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Potential for Time Compression in Creep-Fatigue Property Evaluation

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DARPA CREEP-FATIGUE DAMAGE MODELS WORKSHOP

Marriott Waterfront Hotel
Annapolis, MD
April 23-24, 2001

THE ISSUE

Reduce evaluation time to characterize Creep-Fatigue resistance of new materials

THE APPROACH

Demonstrate short-cuts deriving from a current Creep-Fatigue Crack Initiation Model (SRP)

OUTLINE

0 - INTRODUCTORY STATEMENT

0 - CLASSIFICATION OF 100 EXISTING CREEP-FATIGUE MODELS

- 3 Most Widely Developed for Engineering Use
- Multiple Models Associated with StrainRange Partitioning (SRP)
- Examples of Impetus to Pursue SRP
- Mental-Crutch Model of SRP Cycles

0 - STRAINRANGE PARTITIONING (SRP) APPROACH

- Based on Physical Strain Concepts
- Separates Flow (Rheological) and Failure (Cracking/Fracture) Behavior
- Flow behavior - Inelasticity partitioned into creep/plasticity strains
- Failure behavior - Capacity for damage (inelastic strainrange vs. life)

0 - INELASTIC STRAINRANGE SRP -- LIFE EXTRAPOLATION APPROACHES

- Ductility Normalized Life Relations
- Time-dependent Life Relations

0 - TOTAL STRAIN VERSION OF SRP

- Applicable to Low-Strain/Long-Life Regime
- Enhances Ability to Extrapolate

0 - SUMMARY

0 - REFERENCES

CLASSIFICATION OF 100 CREEP-FATIGUE MODELS
-- 13 OVERLAPPING CATEGORIES

0 - STRESS-LIFE DIAGRAMS

0 - STRAINRANGE - LIFE MODELS

0 - DUCTILITY EXHAUSTION

0 - HYSTERESIS ENERGY MODELS

0 - TIME-TO-FAILURE MODELS

0 - LIFE OR DAMAGE FRACTION RULES

0 - FREQUENCY EFFECT EQUATIONS

0 - DAMAGE RATE MODELS

0 - DAMAGE MECHANICS

0 - CRACK GROWTH

0 - MACRO-PHENOMENOLOGICAL MODELS

0 - MICROMECHANISTIC MODELS

0 - STRAINRANGE PARTITIONING

Ref. Halford, 1991

3 MOST WIDELY DEVELOPED MODELS

0 - TIME-FRACTION (Creep) + CYCLE-FRACTION (Fatigue)
- *ASME CODE, USA*

0 - DAMAGE MECHANICS (Damage erodes load bearing area)
- *ONERA, FRANCE*

0 - STRAINRANGE PARTITIONING (Separates creep & plasticity)
- *NASA-GLENN, USA*

Ref. Halford, 1991

STRAINRANGE PARTITIONING (SRP)

0 - Based on **PHYSICALLY SIGNIFICANT** Strain Components

0 - Separates **FLOW** and **FAILURE** (Cracking/Fracture)

- **FLOW** (Inelastic Strain) is Partitioned into Creep and Plastic Strains

- **FAILURE** (Cracking/Fracture) is resistance to repeated inelastic strain range

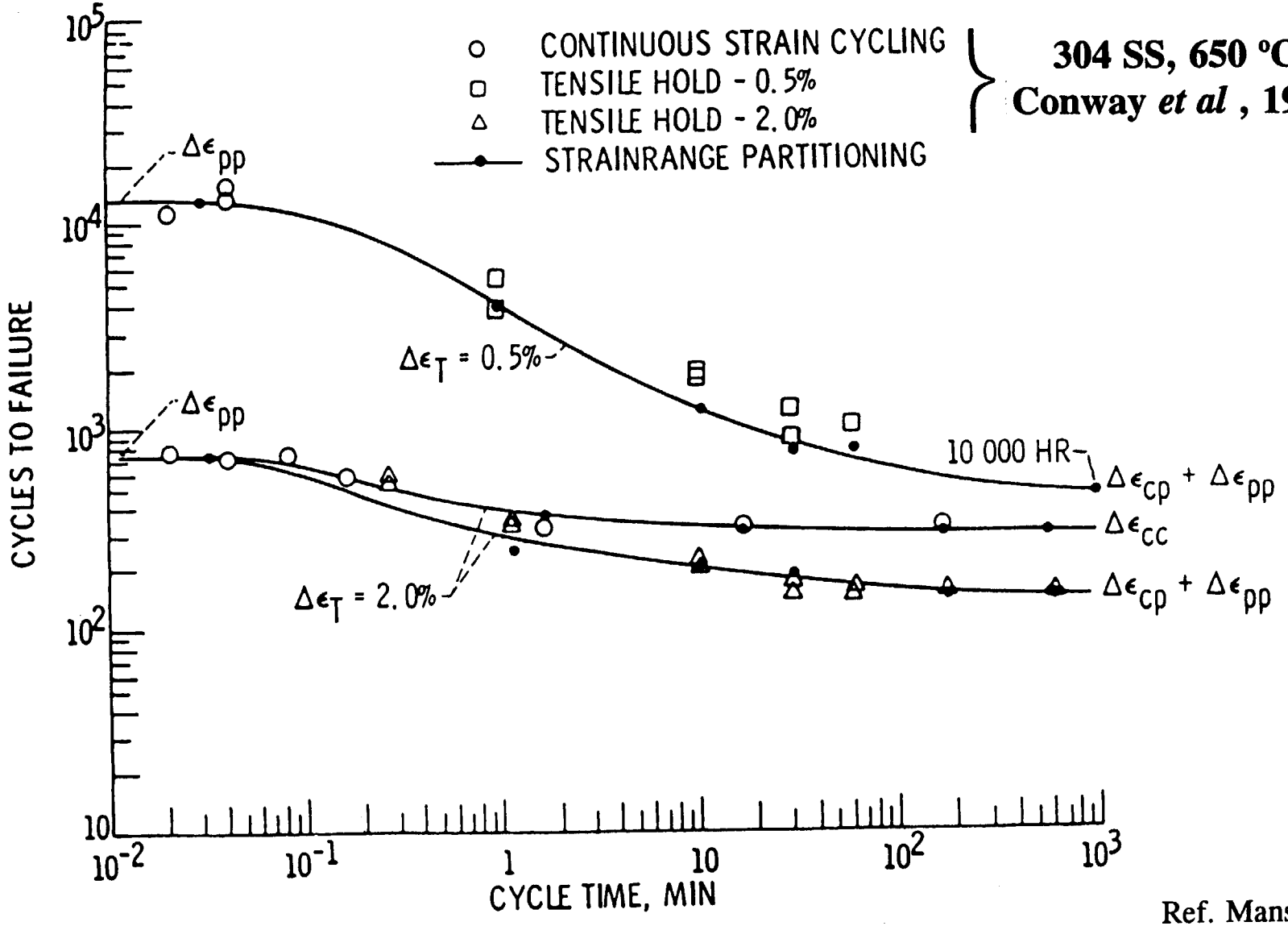
STRAINRANGE PARTITIONING - Specialty Versions

