PNCT N9530 89-002

FBR

MATERIALS DEVELOPMENT SECTION

技術管理室
No.
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動燃事業団大洗工学センター

OARAI ENGINEERING CENTER
POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

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■ INTRODUCTION

Research and Development (R&D) in this section are consist of two activities on which are Materials Development and Liquid Sodium Technology for Fast Breeder Reactor (FBR).

Testing items on Materials Development are ① Tests on Structural Materials in Air, Sodium, Alkali and Water/Steam and ② Tests on Core Materials in Air, Sodium and Alkali. Data obtained from these tests are banked in computer system and are summarized to ③ Materials Data Base and Materials Data Handbook.

Testing items on Sodium Technology are ④ Radioactive Materials Behavior and Control Test in Sodium and ⑤ Sodium Impurity Measurement and Control Test.

The function of this section is showed as follows.

- Materials Development Section
  - Material Development
    - ① Tests on Structural Materials
    - ② Tests on Core Materials
    - ③ Preparation of Materials Data Base and Summarization to Materials Data Hand Book (Materials Data Processing System)
  - Sodium Technology
    - ④ Radioactive Materials Behavior and Control Test in Sodium
    - ⑤ Sodium Impurity Measurement and Control Test

■ OBJECTIVES OF MATERIALS TESTS

1. Development of Structural Materials and Core Materials
   (1) Compilation of Materials Data for Design
   - Materials Specifications : Product Form, Size (Thickness, Length, Width, Diameter, etc.) Chemical Composition, Grain Size, Heat Treatment Condition and others.
   - Mechanical Properties : Tensile, Creep, Fatigue, Stress-Relaxation and others.

   (2) Examination for Application of Modified Materials
   - Structural Materials
     9 Cr Ferritic Steels
     FBR Grade Stainless Steels (Low Carbon-Nitrogen Added)
   - Core Materials
     Modified SUS 316
     Advanced Austenitic Stainless Steel
     High Strength Ferritic/Martensitic Steel
     Advanced Alloys (Precipitation Hardened Austenitic Steel, Oxide Dispersion Strengthened Ferritic Steel (ODS)

   (3) Examination for Application of Large-Scale Materials
   - SUS 304 Forging of Large Diameter and/or Thickness
   - Cr-Mo Steel Pipe of Large Diameter and Thin Thickness

   (4) Evaluation on Strength of Weldments
   - Modification of Weld Metals, Application of High Efficiency Welding Procedure and Non-Destructive Inspection Technique, and Basic Mechanical Property Tests on Weld Metals
   - Elevated Temperature Tests on Welded Joints
   - Development of Strength Evaluation Method on Welded Joint by Inelastic Analysis

   (5) Evaluation on Creep-Fatigue Life
   - Expansion of Long Term Creep-Fatigue Data
   - Expansion of Creep-Fatigue Data Tested with Various Strain Wave Form
   - Examination of Criteria on Creep-Fatigue Interaction

   (6) Development of Inelastic Constitutive Equation
   - Effect of Plastic-Creep Interaction
   - Yield Condition
   - Hardening Rule on Plastic and Creep Strain
   - Flow Rule on Plastic and Creep Strain
   - Compilation of Inelastic Stress-Strain Test Data under Multi-Axial Stress

   (7) Application of Fracture Mechanics at Elevated Temperature
   - Creep Crack Growth Test
   - Fatigue Crack Growth Test
   - Creep-Fatigue Crack Growth Test
   - Fracture Toughness Test

