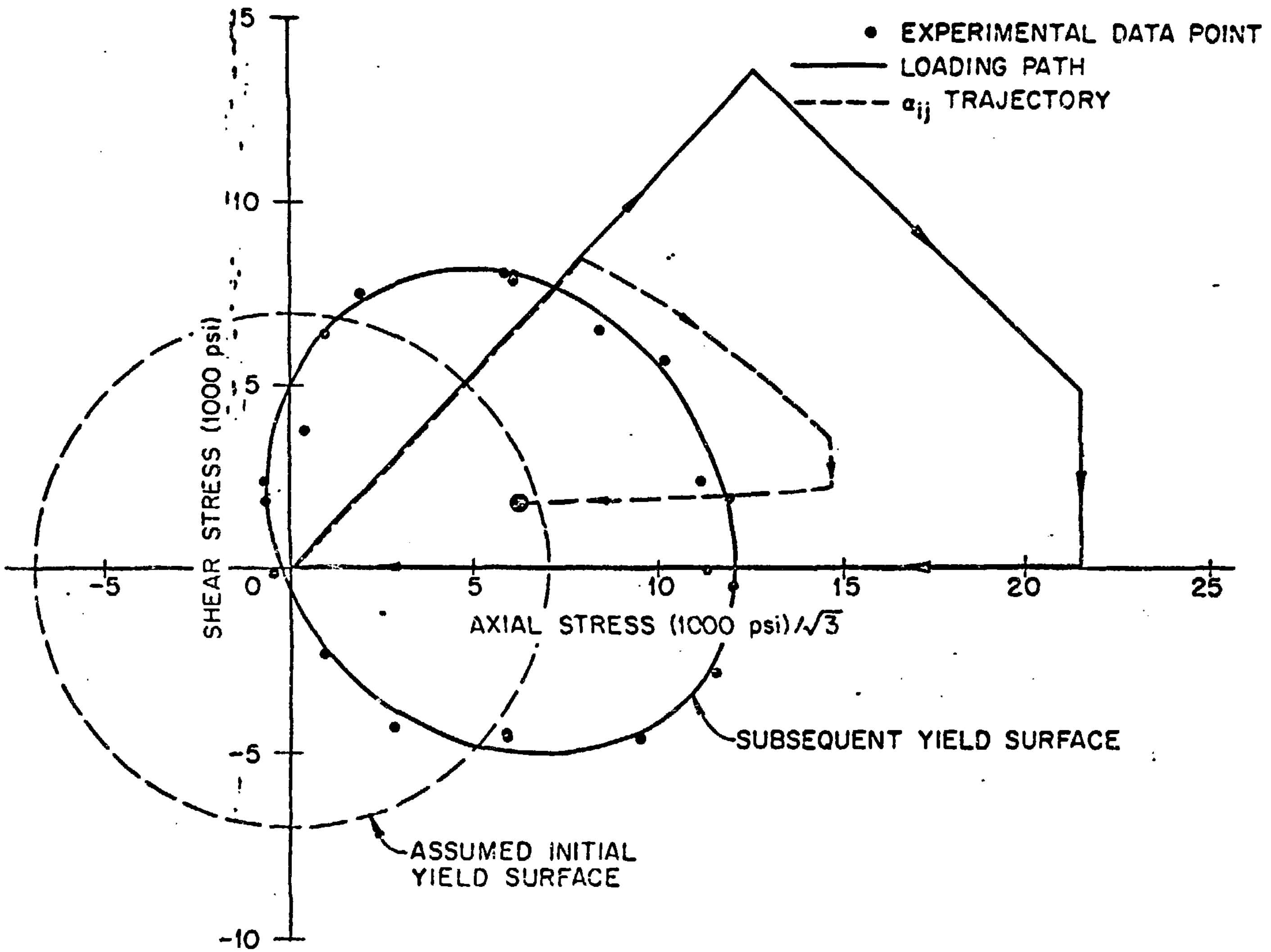
SLIDE 15


ORNL DWG 72-12993
0.417
1.03
2.73
1 DIVISION = 1/2 % STRAIN
0.4142
2.42
INITIAL YIELD SURFACE
EXPERIMENTAL DATA
1 DIVISION = 10,000 PSI

ORNL DWG 72-10043

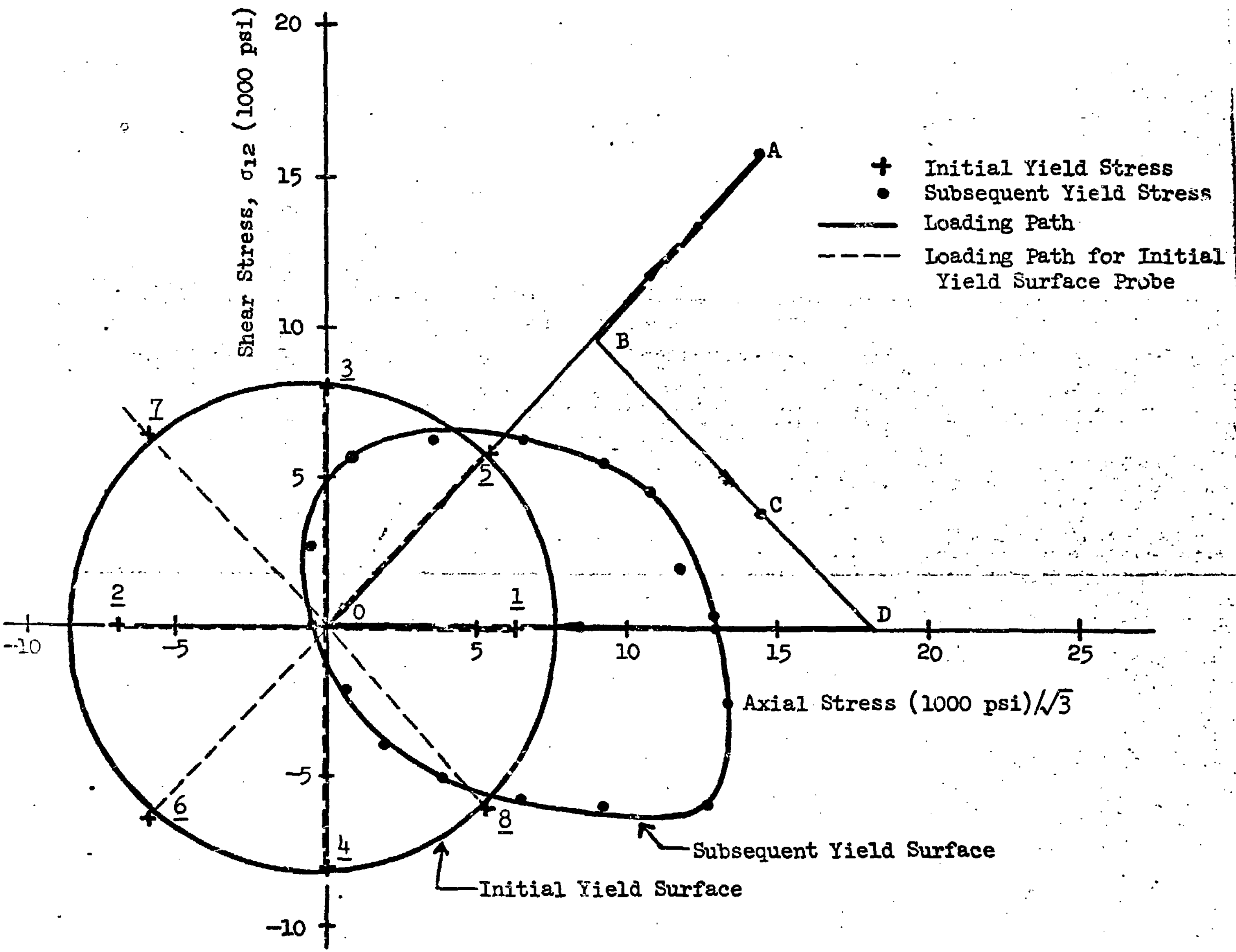


ORNL-DWG 72-12326

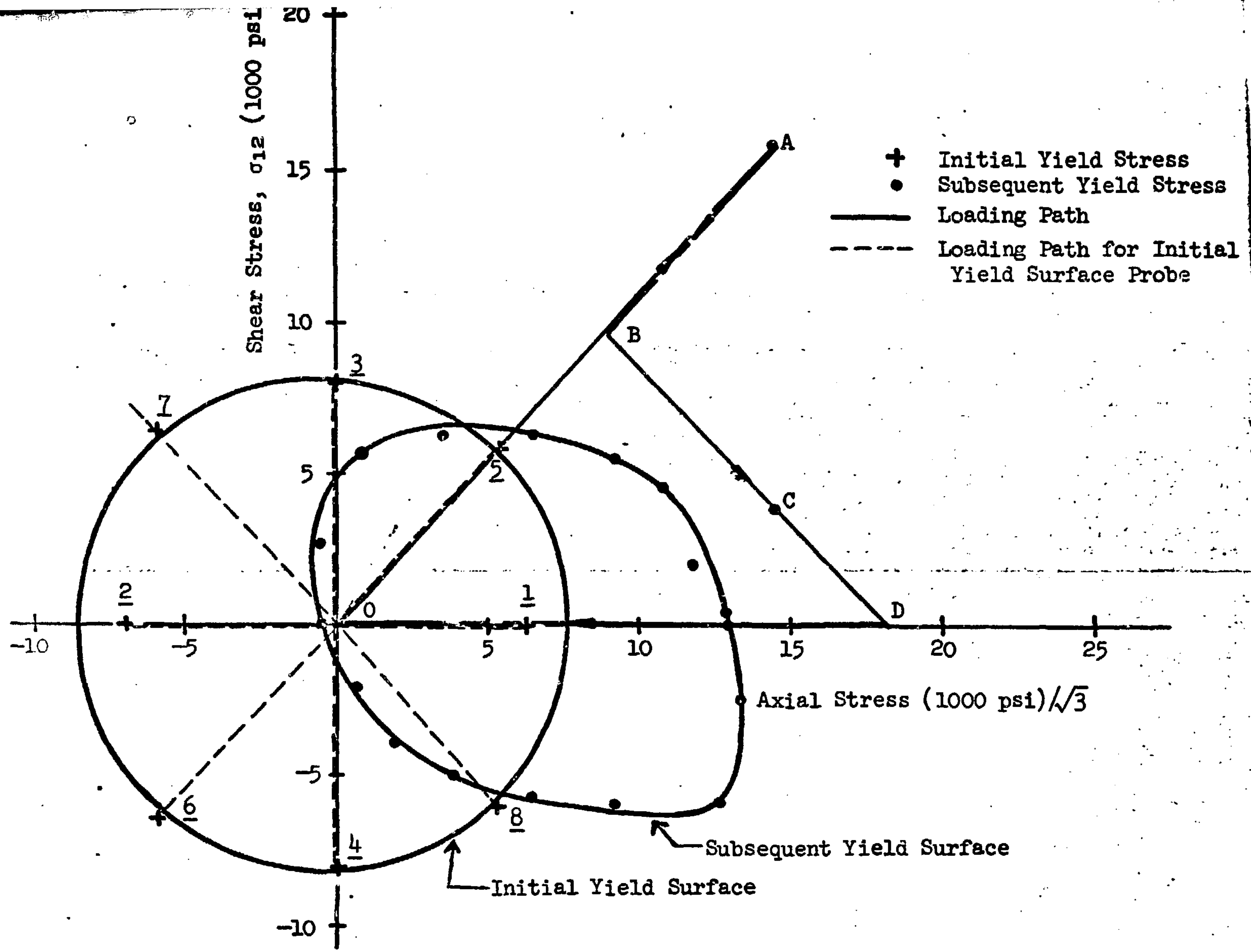


SLIDE 18

ORNL-DWG. 72-13930



SLIDE


Shear Stress, σ12 (1000 psi
Axial Stress (1000 psi)/√3
Initial Yield Stress
Subsequent Yield Stress
Loading Path
Loading Path for Initial Yield Surface Probe
Subsequent Yield Surface
Initial Yield Surface
A
B
C
D
0
1
2
3
4
5
6
7
8
20
15
10
5
-5
-10
25