SRP Strainrange Partitioning/Manson, Halford & Hirschberg (1971)
IDR-SRP Interaction Damage Rule, SRP/Manson (1973)
PDR-SRP Product Damage Rule, SRP/Annis et al. (1976)
ITF-SRP Inelastic Thermal Fatigue, SRP/Halford & Manson (1976)
DEX-SRP Linear Ductility Exh., SRP/Manson & Halford (1976)
PWA-SRP Pratt & Whitney Combustor, SRP/Vogel et al. (1976)
MAF-SRP Multiaxiality Factor, SRP/Manson & Halford (1977)
DNE-SRP Ductility Normalized Equations, SRP/Halford et al. (1977)
PEM Partitioned Energy Model/Leis (1977)
SRC-SRP Strainrange Conversion Principle, SRP/Manson (1979 & 1983)
MSE-SRP Mean Stress Effects, SRP/ Halford & Nachtigall (1980)
CEP-SRP Combustion Engineering Model, SRP/Lawton (1982)
TS-SRP Total Strain Version of SRP/Halford & Saltsman (1983)
DEP-SRP Diesel Engine Piston, SRP/Saugerud (1983)
NDR-SRP Nonlinear Damage Rule, SRP/Hoffelner et al. (1983)
SEP Strain Energy Partitioning/He et al. (1983)
SDA-SRP Statistical Data Analysis, SRP/Wirsching (1984)
SRL-SRP Statistically Refined Life, SRP/Bicego (1984)
ETM-SRP Exposure Time Modified, SRP/Kalluri & Manson (1985)
SSC-SRP Steady State Creep Rate, SRP/Kalluri et al. (1987)
TFM-SRP Time To Failure Modified SRP/Solomon (1988)
TMF-SRP Thermomechanical Fatigue, TS-SRP/Saltsman & Halford (1988)
FMB-SRP Fracture Mechs Basis of SRP/Kitamura & Halford (1989)
MMC-SRP Metal Matrix Composites, TS-SRP/Halford et al (1993)
AES-SRP Automotive Exhaust Systems Bi-TMF, TS-SRP/Liu et al (2000)
TFAC-SRP Thermal Fatigue of Automotive Components/Ogarevic et al (2001)