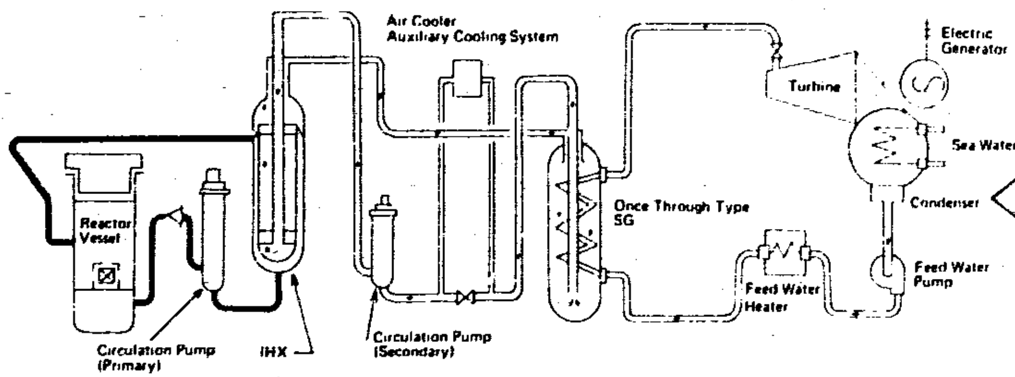
2. Environmental Effect Test
   - In Air : Basic Mechanical Properties
   - In Sodium : Corrosion, Mass Transfer, Aging Effect, and Materials Strength Tests in and after Sodium Exposure
   - Under Neutron Irradiation : Mechanical Properties
   - In H_2O, in Caustic Solution, etc. : Corrosion, Oxidation, Stress Corrosion Cracking, and Hydrogen Penetration Tests

3. Tribological Test
   (1) Development and Evaluation of Co-Free Hard Facing Materials for Decreasing Radiation Exposure
   (2) Evaluation of Tribological Properties for Contact and Sliding Parts
   (3) Development of Advanced Coating Method for Elevation of Economical Ability

4. Development on Materials Data Handbook
   (1) Development on Materials Specifications for FBR
   (2) Formulation on Basic Mechanical Properties for FBR
   (3) Development and Version-up of Materials Strength Standard (Including Design Allowable Stresses) for FBR Design Code
   (4) Compilation of Materials Data Handbook on the above all Results

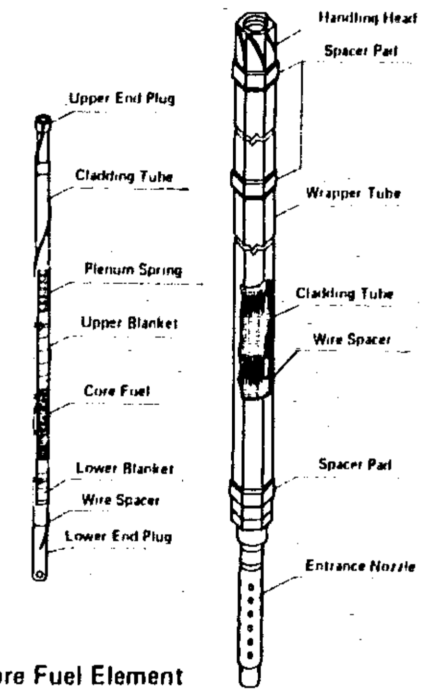
■ SCOPE OF R&D ON MATERIALS

An Example of Large Scale FBR Plant System



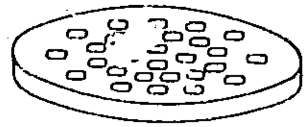
Primary Sodium System   Secondary Sodium System   Water-Steam System

- Reactor Vessel • In-Vessel Structure • Primary Coolant System Pipe
- Intermediate Heat Exchanger (IHX) • Secondary Coolant System Pipe
- Once Through Type Steam Generator • Turbine Generator
- Pump • Valve



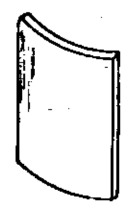
Core Fuel Element

Core Fuel Assembly

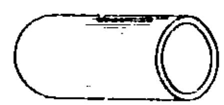


Tube Sheet (Forging)

Tube



Plate



Pipe

Core Materials   Structural Materials

■ MATERIALS

■ Structural Materials

Service Life	• During Life Time of Plant (for Permanent Structure)
Related Components	• R/V, C/S, IHX, Pump, Primary and Secondary Piping System, Once Through Type SG, etc.
Tests	• Metallurgical and Mechanical Tests in Air, Sodium, Water and Caustic Environment