SLIDE 19

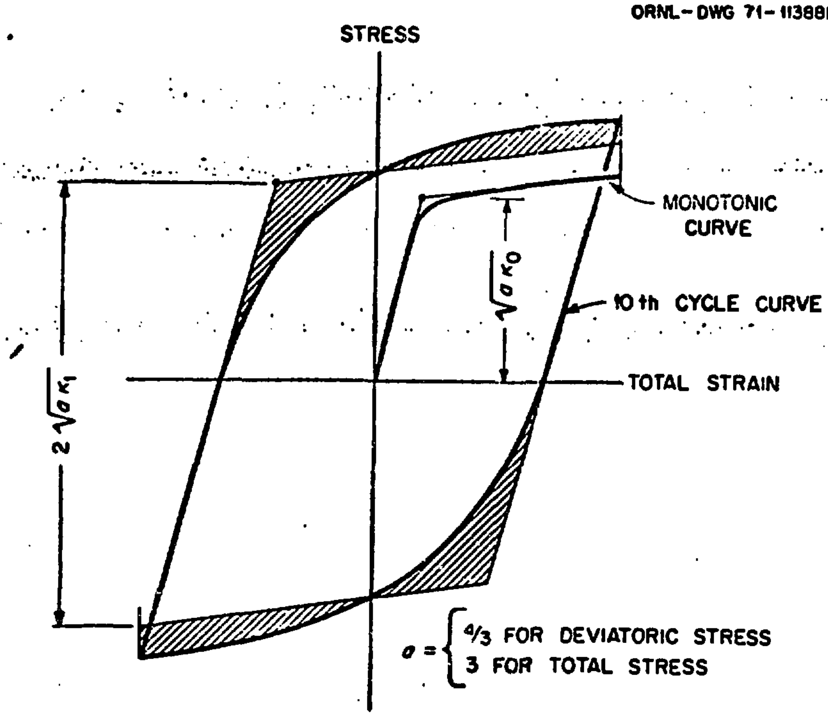
ORNL DWG. 73-3402

Inelastic Analysis Guidelines
Time-Independent Elastic-Plastic Behavior

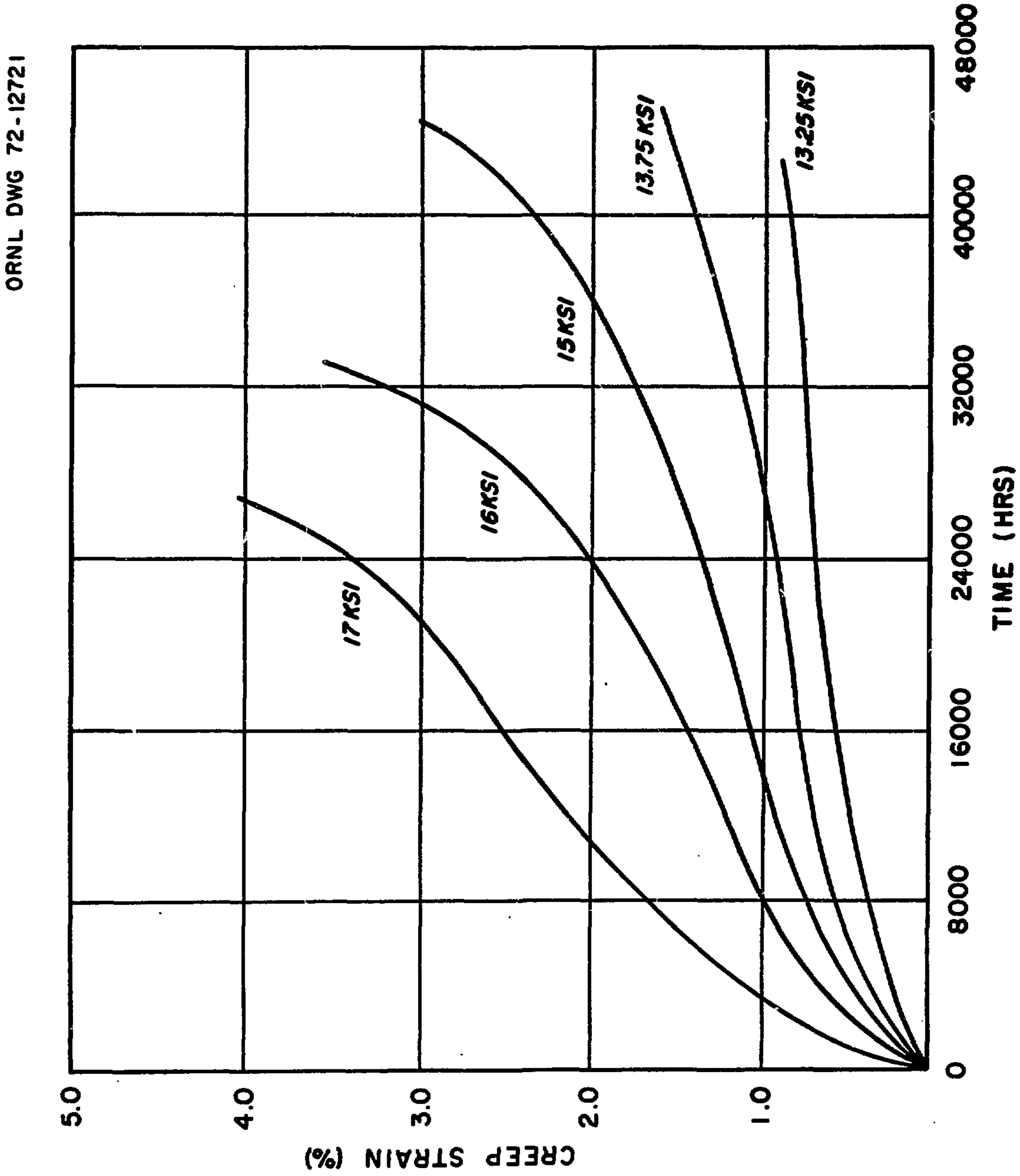
1. Yield Criterion: Von Mises or Tresca,
   $f(\sigma, \epsilon^p, H) = \kappa(T)$
2. Flow Rule: Von Mises Associated Flow Law,
   $$d\epsilon^p \sim \frac{\partial f}{\partial \sigma}$$
3. Hardening Rule: Nonisothermal Kinematic Hardening
4. Stress-Strain Relation: Bilinear Relation Required for Nonradial Loadings, with Specific Rules Provided for Determining the Equivalent Bilinear Curves from Actual Uniaxial Stress-Strain Curves

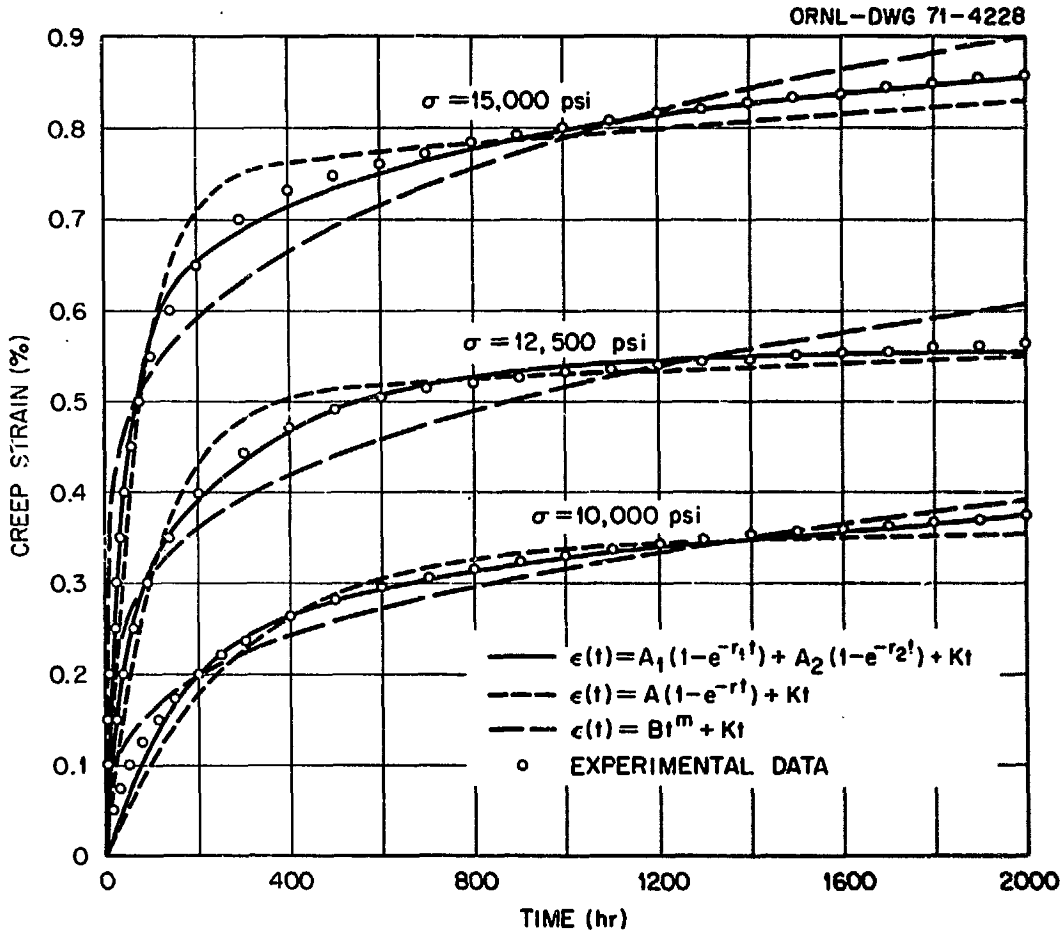
   Nonlinear Relation Acceptable for Radial Loadings
5. Effects of Hardening Due to Cycling and to Prior Creep Approximately Accounted for by Changing from Initial Stress-Strain Curve to Cyclic Stress-Strain Curve

ORNL-DWG 71-11388R



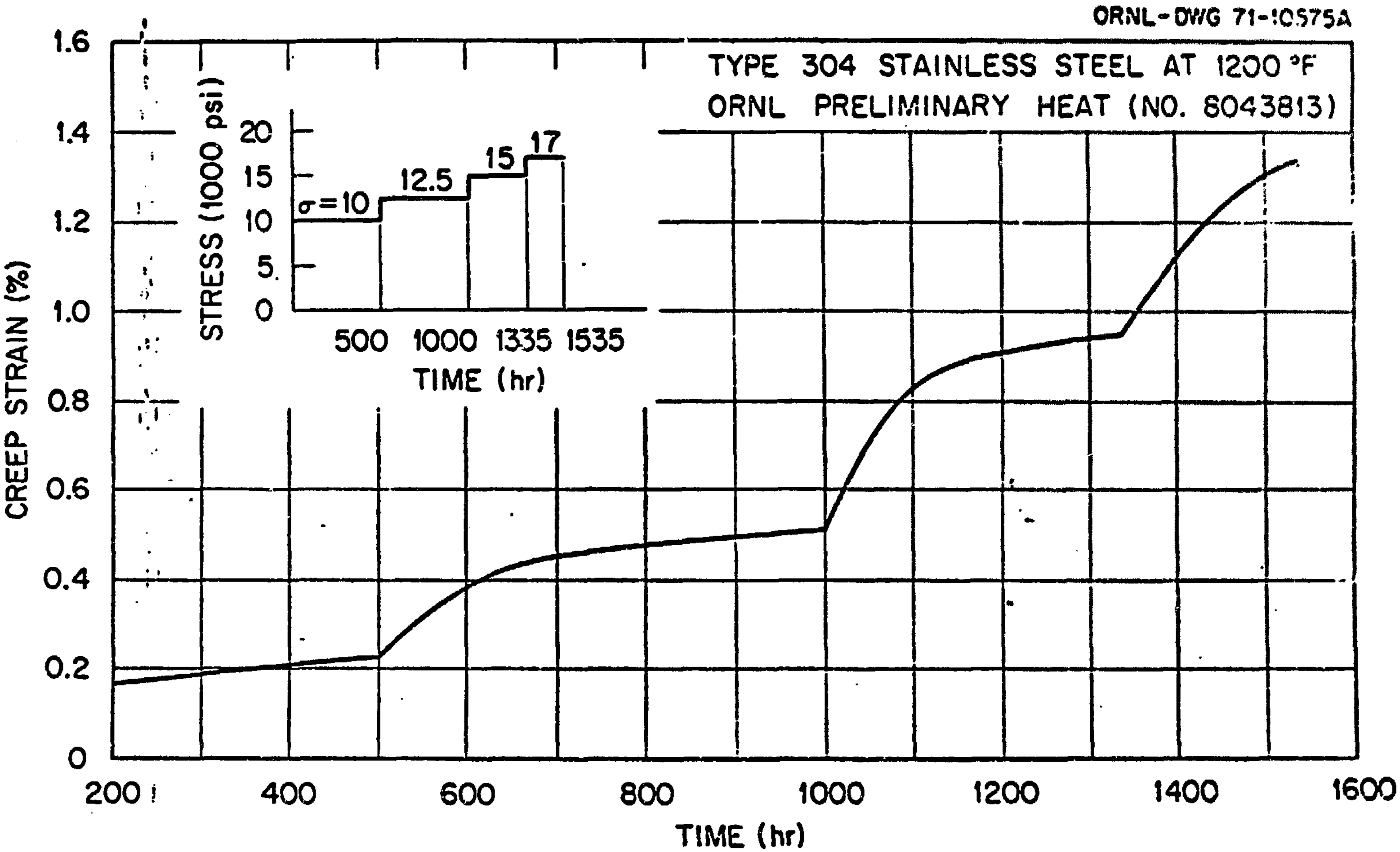
SLIDE 21


ORNL DWG 72-12721
CREEP STRAIN (%)
5.0
4.0
3.0
2.0
1.0
0
8000
16000
24000
32000
40000
48000
TIME (HRS)
17 KSI
16 KSI
15 KSI
13.75 KSI
13.25 KSI

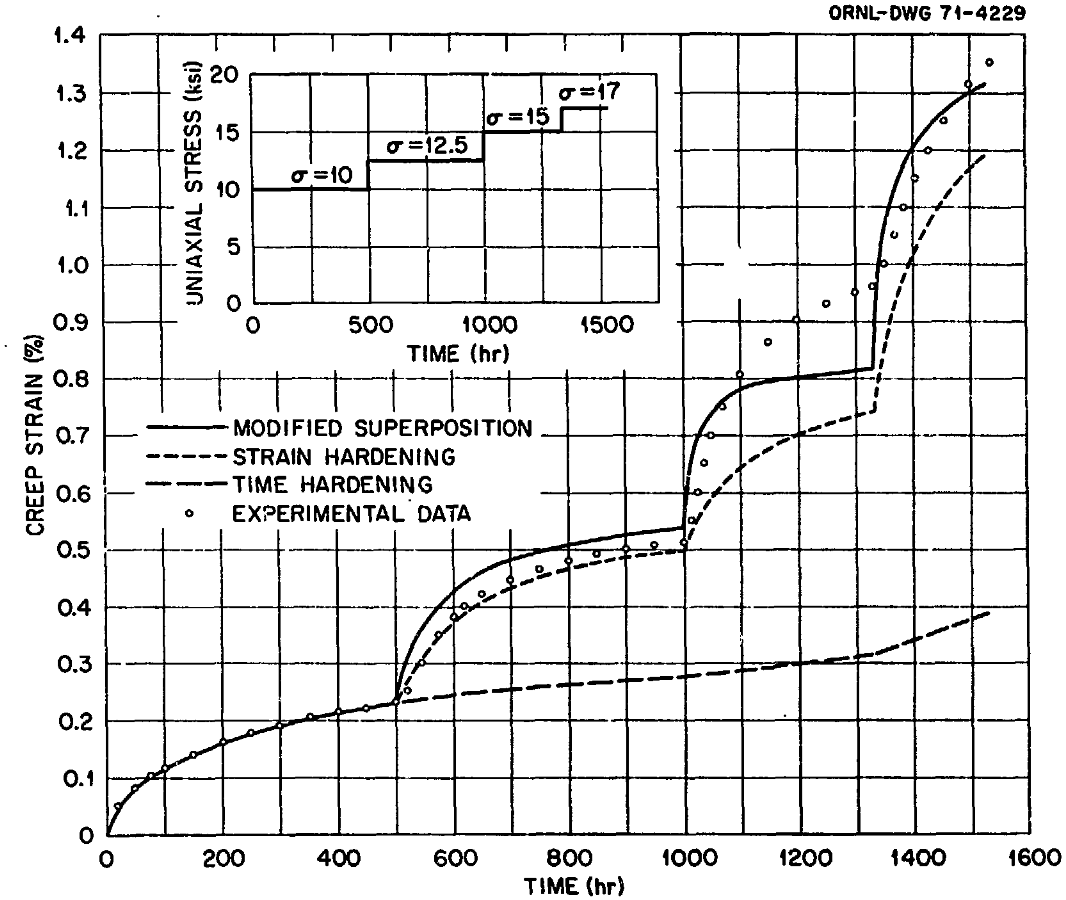


Least Squares Fit to Constant-Load Creep Curves for 304 Stainless Steel (Heat 8043813) at 1200°F.