Ref. Halford, 1991

IMPETUS FOR SRP

SRP CORRELATION

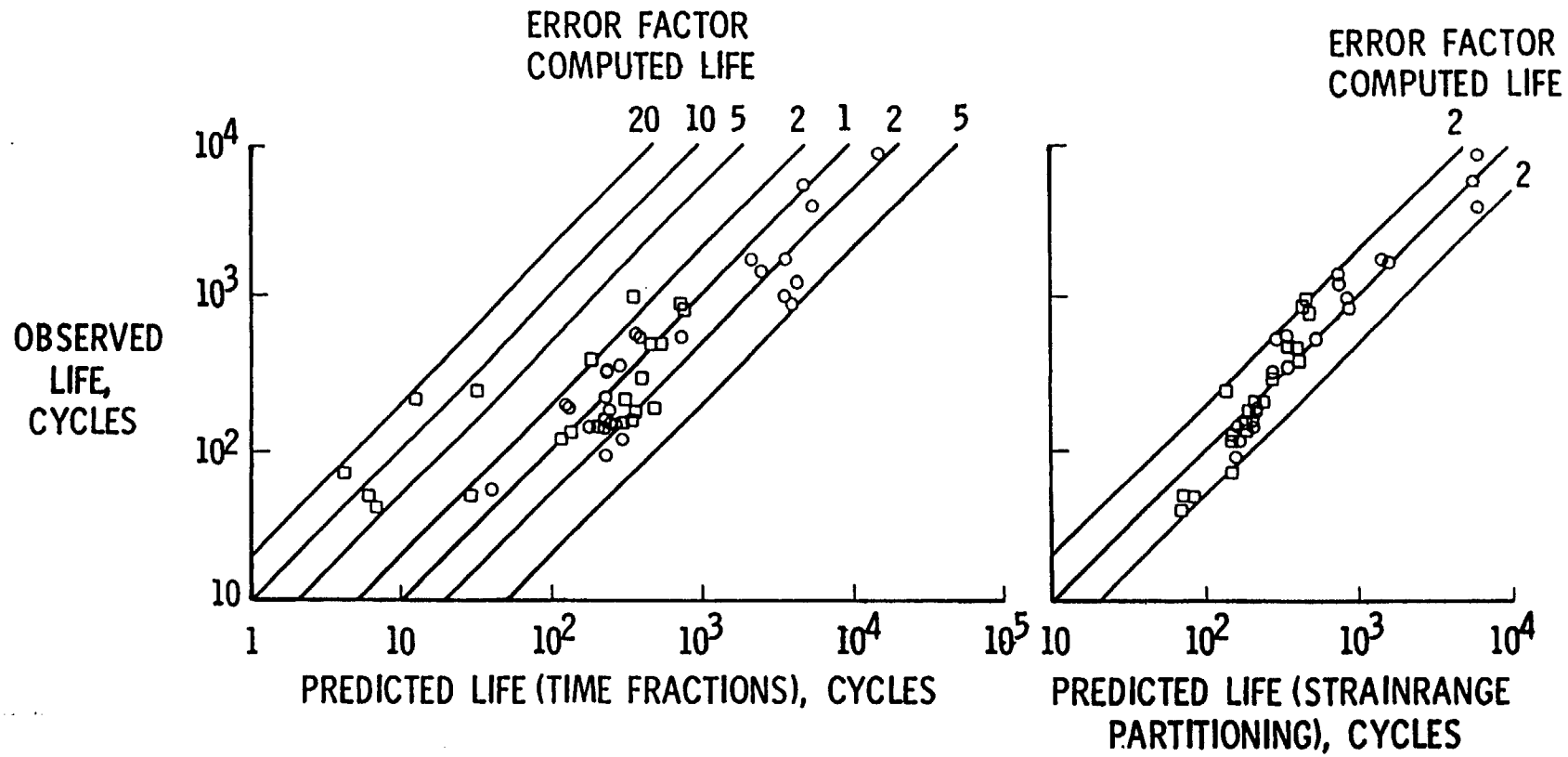


Ref. Manson, 1973

SRP vs. Time- & Cycle-Fraction Rule

□ INCOLOY 800
○ 304 SS

JASKE et al, 1973

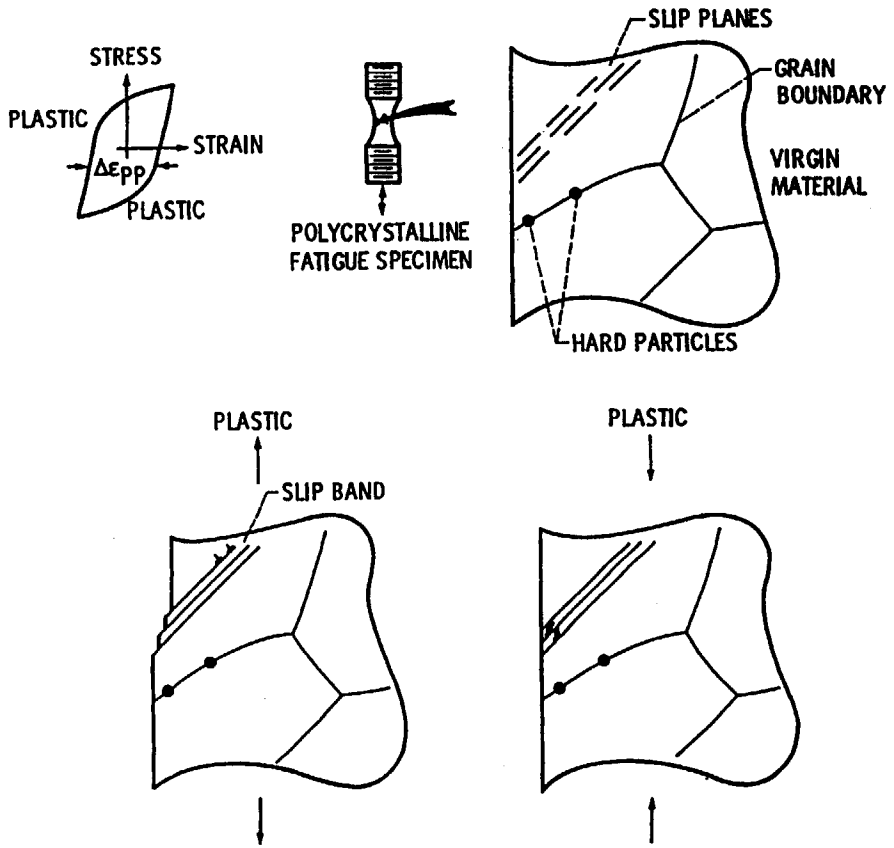


Ref. Manson, 1973

ONE-CYCLE DEFORMATION MODELS

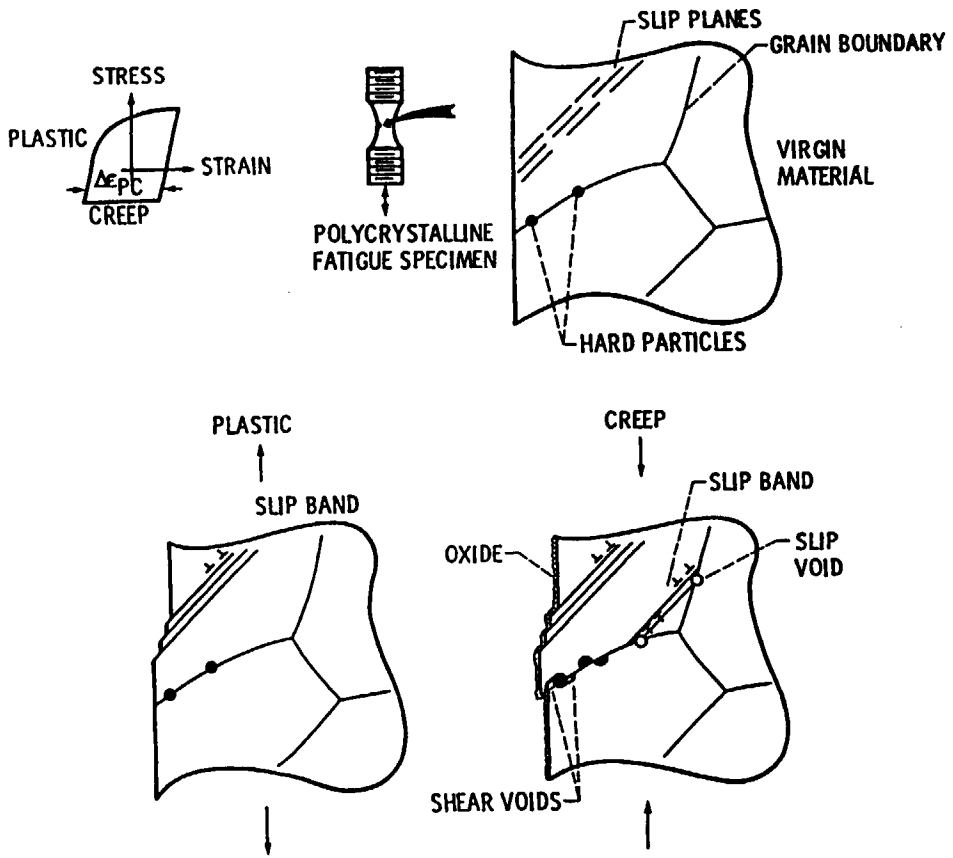
Ref. Manson & Halford

PP Cycle



Ref. Manson & Halford, 1984

PC Cycle



Ref. Manson & Halford, 1984

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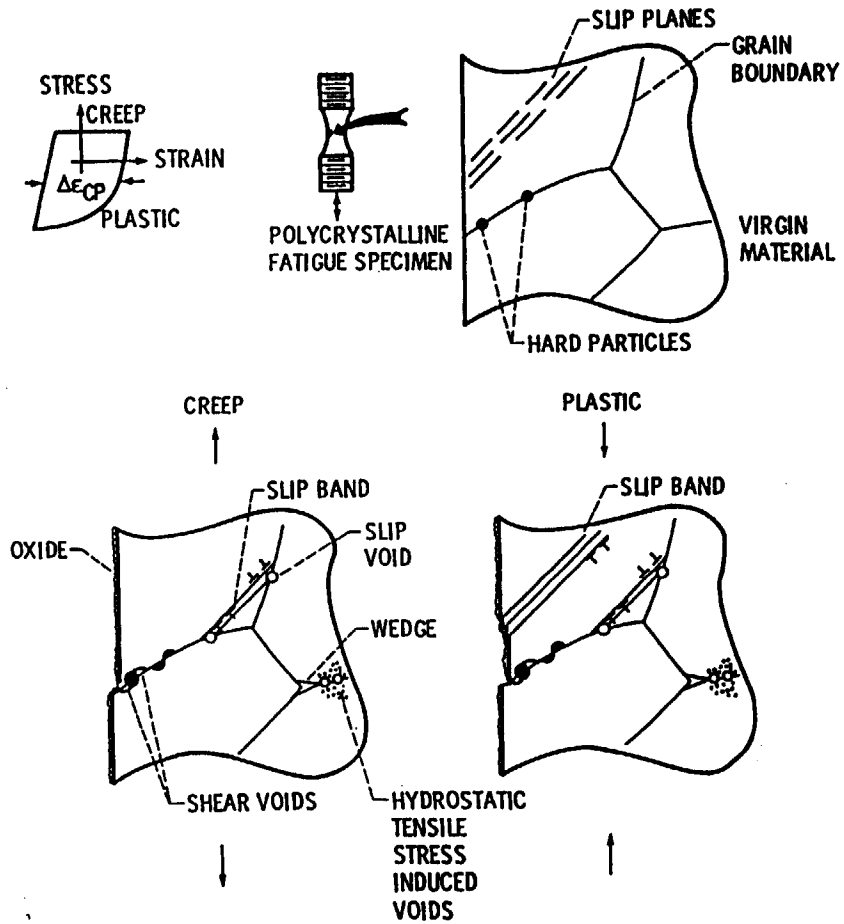
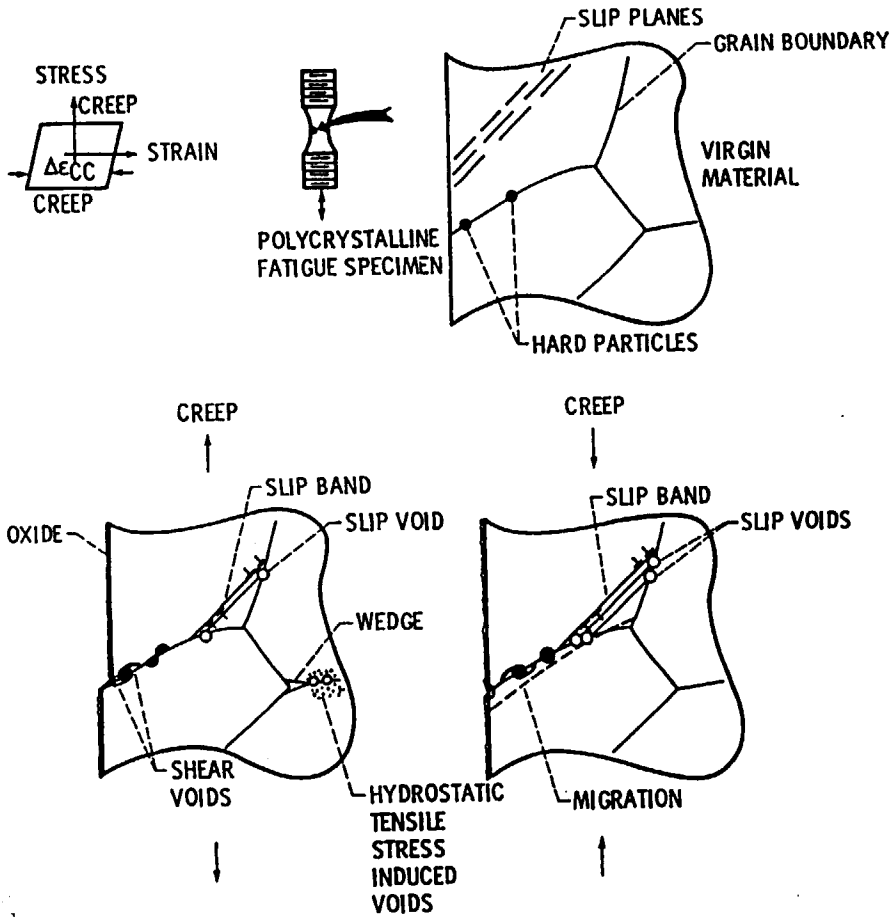