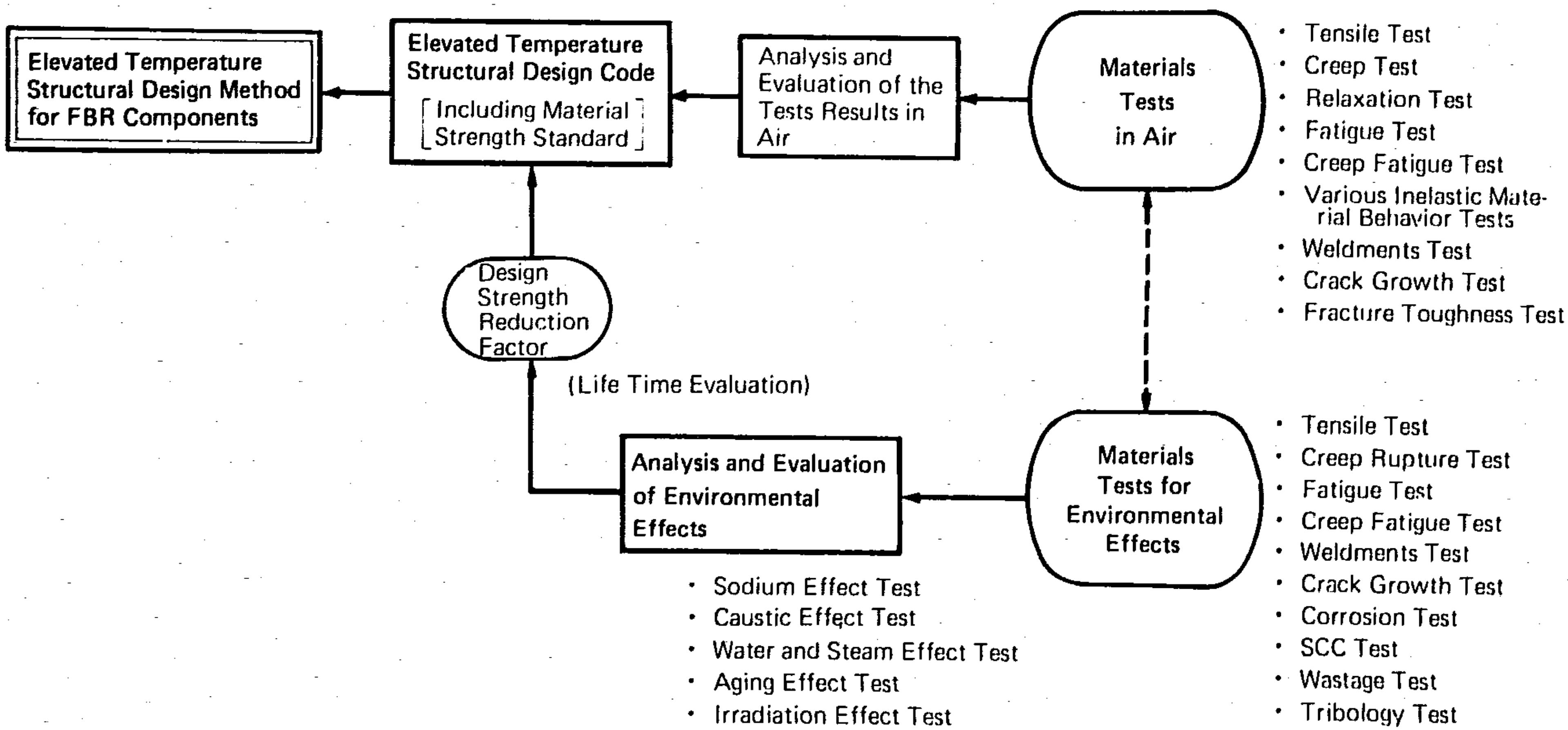
■ Core Materials

Service Life	• During about 2~5 Years (for Changeable Structure)
Related Components	• Cladding Tube, Wrapper Tube, Wrapping Wire, etc.
Tests	• Metallurgical and Mechanical Tests in Air and Sodium Environment

■ Hard Facing Materials

Service Life	• During about 1~30 Years (for both Permanent and Changeable Structure)
Related Components	• Spacer Pad, CR, CRD, Pump Bearing, Valve, etc.
Tests	• Tribology Tests in Sodium Environment