SLIDE 23


ORNL-DWG 71-10575A
TYPE 304 STAINLESS STEEL AT 1200 °F
ORNL PRELIMINARY HEAT (NO. 8043813)
STRESS (1000 psi)
σ=10
12.5
15
17
500 1000 1335 1535
TIME (hr)
CREEP STRAIN (%)
TIME (hr)

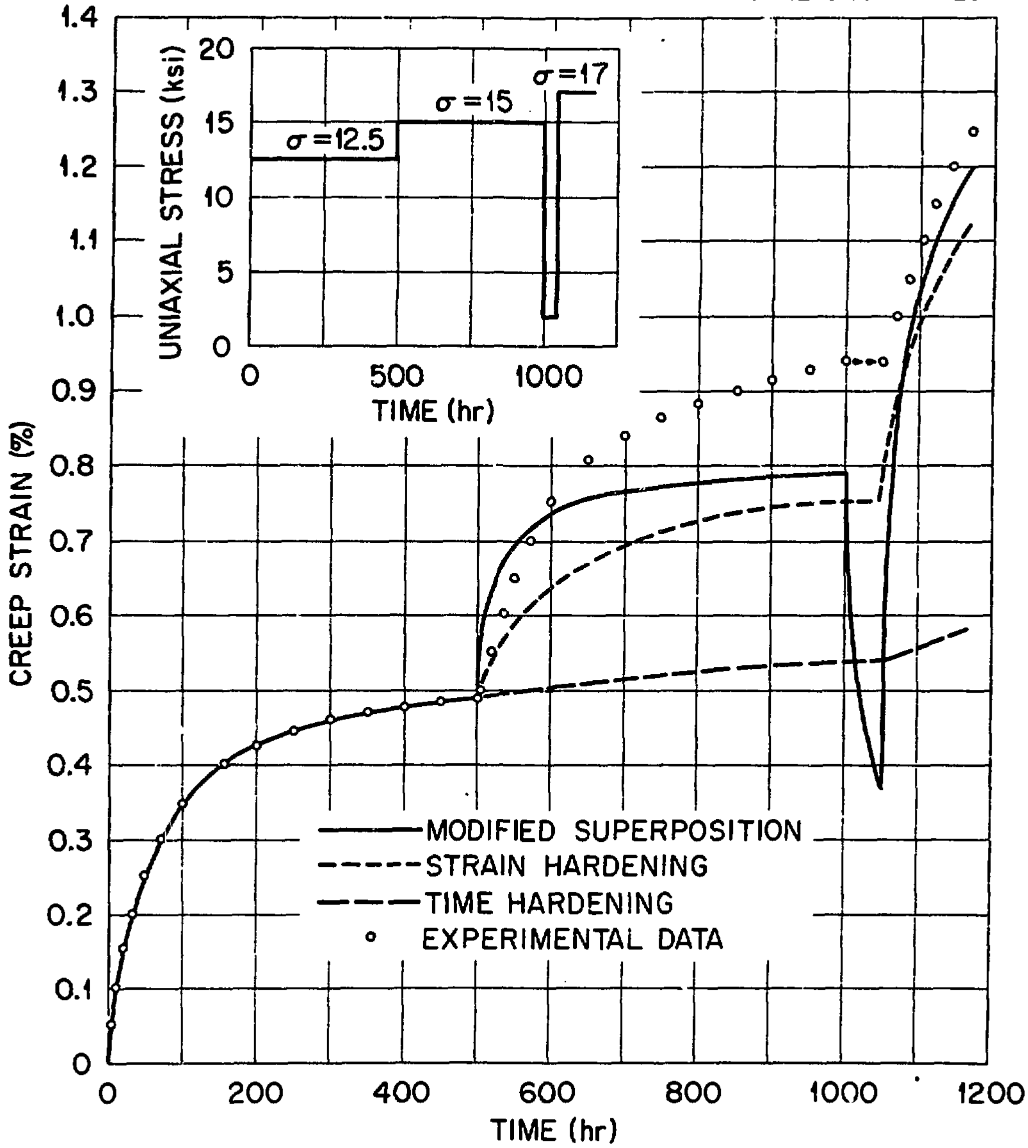
SLIDE 24



Comparisons of Experimental Creep Response to Stepwise Varying Uniaxial Load with Predictions From Various Constitutive Formulations. 304 Stainless Steel (Heat 8043813); Temperature = 1200°F.

SLIDE 25

ORNL-DWG 71-4230



Comparisons of Experimental Creep Response to Stepwise Varying Uniaxial Load with Predictions From Various Constitutive Formulations. 304 Stainless Steel (Heat 8043813); Temperature = 1200°F.

ORNL DWG. 72-12771

INGREDIENTS OF EQUATION-OF-STATE CREEP REPRESENTATIONS

1. Uniaxial Creep Relation
2. Multiaxial Flow Rule
3. Hardening Law for Variable Load Conditions

TIME-DEPENDENT (CREEP) BEHAVIOR

1. Constant-uniaxial-stress creep equation:

$$\epsilon^c(\sigma,T,t) = \epsilon_t(\sigma,T)\left[1 - e^{-r(\sigma,T)t}\right] + \dot{\epsilon}_m(\sigma,T)t\,.$$

2. Multiaxial constitutive equations:

$$\dot{\epsilon}^c_{ij} = \lambda\,\sigma'_{ij}\,.$$

Define

$$\bar{\sigma}^2 = 3J'_2 = \frac{3}{2}\sigma'_{ij}\,\sigma'_{ij}\,,$$

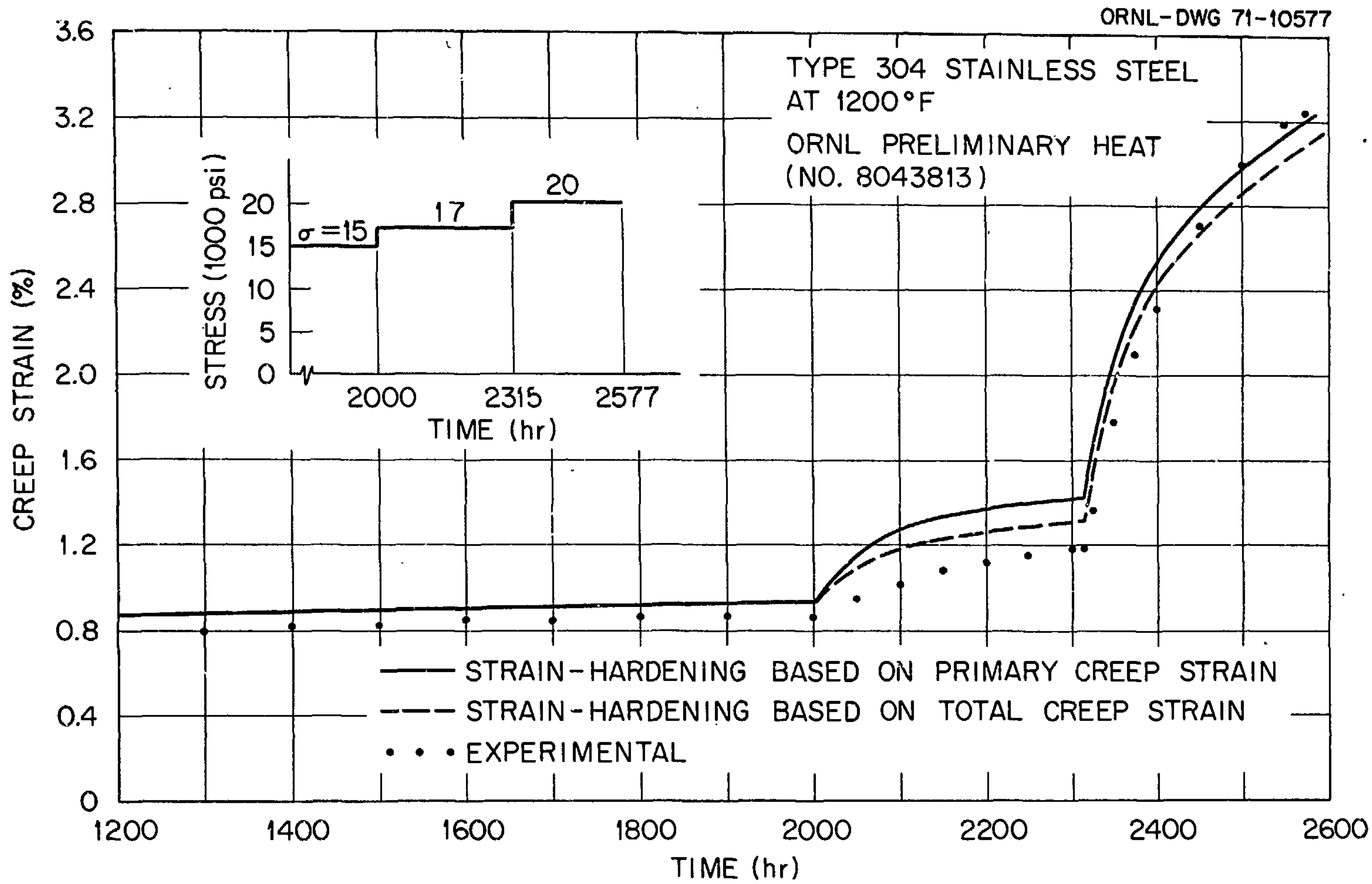
$$\bar{\epsilon}^2 = \frac{4}{3}I_2 = \frac{2}{3}\epsilon^c_{ij}\,\epsilon^c_{ij}\,.$$

Write:

$$\dot{\epsilon}^c_{ij} = \frac{3}{2}\,\frac{\dot{\bar{\epsilon}}(\bar{\sigma},t,T)}{\bar{\sigma}}\,\sigma'_{ij}\,.$$

3. For strain-hardening law:

$$\dot{\epsilon}^c_{ij} = \frac{3}{2}\,\frac{\dot{\bar{\epsilon}}(\bar{\sigma},\bar{\epsilon},T)}{\bar{\sigma}}\,\sigma'_{ij}\,.$$


ORNL-DWG 71-10577
TYPE 304 STAINLESS STEEL
AT 1200°F
ORNL PRELIMINARY HEAT
(NO. 8043813)
STRESS (1000 psi)
σ = 15
17
20
2000
2315
2577
TIME (hr)
CREEP STRAIN (%)
STRAIN-HARDENING BASED ON PRIMARY CREEP STRAIN
STRAIN-HARDENING BASED ON TOTAL CREEP STRAIN
EXPERIMENTAL
TIME (hr)

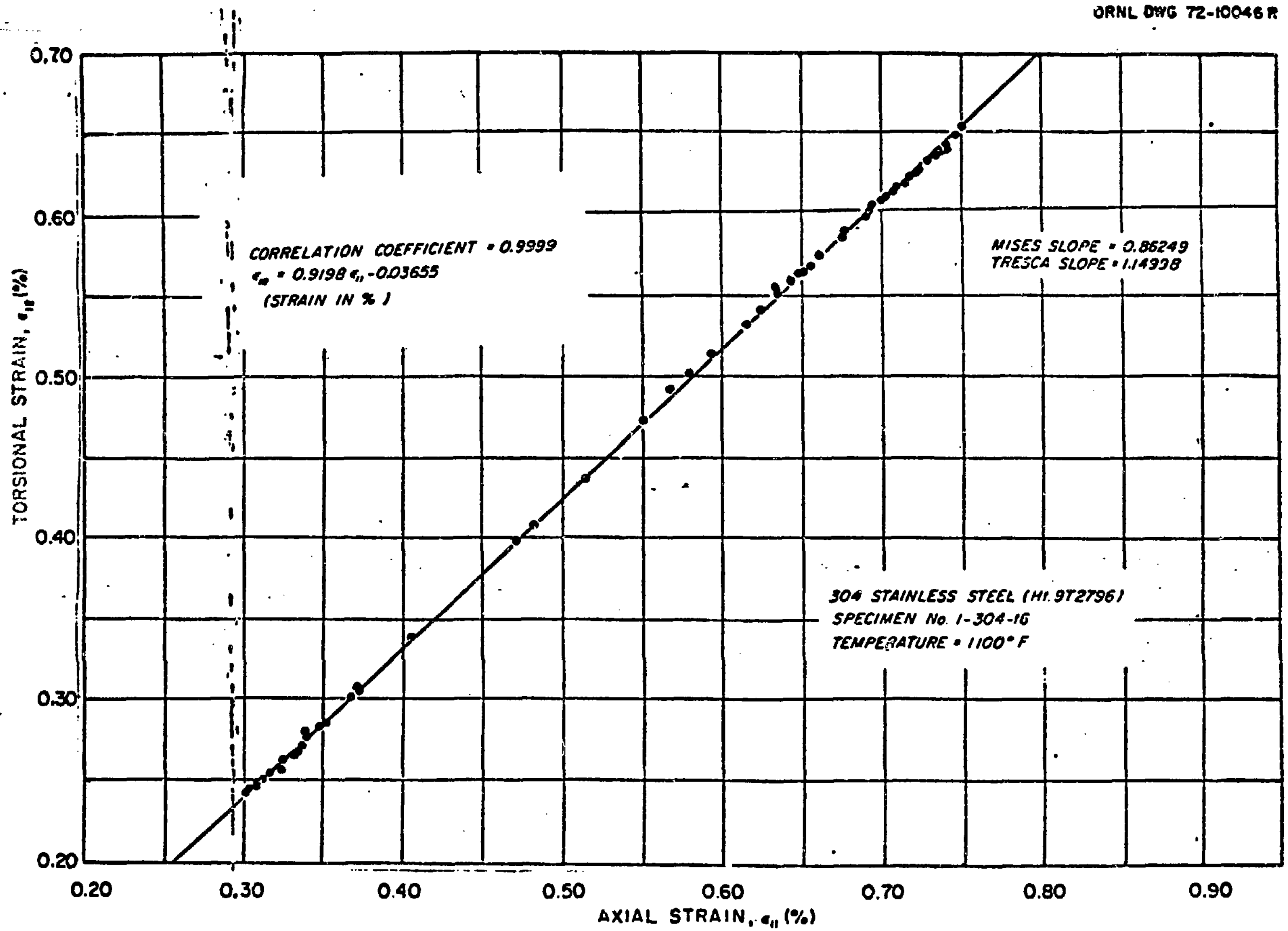
SLIDE 29

ORNL DWG. 72-12770

Creep Strain Ratios for Combined Tension-Torsion Loadings – Type 304 Stainless Steel (Ht. 9T2796), 1100°F