Ref. Manson & Halford, 1984

CC Cycle



Ref. Manson & Halford, 1984

INELASTIC STRAINRANGE SRP

-- LIFE EXTRAPOLATION APPROACHES

0 - DUCTILITY NORMALIZED RELATIONS

- Tensile Plastic Ductility Governs PP and PC Life Relations
- Creep Rupture Ductility Governs CC and CP Life Relations

0 - TIME-DEPENDENT LIFE RELATIONS

- Exposure Time Modified PC, CC, & CP Life Relations
- Steady State Creep Rate Mod. PC, CC, & CP Life Relations

DUCTILITY NORMALIZED SRP LIFE RELATIONS

$$\Delta\varepsilon_{PP} = 0.50\, D_P\, (N_{PP})^{-0.6}$$

$$\Delta\varepsilon_{PC} = 0.25\, D_P\, (N_{PC})^{-0.6}$$

$$\Delta\varepsilon_{CC} = 0.25\, (D_C)^{0.6}\, (N_{CC})^{-0.6}$$

$$\Delta\varepsilon_{CP} = 0.20\, (D_C)^{0.6}\, (N_{CP})^{-0.6} \quad \textbf{Transgranular}$$

or,

$$\Delta\varepsilon_{CP} = 0.10\, (D_C)^{0.6}\, (N_{CP})^{-0.6} \quad \textbf{Intergranular}$$

Ref. Halford *et al*, 1977

INTERACTION DAMAGE RULE SRP

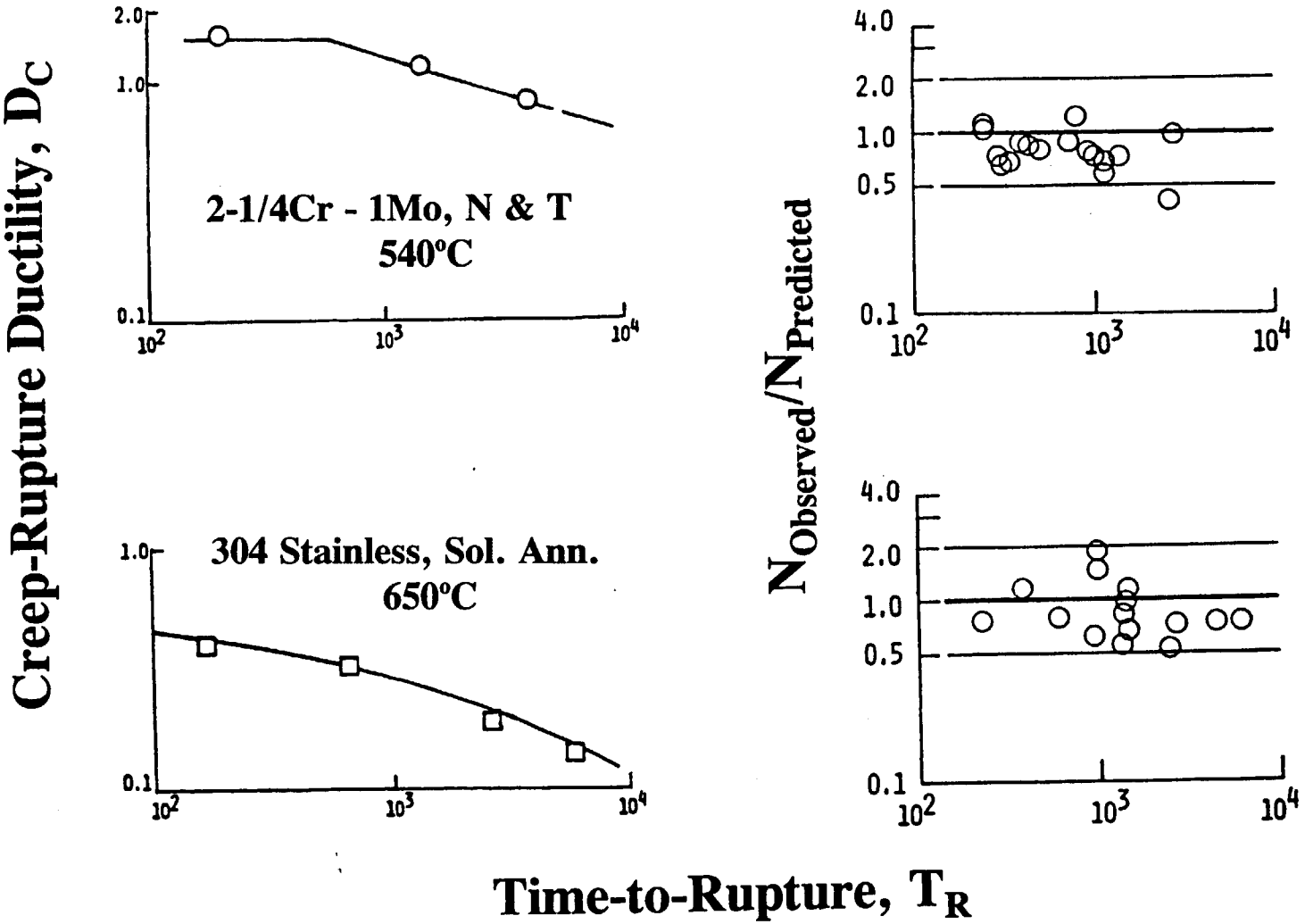
$$\frac{1}{N_f} = \frac{F_{PP}}{N_{PP}} + \frac{F_{CC}}{N_{CC}} + \frac{F_{PC}}{N_{PC}} + \frac{F_{CP}}{N_{CP}}$$

$$F_{PP} = \frac{\Delta\varepsilon_{PP}}{\Delta\varepsilon_{IN}} \qquad F_{PC} = \frac{\Delta\varepsilon_{PC}}{\Delta\varepsilon_{IN}} \qquad F_{CC} = \frac{\Delta\varepsilon_{CC}}{\Delta\varepsilon_{IN}} \qquad F_{CP} = \frac{\Delta\varepsilon_{CP}}{\Delta\varepsilon_{IN}}$$

$$\Delta\varepsilon_{IN} = \Delta\varepsilon_{PP} + \Delta\varepsilon_{PP} + \Delta\varepsilon_{PP} + \Delta\varepsilon_{PP}$$