■ FLOW DIAGRAM ON DEVELOPMENT OF ELEVATED TEMPERATURE STRUCTURAL DESIGN METHOD



■ RELATIONSHIP OF MATERIALS STRENGTH TESTS TO MATERIALS STRENGTH STANDARD

(1) Allowable Stress (Material Strength Standard)

Sm	Design Stress Intensity (Limits in Short Term Load)	← Room and Elevated Temperature Tensile Test
Sy	Design Yield Strength	
Su	Design Tensile Strength	
So	Maximum Allowable Stress Intensity	← Constant Load Elevated Temperature Creep Test
St	Design Stress Intensity (Limits in Long Term Load)	
S_R	Design Creep-Rupture Stress Intensity	
Sr	Design Relaxation Strength	← Relaxation Test

(2) Creep Fatigue Strength (Evaluation Method of Creep Fatigue)

a)	Design Fatigue Curve $\epsilon_t - N_d$ curve (Temperature and cyclic strain rate are used as parameters)	← Strain Controlled Fatigue Test
b)	Isochronous Stress-Strain Curve	← (Constant Load Elevated Temperature Creep Test)
c)	Criteria for Creep-Fatigue Damage Evaluation of $(D_f + D_c \leqq D)$	← Fatigue Test Including Hold Time

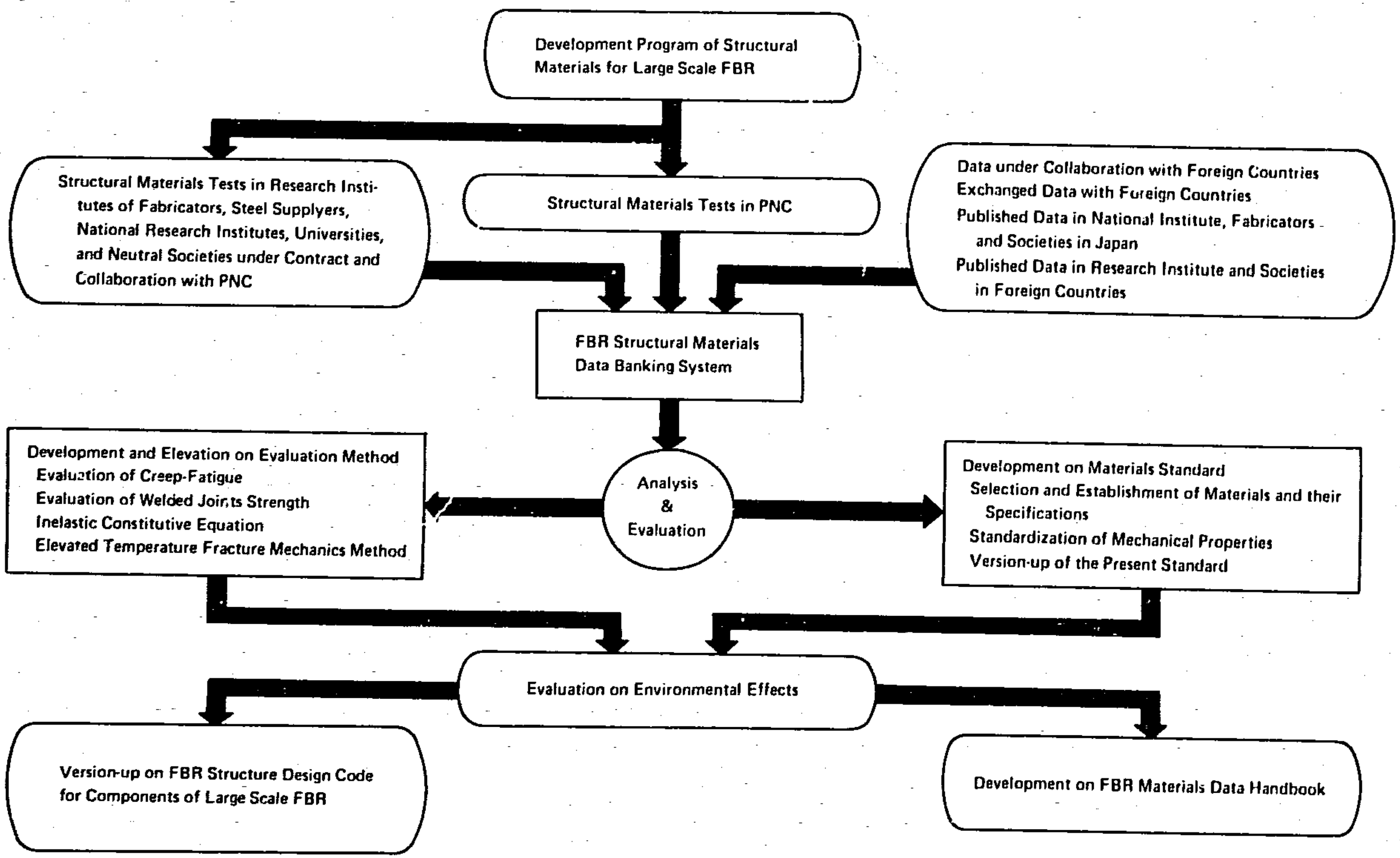
(3) Strain Evaluation by Inelastic Analysis (Including Multi Axial Stress Test) (Inelastic Analysis Method)