Test No.	Axial Stress, σ (ksi)	Torsional Stress, τ (ksi)	Effective Stress, $\bar{\sigma}$ (ksi)	Stress Ratio, τ/σ	Creep Strain Ratio: Torsion/Axial $\epsilon_{12}/\epsilon_{11}$	
					Observed	Predicted
1	10.628	6.111	15.00	0.575	0.92	0.862
2	13.975	3.407	15.17	0.244	0.37	0.366
3	5.570	7.934	14.83	1.424	2.18	2.137

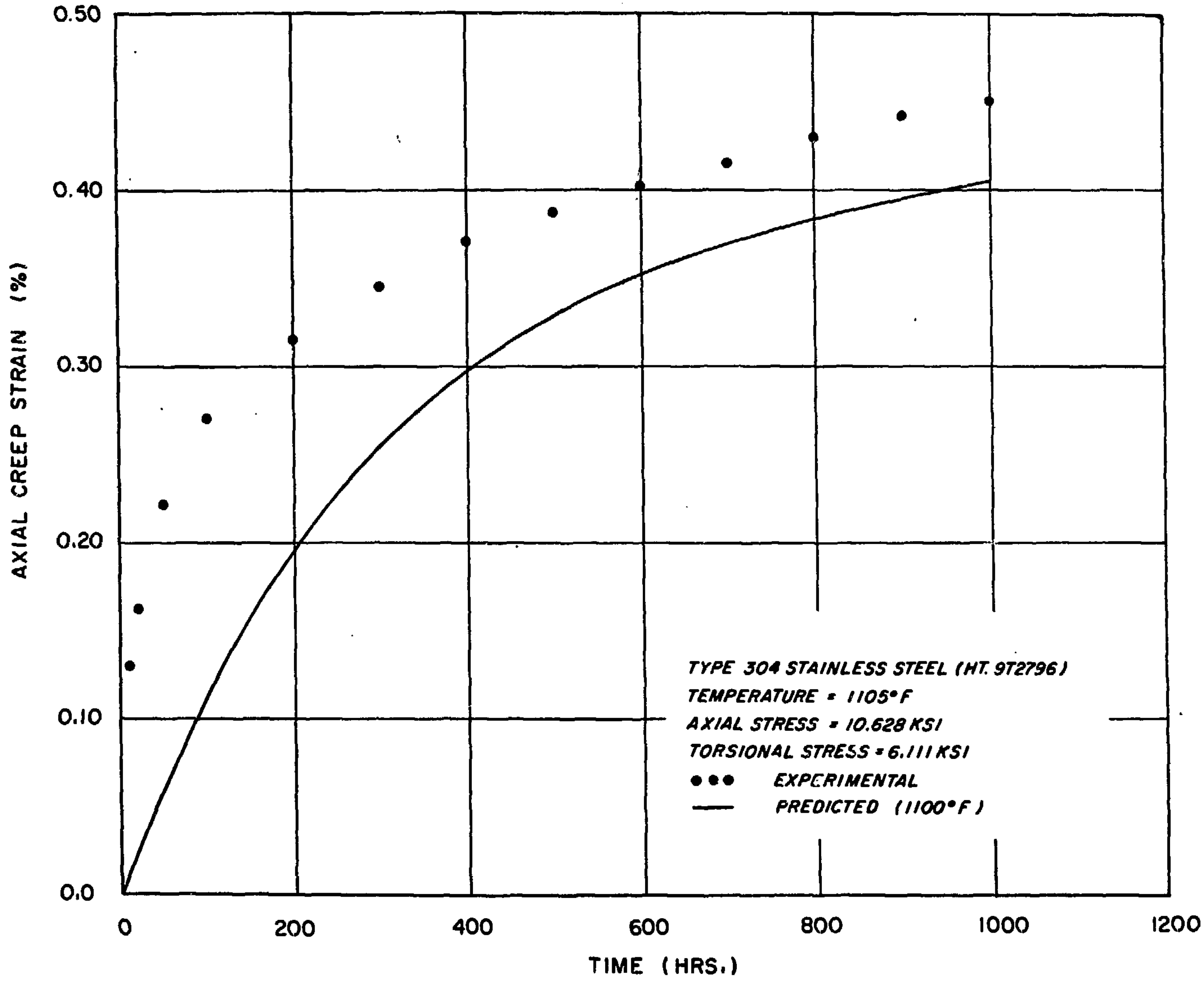
SLIDE 30



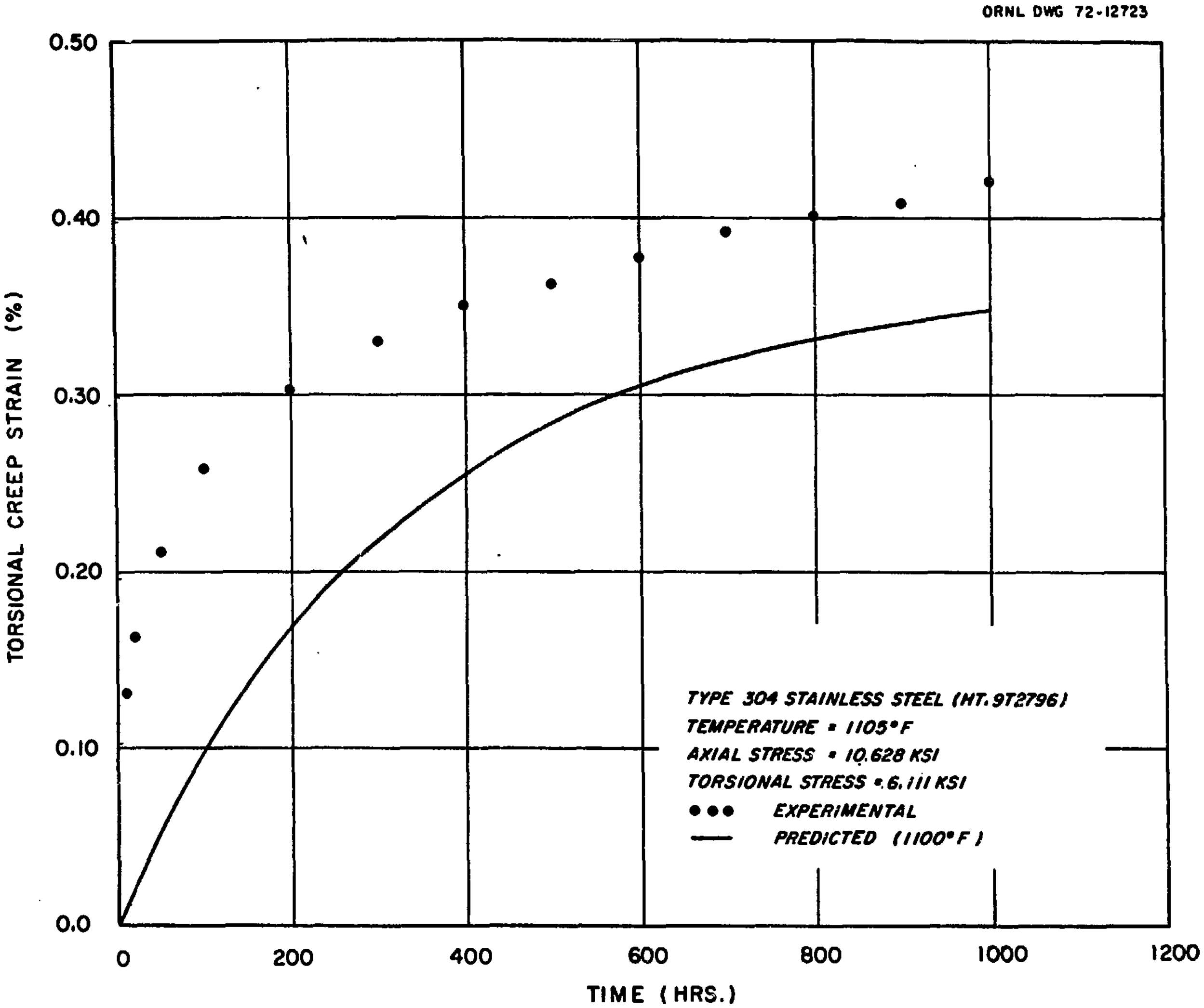
ORNL DWG 72-10046 R
CORRELATION COEFFICIENT = 0.9999
ε₁₂ = 0.9198 ε₁₁ - 0.03655
(STRAIN IN %)
MISES SLOPE = 0.86249
TRESCA SLOPE = 1.14998
304 STAINLESS STEEL (Ht. 9T2796)
SPECIMEN No. 1-304-16
TEMPERATURE = 1100° F
TORSIONAL STRAIN, ε₁₂ (%)
AXIAL STRAIN, ε₁₁ (%)
0.70
0.60
0.50
0.40
0.30
0.20
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90

SLIDE 31

ORNL DWG 72-12722

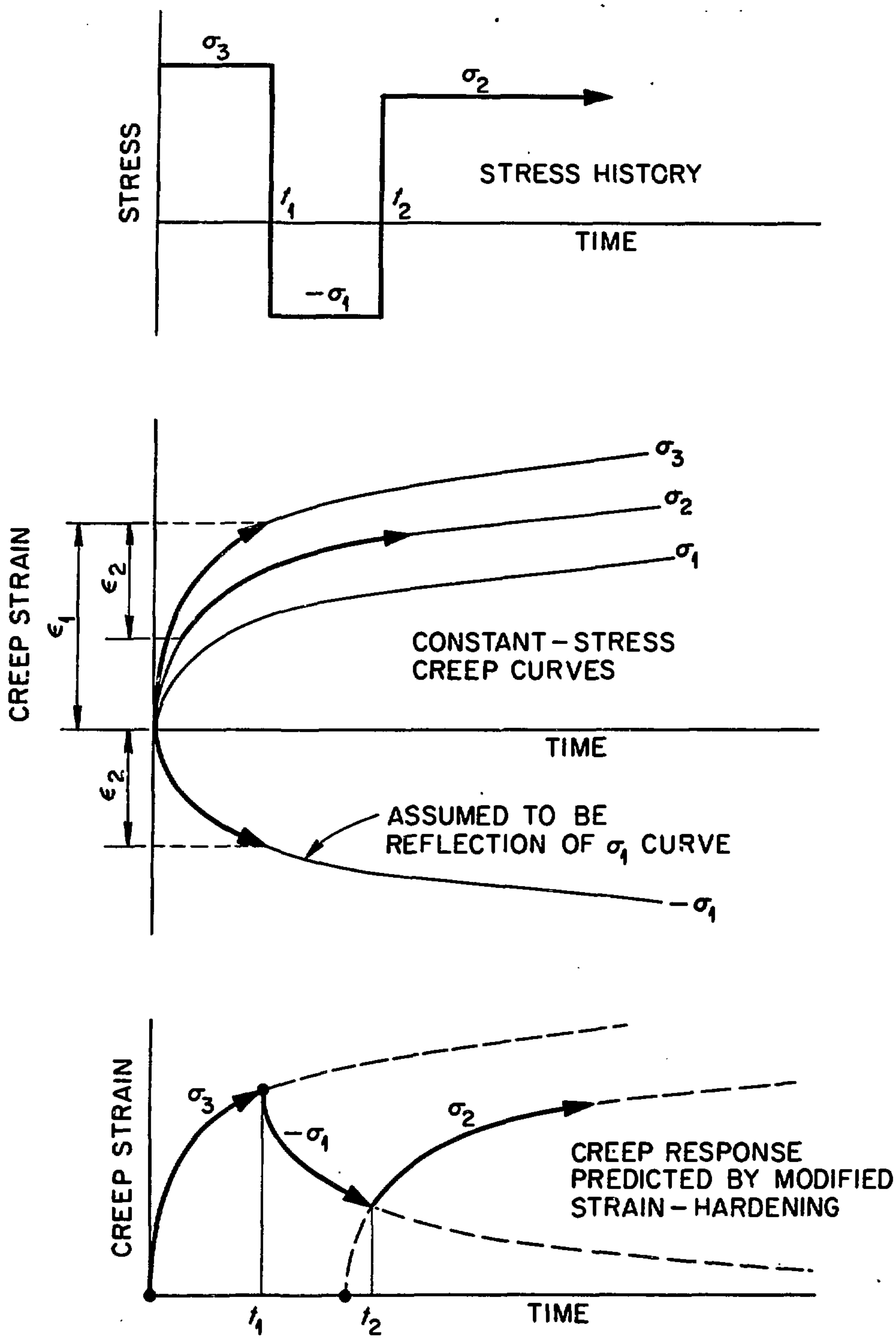


SLIDE 32


ORNL DWG 72-12723
TORSIONAL CREEP STRAIN (%)
0.50
0.40
0.30
0.20
0.10
0.0
0
200
400
600
800
1000
1200
TIME (HRS.)
TYPE 304 STAINLESS STEEL (HT. 9T2796)
TEMPERATURE = 1105°F
AXIAL STRESS = 10.628 KSI
TORSIONAL STRESS = 6.111 KSI
EXPERIMENTAL
PREDICTED (1100°F)