Ref. Manson, 1973

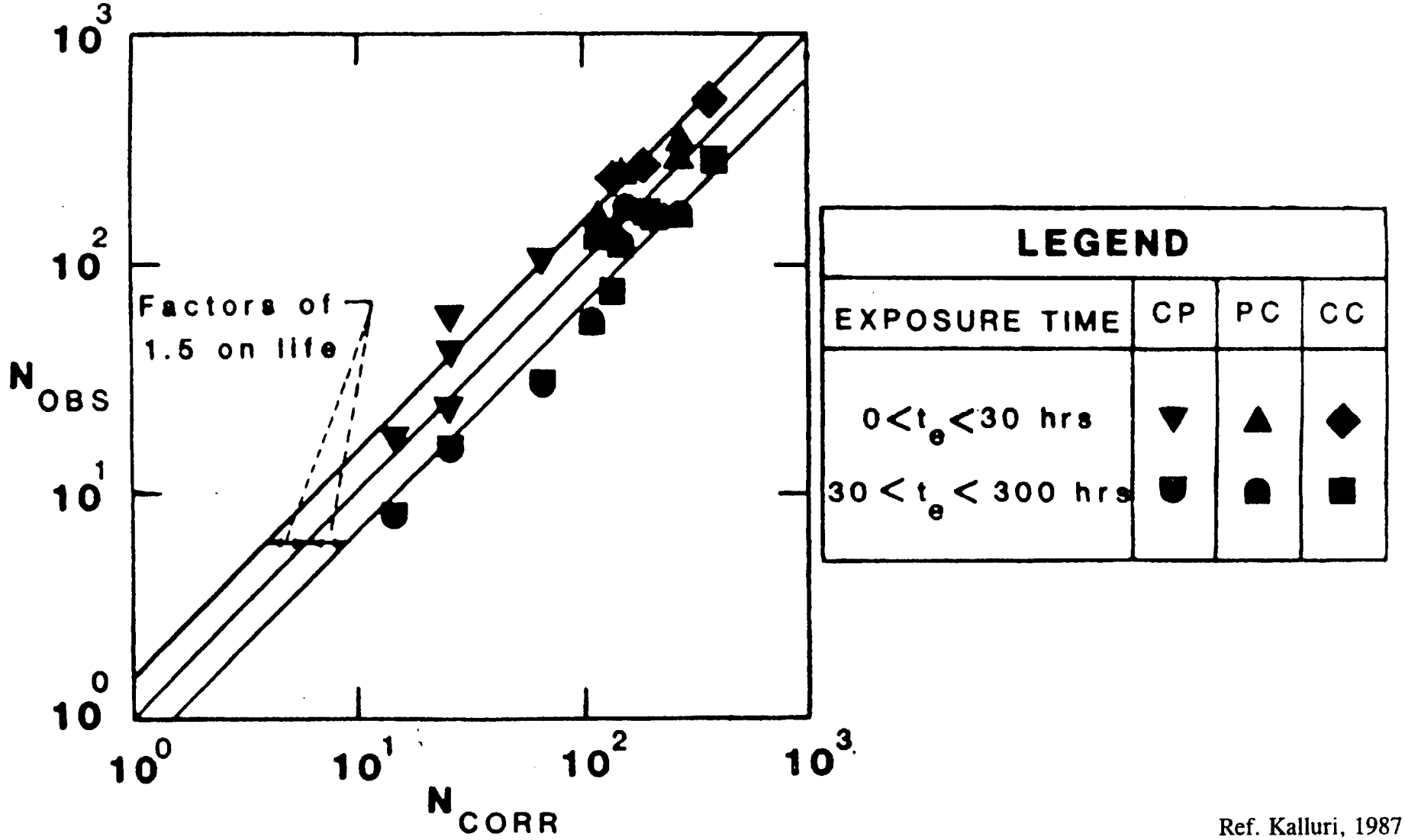
DN-SRP Predictions of Long-Term MPC Data



Ref. Saltsman and Halford, 1979

CORRELATION OF CREEP-FATIGUE DATA BY SRP

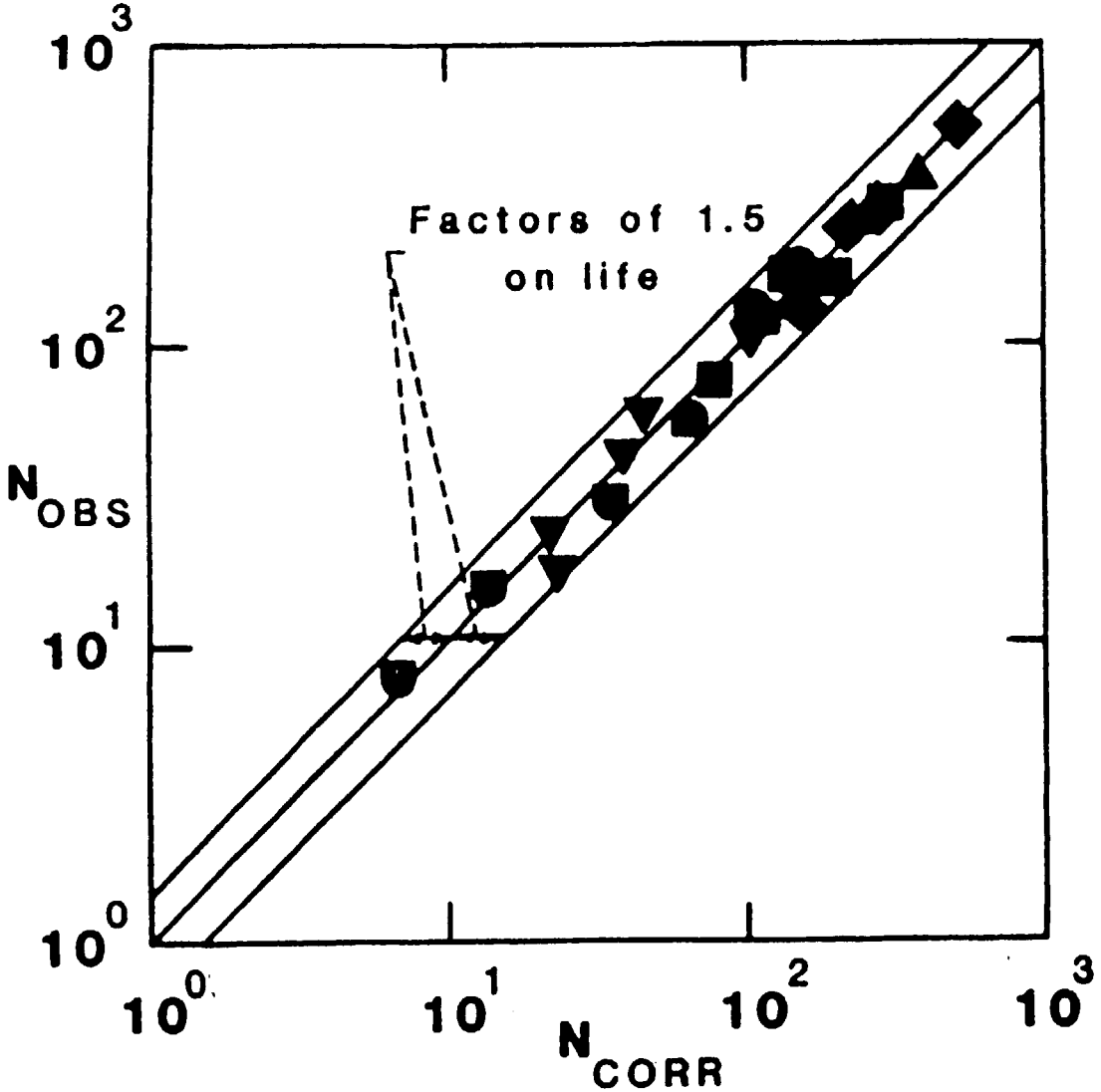
316 Stainless , 816 °C



Ref. Kalluri, 1987

CORRELATION BY SS CREEP RATE MODIFIED SRP

316 Stainless , 816 °C



Ref. Kalluri, 1987

But, Small Inelastic Strains are Too Impractical to Work With

TOTAL STRAIN VERSION OF SRP

0 - APPLICABLE TO LOW-STRAIN/LONG-LIFE

-- Region of Common Use
-- Akin to Method of Universal Slopes
(Aside Comments w.r.t. MUS & 10% Rule - next chart)
-- Compensating Errors in Elastic and Inelastic lines

0 - ANOTHER MEANS FOR EXTRAPOLATION

-- Cyclic Stress-Strain Behavior (Constitutive Models)
-- Elastic Line - Influenced by Flow & Failure (Exp. PP)

METHOD OF UNIVERSAL SLOPES (MUS)

0 - Tensile Properties used to predict Strain-Life Fatigue Curves

-- Widespread Use - Ref., Manson (1965)

-- Used by Rocketdyne (now Boeing) to develop fatigue design curves for Space Shuttle Main Engines for virtually every material, in every condition, at every temperature, for every environment! - Ref., Newell (1994)