a)	Elastic-Plastic Stress-Strain Relation	← (Room and Elevated Temperature Tensile Test; Constant Load Elevated Temperature Creep Test)
b)	Yield Condition (Mises's Condition)	← Elastic-Plastic Behavior Tests under Variable Loads
c)	Hardening Rule (Kinematic Hardening Rule)	
d)	FLow Rule (Plandtl-Reuss Equation)	
e)	Creep Equation	← (Constant Load Elevated Temperature Creep Test)
f)	Creep Hardening Rule (Strain Hardening Rule)	← Creep Behavior Tests under Variable Loads
g)	The Effect of Plastic Deformation on Creep	
h)	Creep Flow Rule	

(4) Crack Growth and Fracture Toughness (Method of Fracture Mechanics at Elevated Temperature — Establishment and Expansion of LBB Theory)

a)	Fracture Mechanics Parameters and Analysis Method	← Crack Growth Test
b)	Crack Growth Rates under Creep, Fatigue and Creep Fatigue	
c)	Fracture Toughness Data	← Fracture Toughness Test

■ FLOW DIAGRAM OF RESEARCH AND DEVELOPMENT ON FBR STRUCTURAL MATERIALS



■ R&D SUBJECTS FOR STRUCTURAL MATERIALS IN AIR

Subject	Test Item	Contents	Material
Standardization of Basic Mechanical Properties on Base Metals	Tensile Test	Tensile Test under the Condition of Strain Rate 0.3~7.5 %/min.	SUS 304 2¼Cr−1Mo Inconel 718 FBR Grade SUS316 9 Cr Ferritic Steels
	Creep Test	Creep Test under the Condition of Constant Load Condition	Ditto
	Low Cycle Fatigue Test	Low Cycle Fatigue Test under the Condition of Strain-Controlled Reversed Loading including Strain Rate Effects	Ditto
	High Cycle Fatigue Test	Ditto (including Load-Controlled Test)	Ditto
	Relaxation Test	Relaxation Test under the Condition of Constant Strain.	Ditto
Development of Evaluation Methods on Strength of Welded Joints	Basic Mechanical Property Tests	Same as the Content in case of Base Metal	Weld Metals of SUS304, 2¼Cr−1Mo, FBR Grade SUS316 and 9 Cr Ferritic Steels
	Verification Test of Welded Joint	Verification Test of Welding Procedures and Application Test of Non-Destructive Inspection-Techniques	Similar and Dissimilar Welded Joints Welded Joints for Large Scale Forged SUS 304 Welded Joints for Large Scale 2¼Cr−1Mo Pipe Welded Joints for FBR Grade SUS316 Welded Joints for 9 Cr Ferritic Steels
Development of Creep-Fatigue Life Evaluation Method	Creep Fatigue Test	Creep-Fatigue Test under the Condition of Strain Hold Time including Long Life (More than 1 year) and the Condition of Specified Strain Wave Form, Multi Axial Creep-Fatigue Test.	SUS 304 2¼Cr−1Mo FBR Grade SUS316 9 Cr Ferritic Steels