50 80%

ORNL-DWG 71-10680



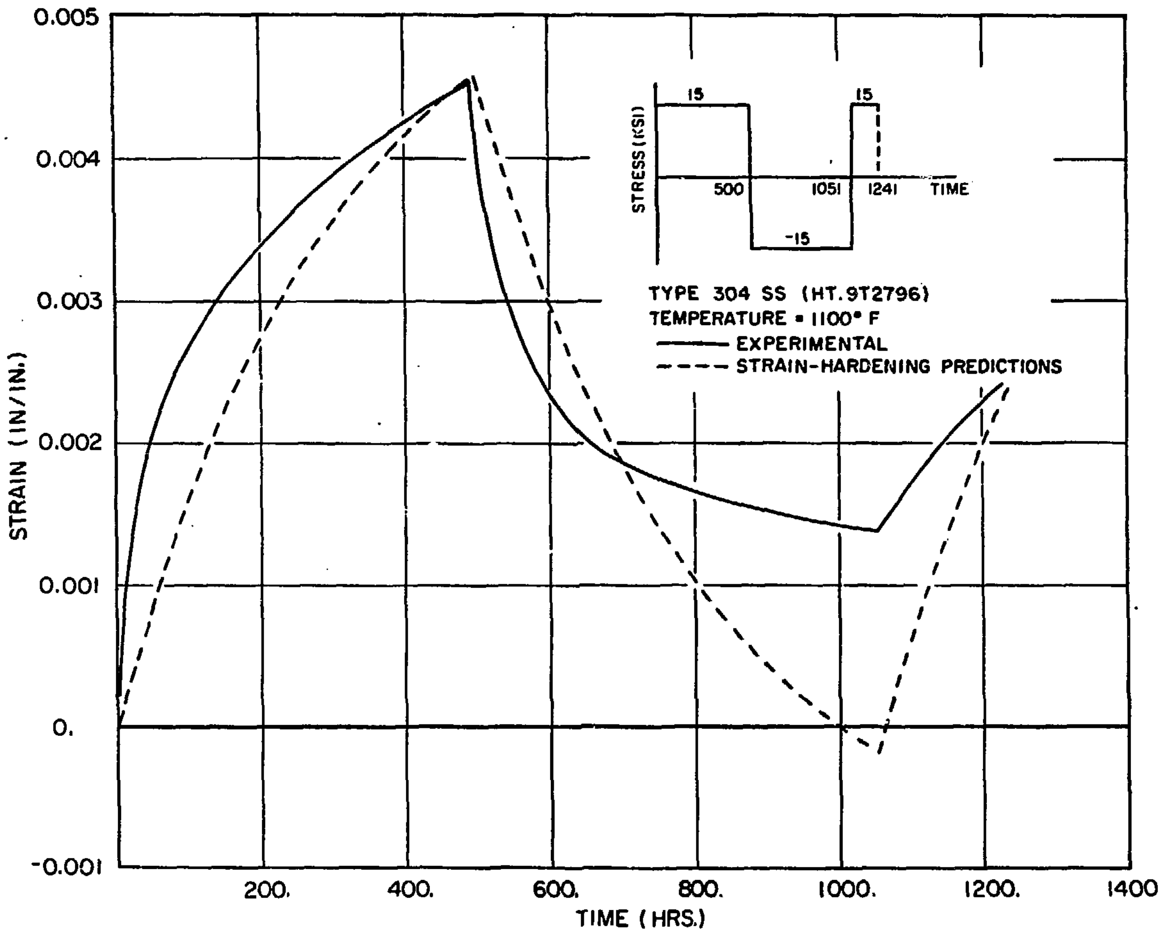
SLIDE 34

4

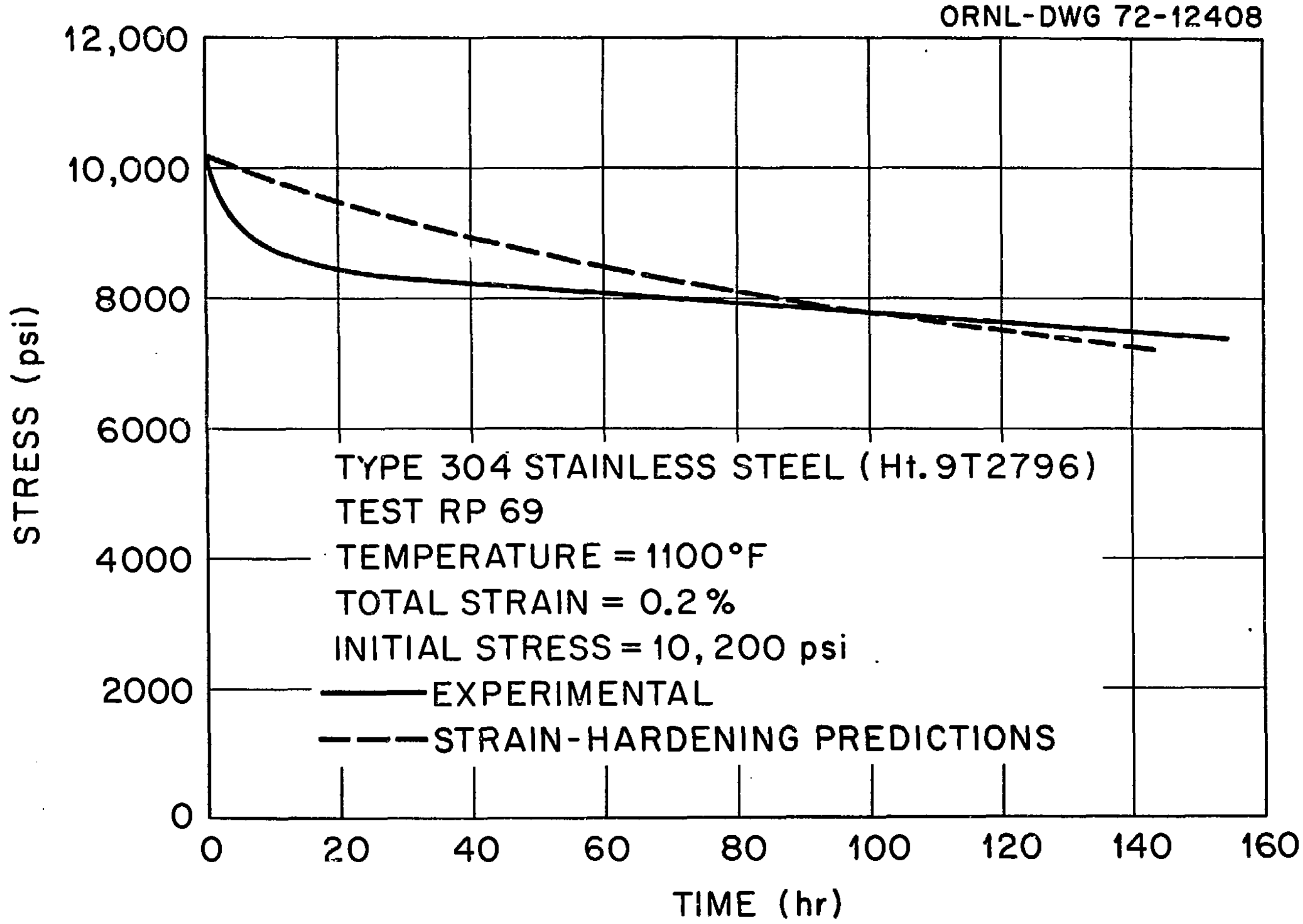
80%

Fig. 4.2

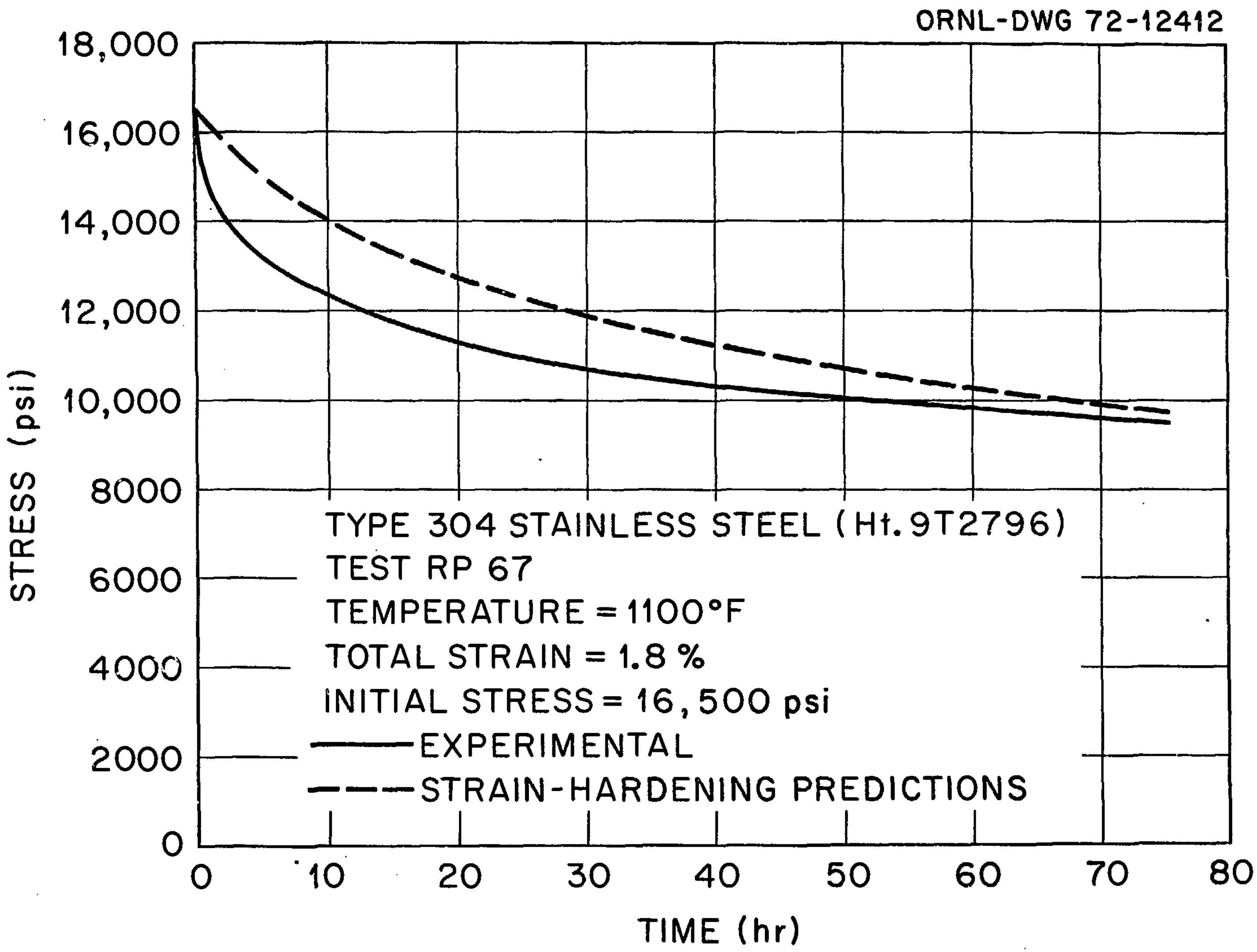
ORNL DWG 72-12265



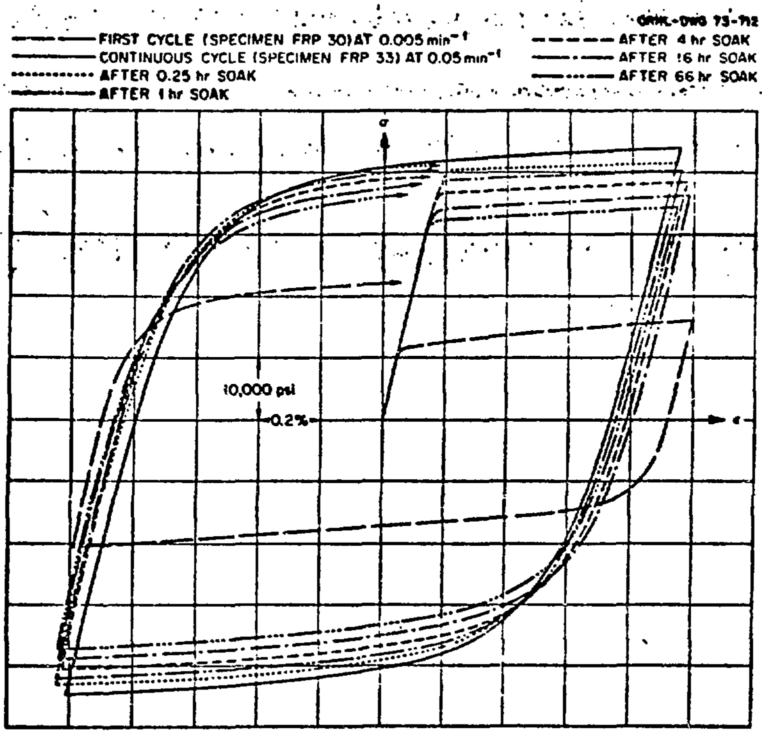
SLIDE 35


ORNL-DWG 72-12408
12,000
10,000
8000
6000
4000
2000
0
STRESS (psi)
TYPE 304 STAINLESS STEEL (Ht. 9T2796)
TEST RP 69
TEMPERATURE = 1100°F
TOTAL STRAIN = 0.2 %
INITIAL STRESS = 10, 200 psi
EXPERIMENTAL
STRAIN-HARDENING PREDICTIONS
0
20
40
60
80
100
120
140
160
TIME (hr)

SLIDE 36


ORNL-DWG 72-12412
18,000
16,000
14,000
12,000
10,000
8000
6000
4000
2000
0
STRESS (psi)
0
10
20
30
40
50
60
70
80
TIME (hr)
TYPE 304 STAINLESS STEEL (Ht. 9T2796)
TEST RP 67
TEMPERATURE = 1100°F
TOTAL STRAIN = 1.8 %
INITIAL STRESS = 16,500 psi
EXPERIMENTAL
STRAIN-HARDENING PREDICTIONS