10 % RULE FOR CREEP-FATIGUE

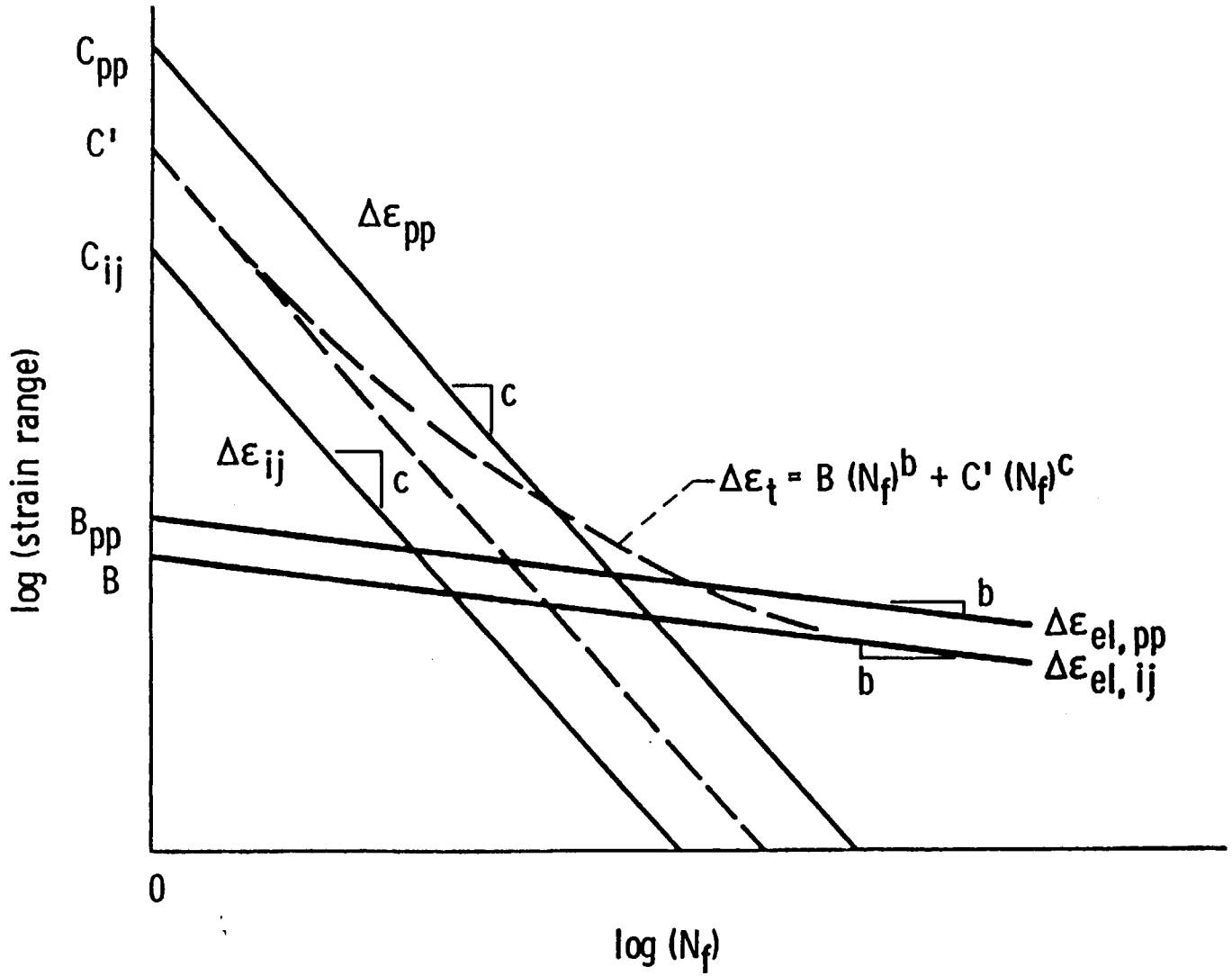
0 - Tensile Properties at temperature used in MUS + Life loss to 10%

-- First cut

-- Limited accuracy

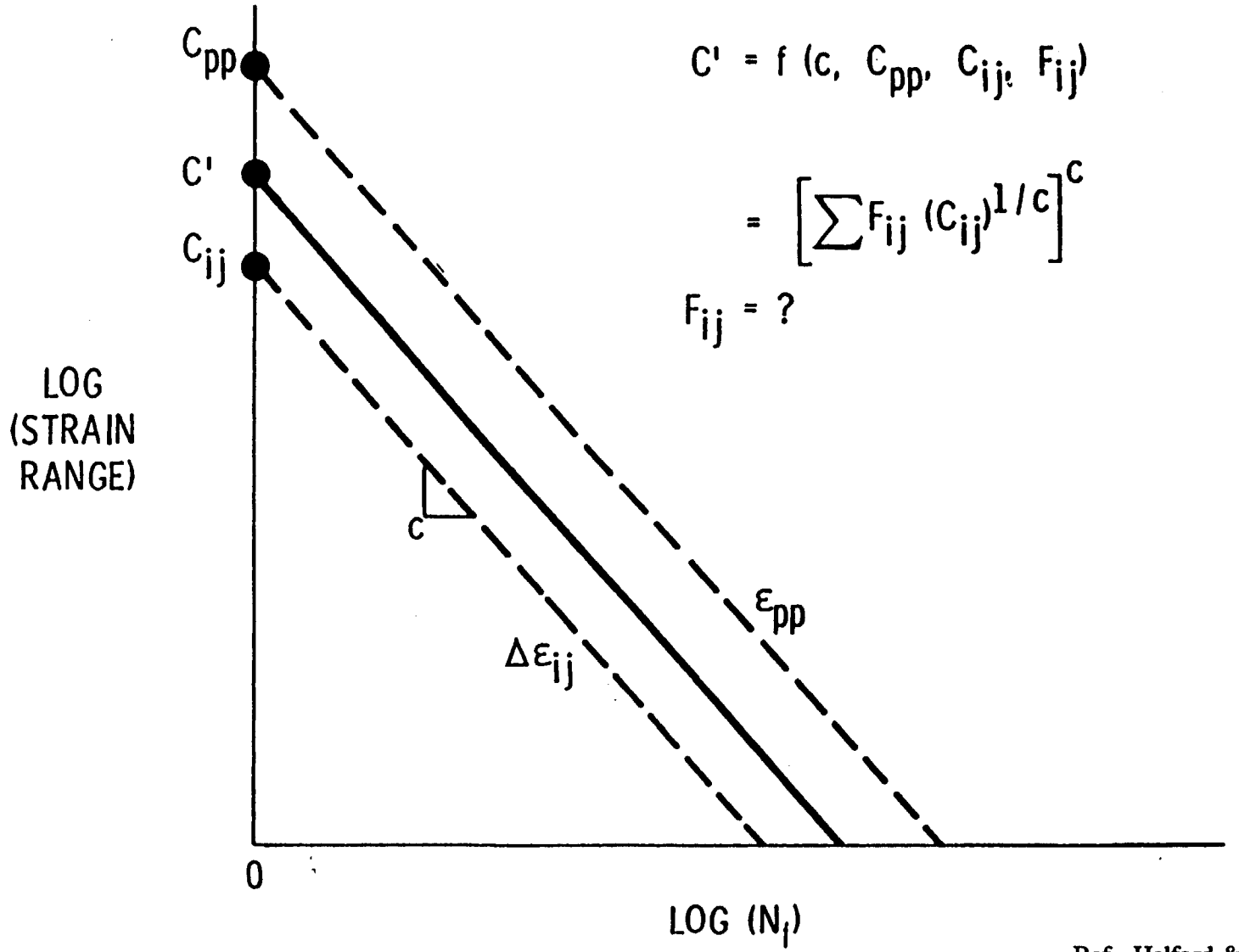
-- Estimation of Creep-Fatigue testing parameters, - Ref., Manson & Halford (1968)