■ R&D SUBJECTS FOR STRUCTURAL MATERIALS IN AIR (CONTINUE)

Subject	Test Item	Contents	Material
Development of Inelastic Constitutive Equation	Elastic-Plastic Behavior Test under Uniaxial and Multiaxial Loading	Elastic-Plastic Behavior Test under Uniaxial Various Cyclic Loading for Development of Hardening Rule and Multiaxial Cyclic Loading for Development of Flow Rule	SUS 304 2¼Cr−1Mo 9 Cr Ferritic Steels FBR Grade SUS316
	Creep Behavior Test under Unaxial and Multiaxial Loading	Creep Behavior Test under Unaxial Variable Loading for Development of Hardening Rule and Multiaxial Variable Loading for Development of FLow Rule	Ditto
Development of Evaluation Method on Various Creep-Fatigue Strength Reduction	Pre-Strain Effect Test	Creep and Fatigue Damage Estimation Test on Pre-Strained (Max. 5%, by Tensile Test) Material	SUS 304 2¼Cr−1Mo 9 Cr Ferritic Steels FBR Grade SUS316 Base Metal Weld Metal
	Notched Effect Test	Creep-Fatigue Test on Notched Specimens	
	Mean Stress and Mean Strain Effect Test	Creep-Fatigue Test with Mean Stress and/or Mean Strain	
Development of Evaluation Method on Crack Growth	Creep Crack Growth Test	Creep Crack Growth Test for Development of Predication and Evaluation on Crack Growth under Constant Loading at Elevated Temperature	SUS 304 2¼Cr−1Mo 9 Cr Ferritic Steels FBR Grade SUS316 Base Metal Weld Metal Welded Joint
	Low Cycle Fatigue Crack Growth Test	Crack Growth Test under Uniaxial Various Cyclic Loading with/without Strain Hold Time for Development of Prediction and Evaluation on Low Cycle Fatigue Crack Growth	
	Fracture Toughness Test	Static and Dynamic Fracture Toughness Test at Elevated Temperature	2¼Cr−1Mo 9 Cr Ferritic Steels FBR Grade SUS316 Base Metal Weld Metal Welded Joint

R&D SUBJECTS FOR STRUCTURAL MATERIALS TESTS IN VARIOUS ENVIRONMENTS

Subject	Test Item	Material	Condition
Evaluation of Basic Properties on the Conventional Materials in Sodium	Tensile, Creep, and Fatigue Test	SUS 304, FBR Grade SUS316 2¼Cr–1Mo, Inconel 718	As Received, Sodium-Exposed, In-Sodium, Thermally Aged
Evaluation of Corrosion and Mass Transfer Behavior on the Conventional Materials in Sodium	Metallurgical Examination etc.	SUS 304, FBR Grade SUS316 and Inconel 718	As-Received
Evaluation of Carbon Transfer Behavior in Bimetallic Sodium System of FBR	Ditto	SUS 304, 2¼Cr–1Mo, FBR Grade SUS316 9 Cr Ferritic Steels	As-Received
Evaluation of Sodium Impurity Effect	Ditto	Ditto	Ditto
Evaluation of Corrosion and Mass Transfer Behavior of Advanced Materials in Sodium	Metallurgical Examination, Tensile Test	•9 Cr Ferritic Steels and FBR Grade SUS316 •Base Metal and Welded Joints	As-Received, Sodium-Exposed, Thermally Aged
Evaluation of Basic Properties on Advanced Materials in Sodium	Tensile, Creep, and Fatigue Test	•9 Cr Ferritic Steels and FBR Grade SUS316 •Base Metal and Welded Joints	As-Received, Sodium-Exposed, Thermally Aged, In Sodium
Evaluation of Time-Dependent Change of Mechanical Properties of Materials by Surveillance Tests for "JOYO"	Metallurgical Examination, Tensile and Creep Test	SUS 304, 2¼Cr–1Mo	As-Received, Sodium-Exposed
Evaluation of Sodium-Environmental Effect for Crack Growth	Fatigue Crack Growth Test	SUS 304, 2¼Cr–1Mo and 9 Cr Ferritic Steels	Sodium-Exposed In Sodium
Evaluation of Corrosion and Cracking Behavior in Caustic Environment	Metallurgical Examination, SERT Test, U-Bend Test, Constant Load Test	SUS 304 and 9 Cr Ferritic Steels	As-Received
Evaluation of Tribology on Contacting and Sliding Parts	Self-Welding, Friction and Wear Test	SUS 304, Inconel 718, Co-Free Hard Facing Materials, 9 Cr Ferritic Steels, etc.	As-Received Sodium-Exposed
Evaluation of Thermal Fatigue Effect of Crack Growth in Sodium	Thermal Fatigue Test	SUS 304, 2¼Cr–1Mo 9 Cr Ferritic Steels	In Sodium-Exposed