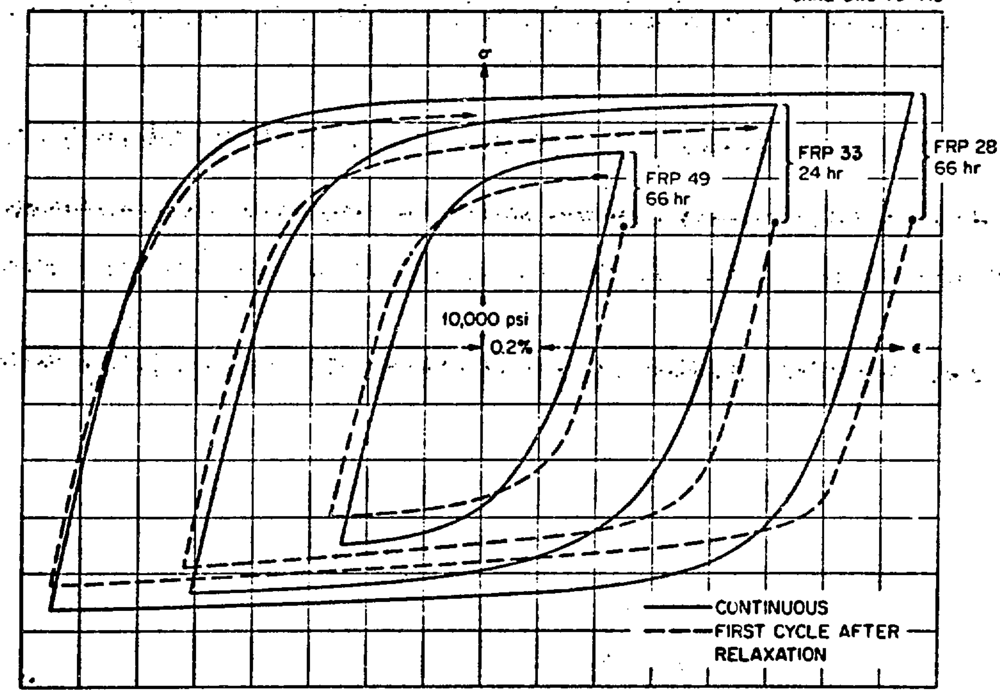
SLIDE 37



Effect of Soaking at Zero Stress and Strain on the Subsequent Cyclic Curve at 1100°F and 2% Strain Range. Type 304 Stainless Steel Heat 9T2796 (Re-annealed at 2000°F for ½ hr).

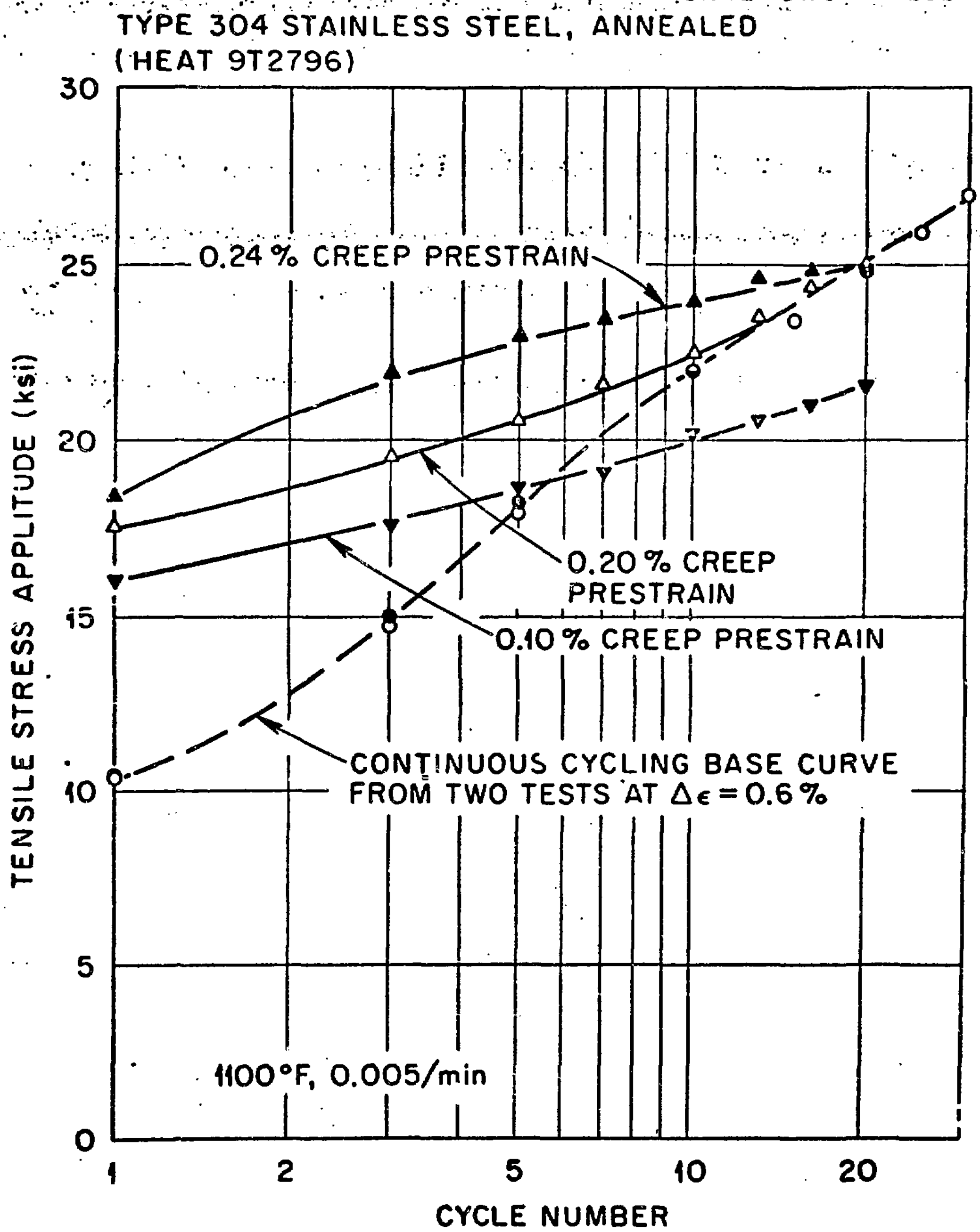
SLIDE 38

ORNL-DWG 73-713

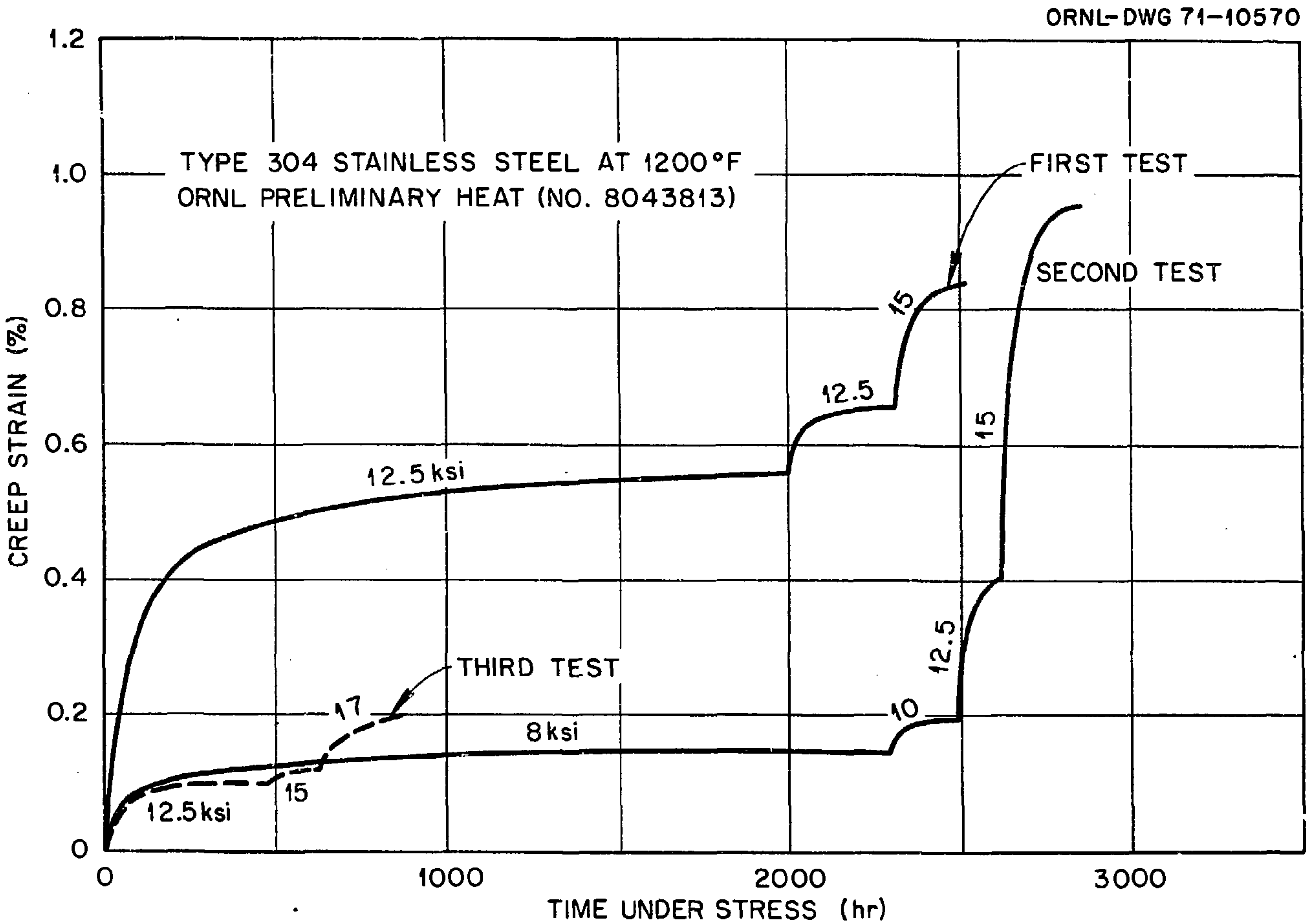


Effect of Relaxation at the Tensile Strain Limit on the Subsequent Cyclic Curve at 1100°F and Three Cyclic Strain Ranges. Type 304 Stainless Steel Heat 9T2796 (Re-annealed at 2000°F for ½ hr).

ORNL-DWG 73-2825



SLIDE 40


ORNL-DWG 71-10570
TYPE 304 STAINLESS STEEL AT 1200°F
ORNL PRELIMINARY HEAT (NO. 8043813)
FIRST TEST
SECOND TEST
THIRD TEST
CREEP STRAIN (%)
TIME UNDER STRESS (hr)
12.5 ksi
12.5
15
15
12.5
10
8 ksi
17
15
12.5 ksi
1.2
1.0
0.8
0.6
0.4
0.2
0
0
1000
2000
3000