TOTAL STRAIN VERSION OF SRP



Ref., Halford & Saltsman, 1983

INELASTIC LIFE RELATIONS



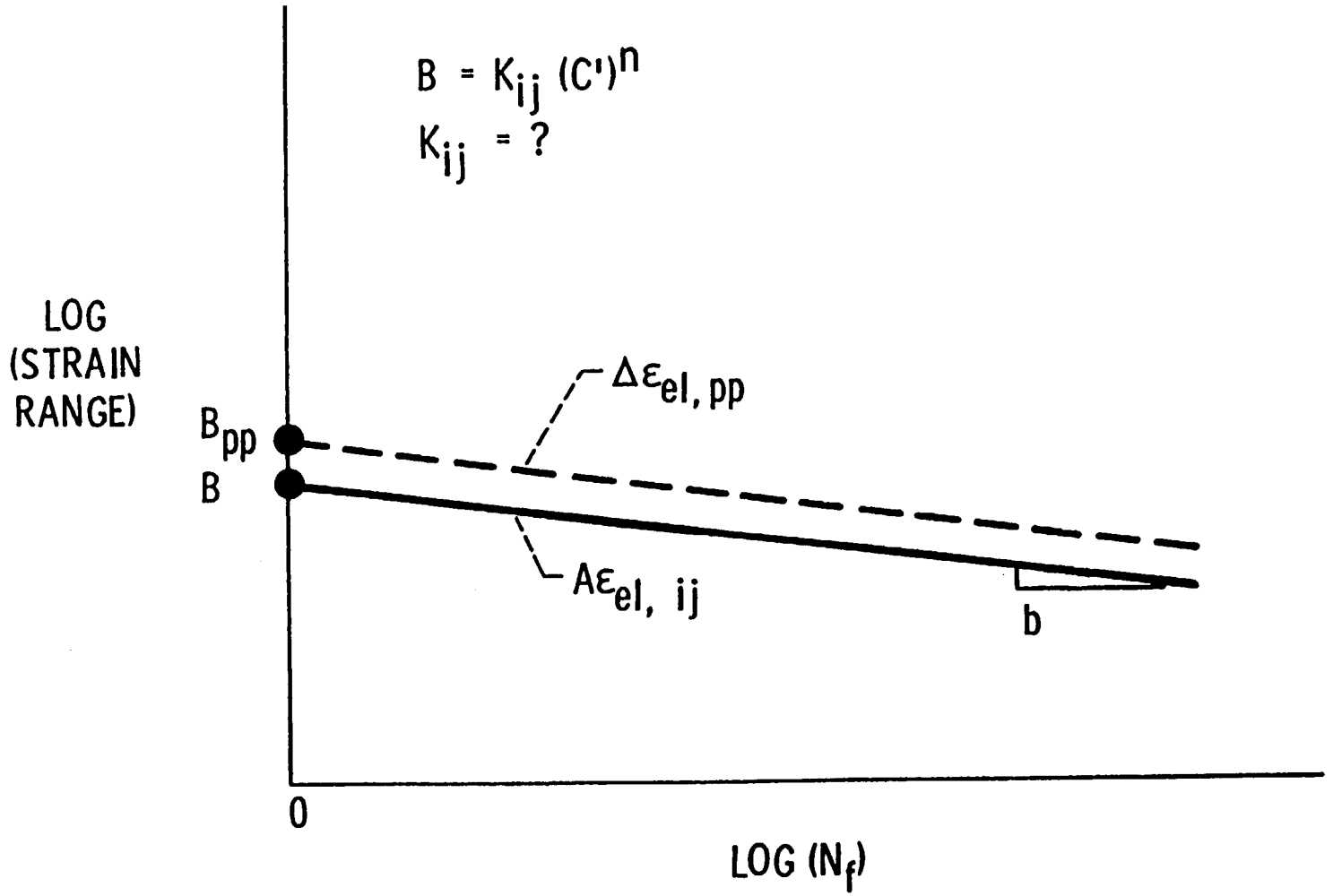
$$C' = f(c, C_{pp}, C_{ij}, F_{ij})$$

$$= \left[\sum F_{ij} (C_{ij})^{1/c}\right]^c$$

$$F_{ij} = ?$$

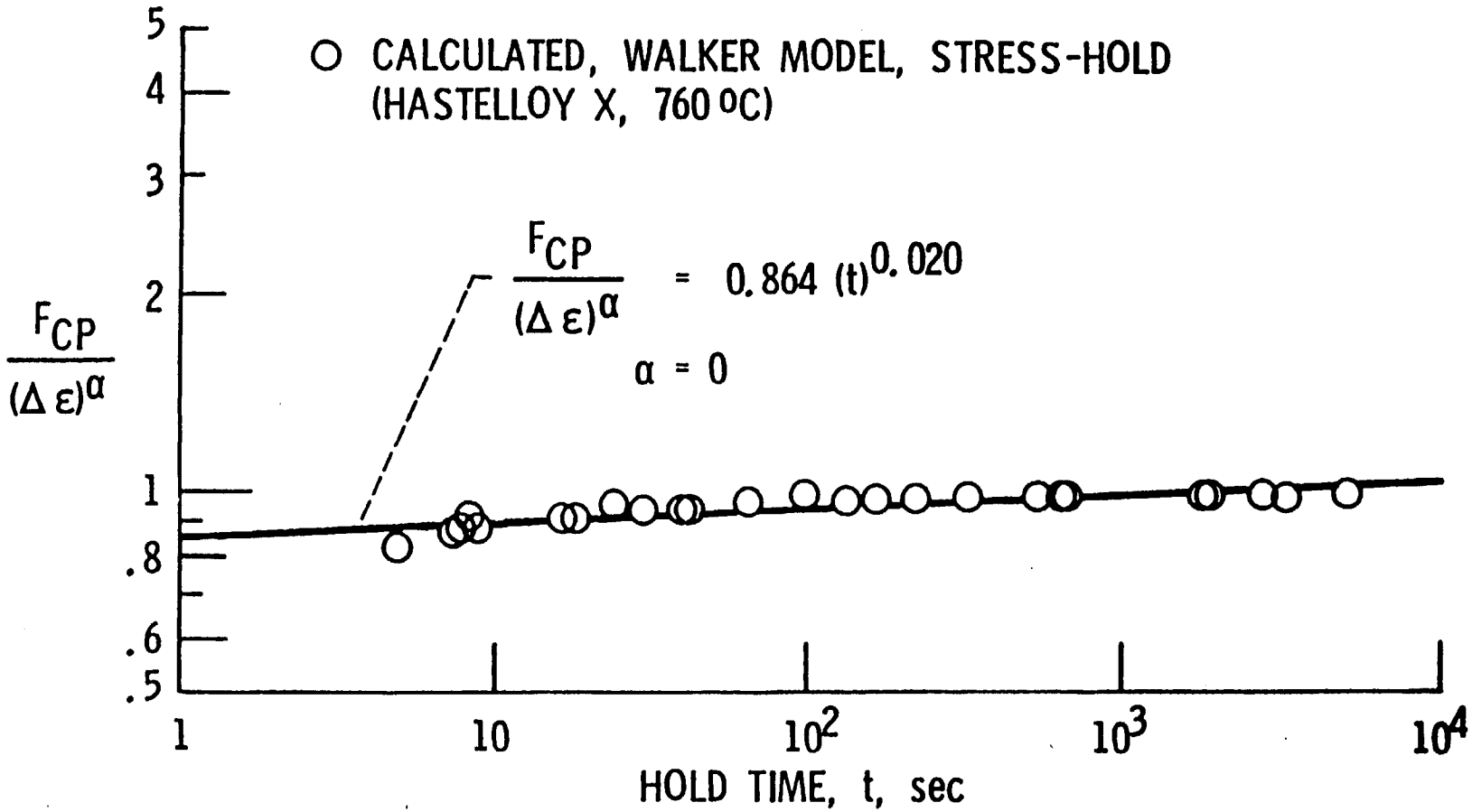
Ref., Halford & Saltsman, 1983

ELASTIC LIFE RELATIONS



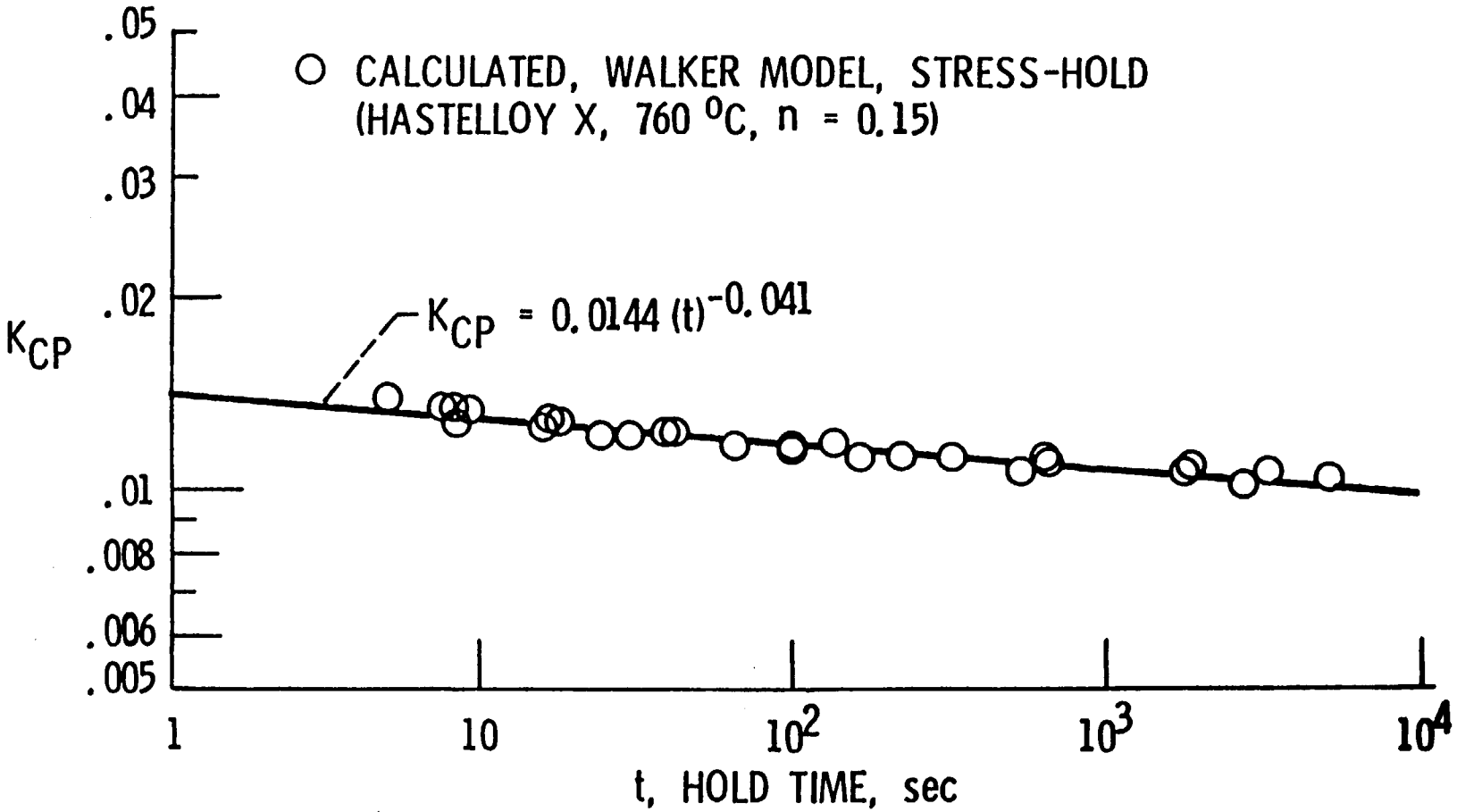
Ref., Halford & Saltsman, 1983

POWER LAW PARTITIONING



Ref., Halford & Saltsman, 1983

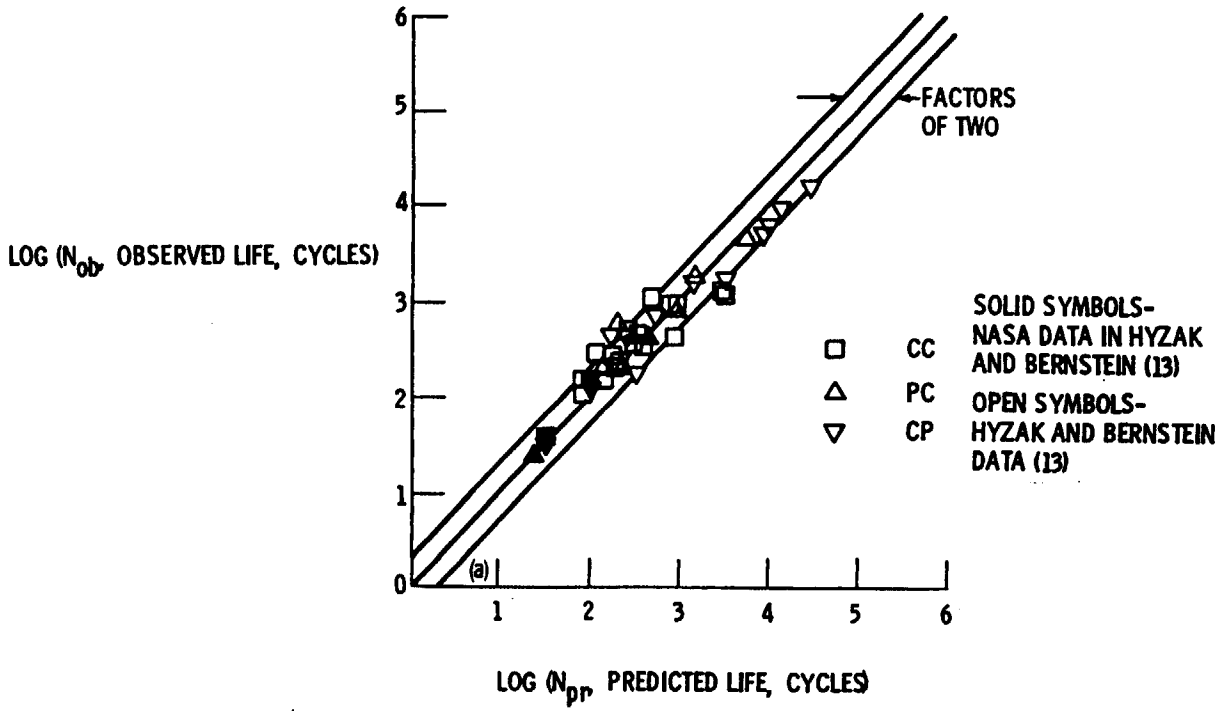
POWER LAW FOR K_{ij}



Ref., Halford & Saltsman, 1983

PREDICTABILITY USING TS-SRP

Rene` 95 at 650°C



Ref., Halford & Saltsman (1983)

SUMMARY

0 - Useful engineering techniques have evolved that allow **Short-Time** or **Less-Costly** testing to estimate **Long-Time** Creep-Fatigue properties.

0 - These techniques could also be applied to compress the time to evaluate the Creep-Fatigue resistance of new alloys, allowing them to enter service sooner.

0 - High-Temperature research at NASA-Glenn over the years has produced some of the following applicable techniques:

1. Method of Universal Slopes
2. Ten Percent Rule
3. StrainRange Partitioning (SRP) Model for rationalizing Creep-Fatigue Behavior
4. Ductility Normalized equations for estimating long-time Creep-Fatigue and for scaling to other material conditions and operating environments
5. Total Strain SRP (TS-SRP) for dealing with long-lives & low-$\Delta\varepsilon$ (long-times)
6. Separation of FLOW and FAILURE behavior in Creep-Fatigue modeling
7. FLOW behavior associated with low frequencies (long times/cycle) can be treated and modeled in reasonable short time frames.

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