SLIDE 41

ORNL-DWG 72-12420

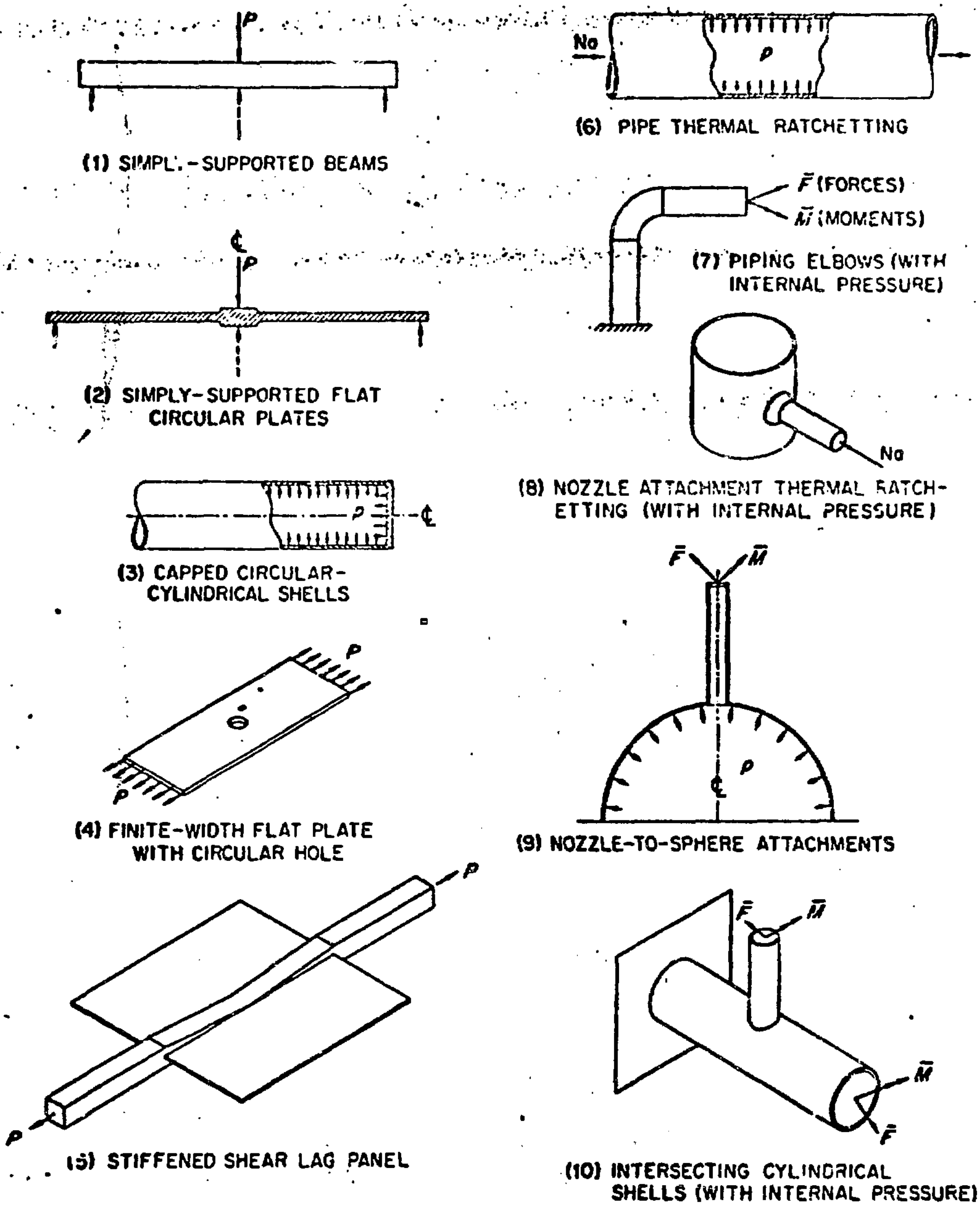
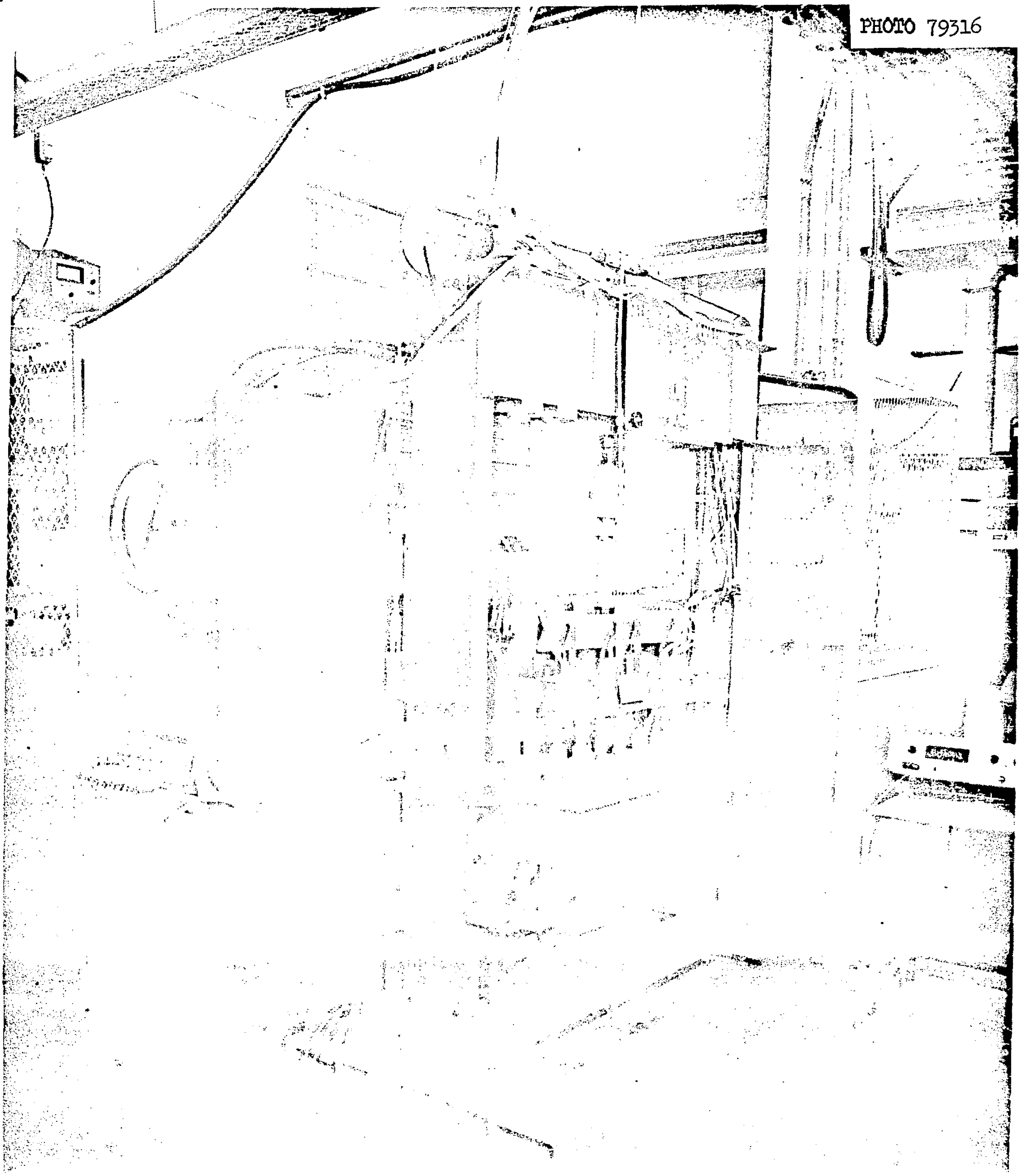


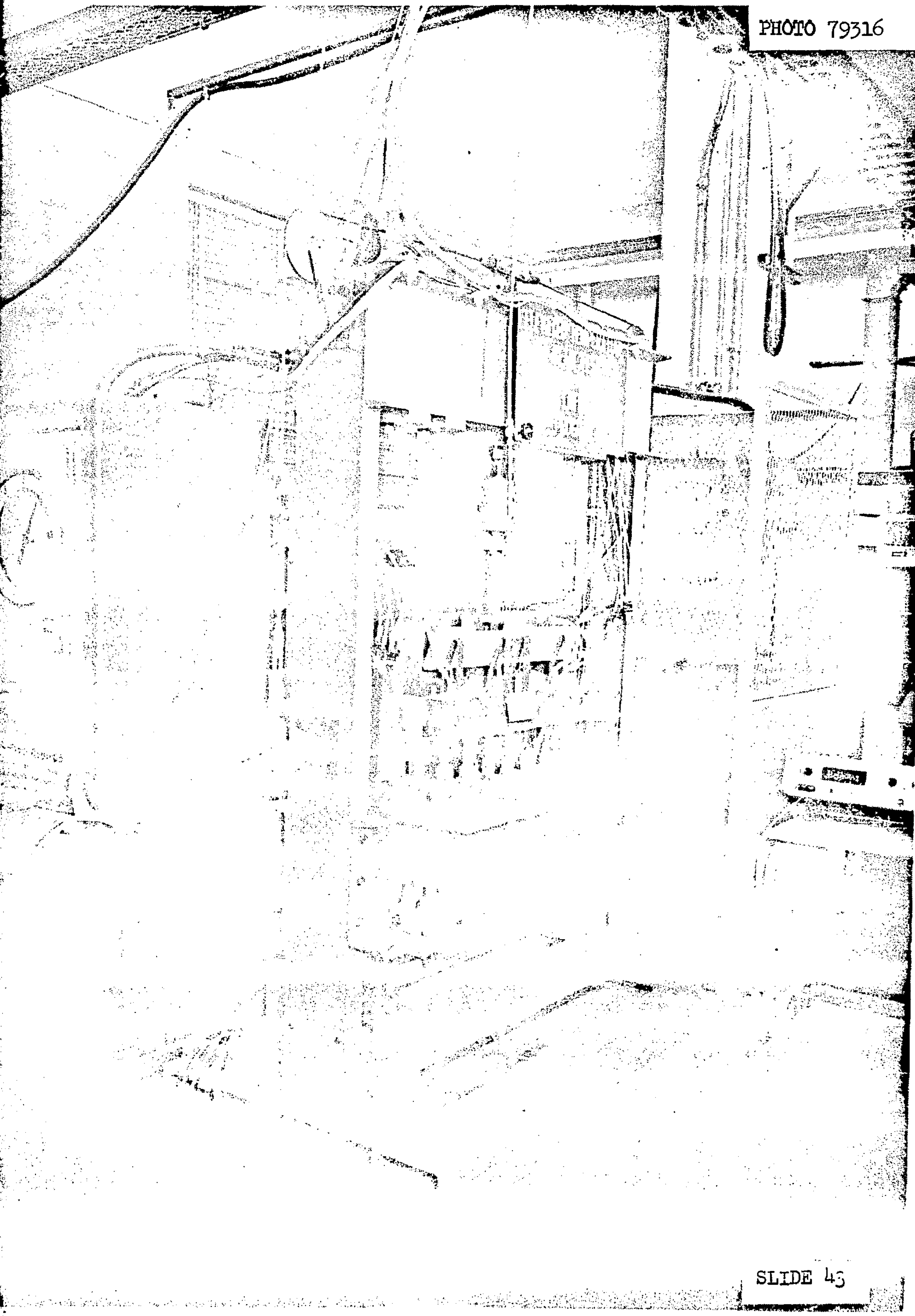
PHOTO 79316



SLIDE 43

5.4

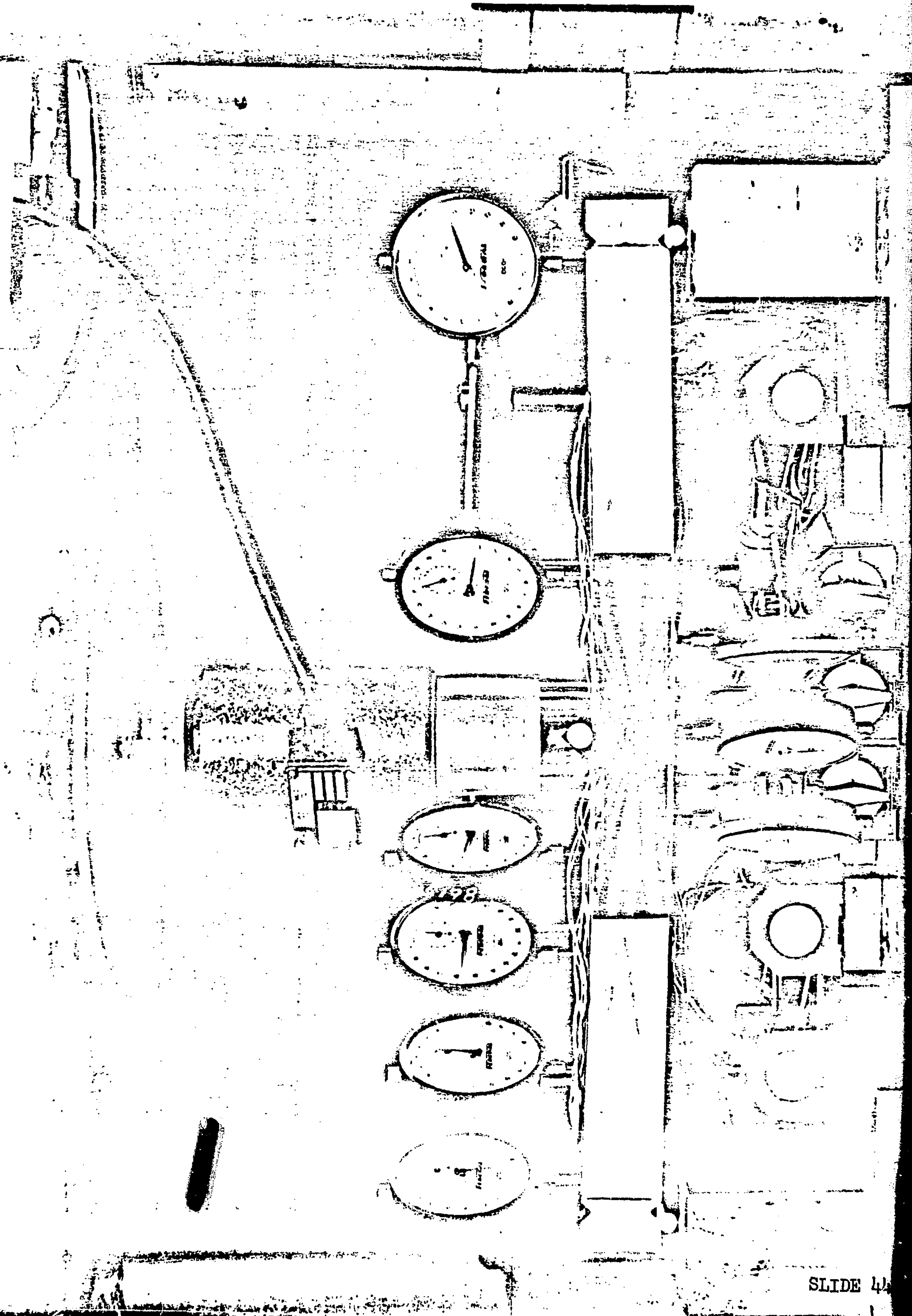
PHOTO 79316



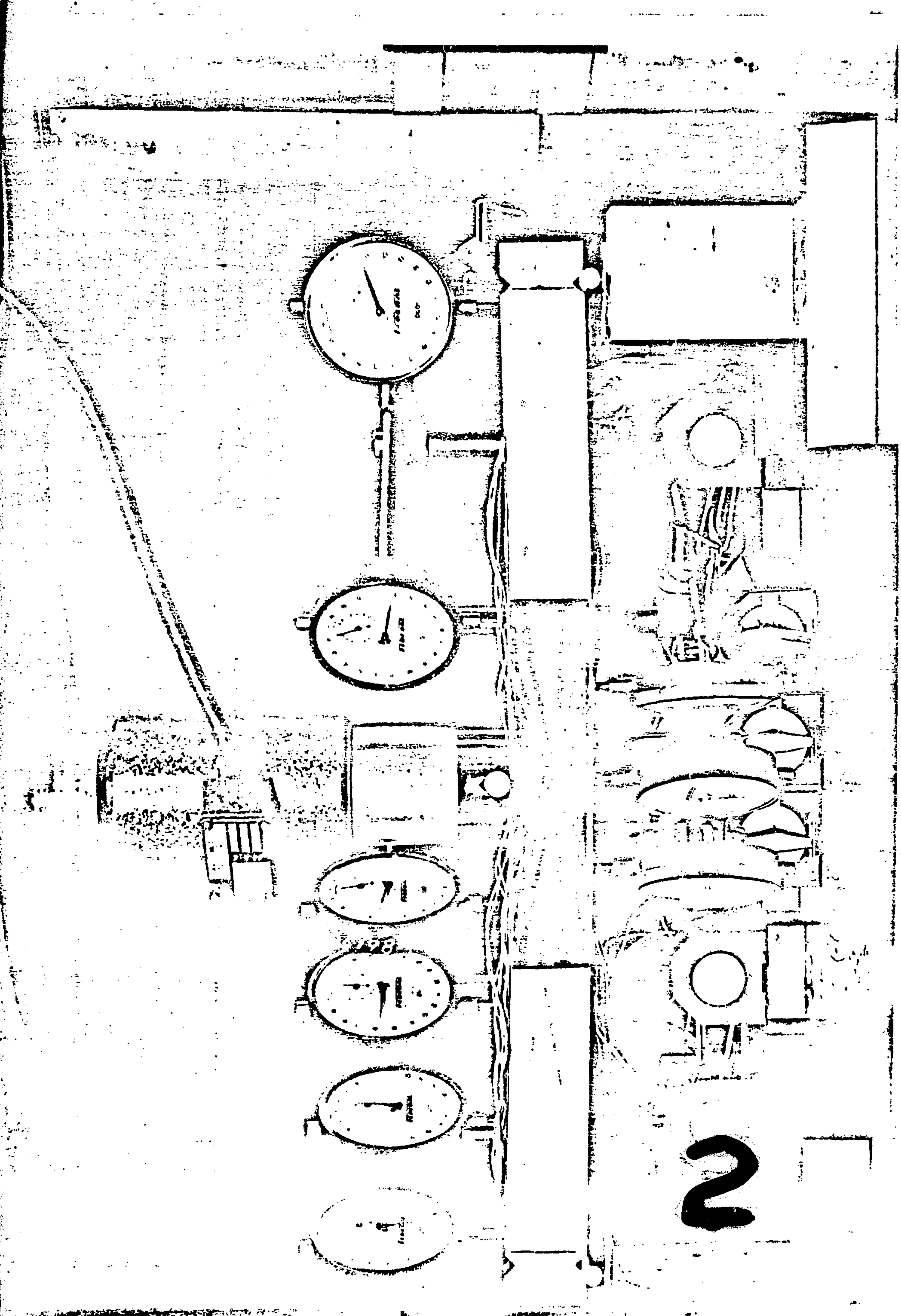
SLIDE 43

2

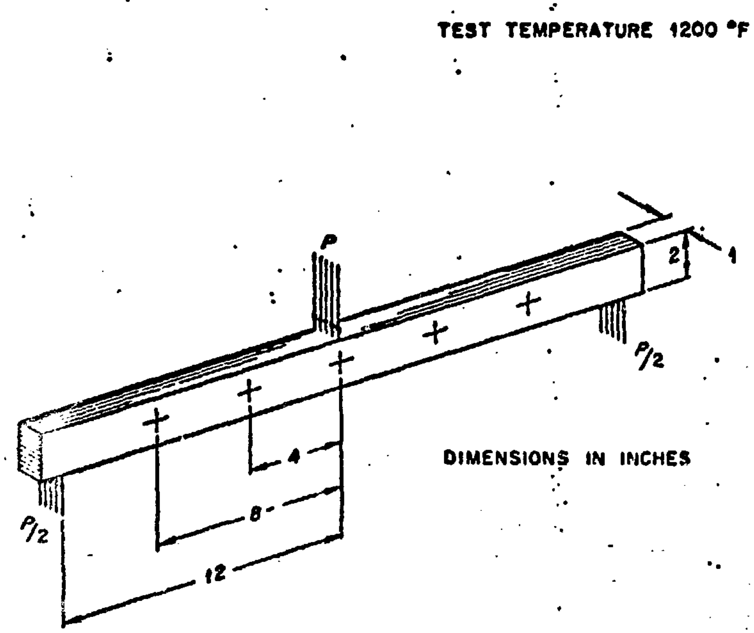
PHOTO 78124



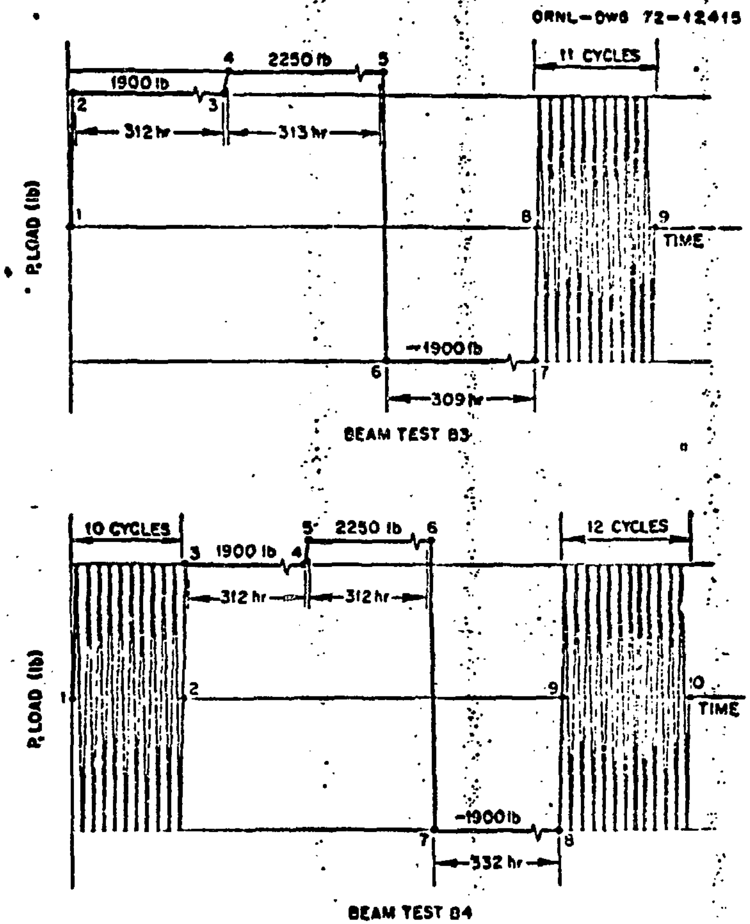
SLIDE 44



SLIDE 44



(a) TEST SPECIMEN

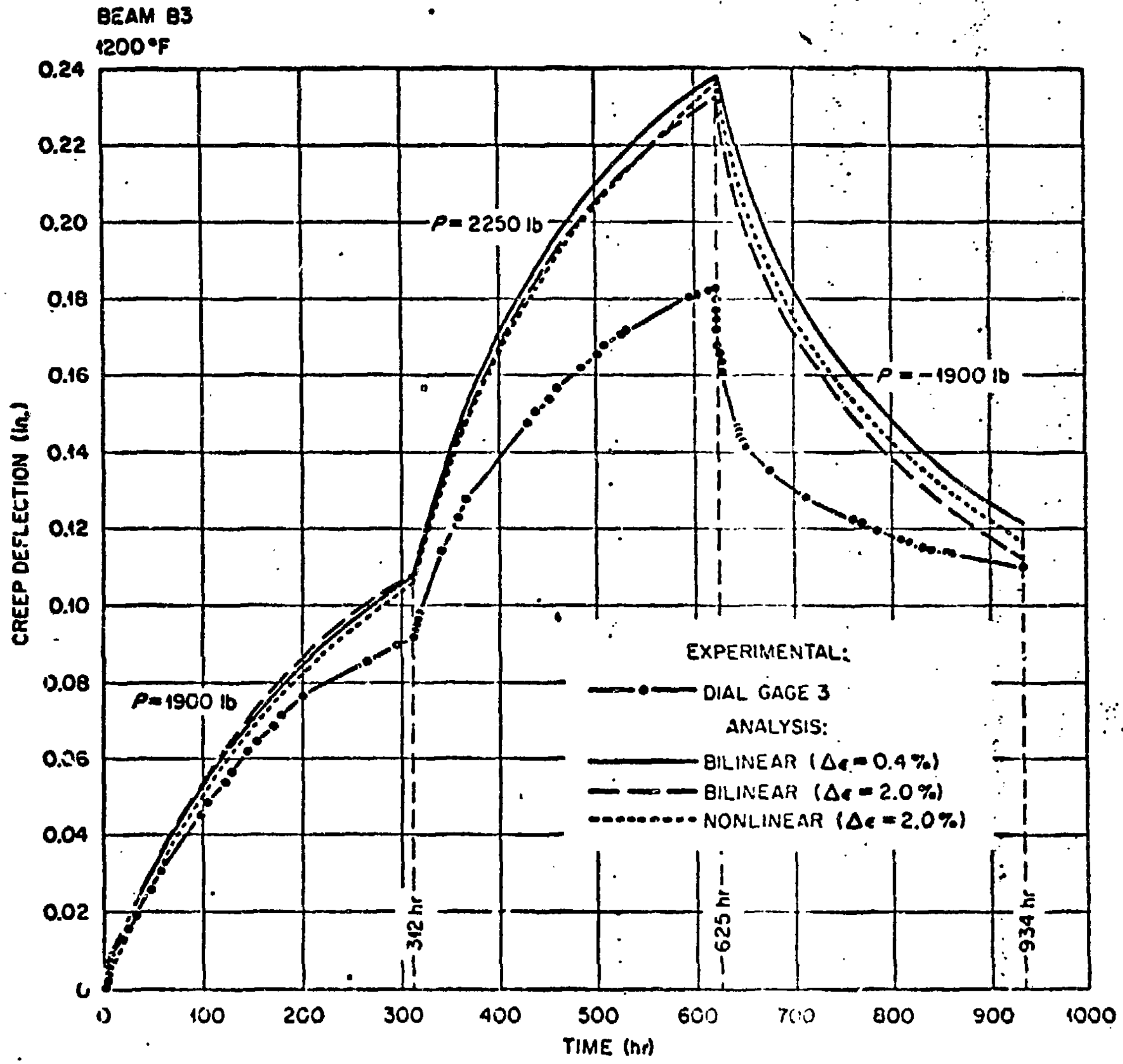


(b) LOADING HISTORIES

Elevated-Temperature Beam Tests.

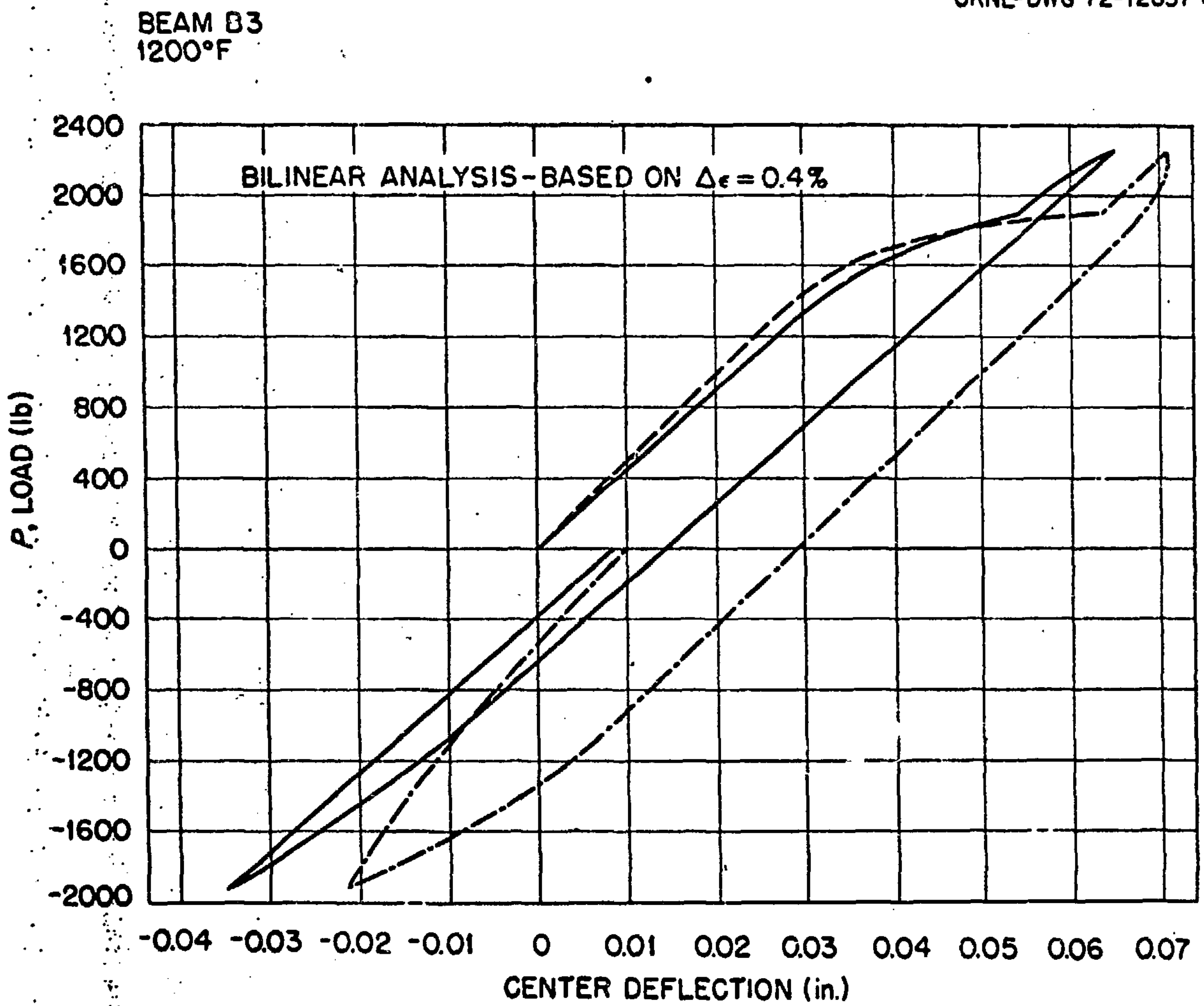
SLIDE 45

ORNL-DWG 72-10066A



SLIDE 46

ORNL-DWG 72-12837 R



SLIDE 47

ORNL DWG. 73-3404

Areas Requiring Research and Development

MATERIAL BEHAVIOR

- Representation of Multiaxial Behavior for General Load Histories
  - Plasticity
  - Creep
  - Plasticity-Creep Interaction
- Creep-Fatigue
- Strain Limits
- Environmental Effects
- Fracture Mechanics

ANALYSIS METHODS

- Development of Efficient General Procedures for Treating Inelastic Behavior

STRUCTURAL TESTING

- High-Temperature Instrumentation
- Basic High-Temperature Tests – Deformation and Failure