R&D SUBJECTS FOR CORE MATERIALS

Subject	Test Item	Material	Condition	Remark
Evaluation of Basic Properties Data on Fuel Cladding Tube and Duct Materials	Tensile, Internal Pressure Creep Rupture, Fatigue, etc.	Cold-Worked SUS 316 Modified Stainless Steels	As-Received Sodium-Exposed	In-Air In-Sodium
Evaluation of Corrosion Behavior on Fuel Cladding Tube and Duct Materials	Metallurgical Examination	Cold-Worked SUS 316 Modified Stainless Steels	As-Received	In-Sodium
Evaluation of Fatigue and Creep-Fatigue Strength on Cold-Worked Materials	Fatigue, Creep-Fatigue	Cold-Worked SUS 316 Modified Stainless Steels	As-Received	In-Air
Evaluation of Thermal Aging Effect on Tensile Strength of Cold-Worked Fuel Cladding Tube	Tensile	Cold-Worked SUS 316 Cold-Worked Modified Stainless Steel	As-Received Thermally-Aged	In-Air In-Inert Gas
Evaluation of Basic Properties on Advanced Alloys for Fuel Cladding Tube and Duct Materials	Tensile, Internal Pressure Creep Rupture and Mass-Transfer, etc.	12 Cr Ferritic Steels ODS Ferritic Steels Other Advanced Alloys	As-Received Sodium-Exposed	In-Air In-Sodium
Evaluation of Tribological Properties on Hard-Facing Materials for Duct Load Pads	Self-Welding, Friction and Wear, Thermal Cycle, Sodium Compatibility, etc.	Chromium Carbide	As-Received Sodium-Exposed	In-Sodium
Evaluation of Tribological Properties on Co-Free Hard-Facing Materials for Control Rod Drive Mechanism	Self-Welding, Friction and Wear, Sodium Compatibility, etc.	Inconel 718, Fukudalloys, Metco, etc.	As-Received	In-Sodium
Evaluation of Wear Behavior of Heat Transfer Tube Support of Steam Generator	Friction, Wear	9 Cr Ferritic Steels	As-Received Sodium-Exposed	In-Sodium

■ OUTLINE OF IN-AIR TEST MACHINES FOR STRUCTURAL MATERIALS

Testing Machine	Specification	Unit	Remarks
Tensile Testing Machine	Max. Load : 25 ton/5 ton Instoron type	3	5 ton : 1 25 ton : 2
Creep Testing Machine (Unaxial Tensile)	Max. Load : 5 ton	99	Single Typo 5 ton : 5 3 ton : 74 1.5 ton : 15 0.75 ton : 5
Relaxation Testing Machine	Max. Load : 3 ton Max. Temp. : 800°C	2	Lever Type : 2
Low Cycle Fatigue & Creep-Fatigue Testing Machine (Uniaxial Push/Pull)	Max. Load : ± 10 ton	11	Furnace Type : 3 Induction Heating : 7
High Cycle Fatigue Testing Machine (Uniaxial Push/Pull)	Max. Load : ± 10 ton	1	Induction Heating (Strain Control Type) : 1
Long Life Creep-Fatigue Testing Machine (Uniaxial Push/Pull)	Max. Load : ± 5 ton	8	Mechanical Load : 7 Thermal Expansion Load : 1
Biaxial Fatigue Testing Machine (Internal Pressure–Push/Pull)	Max. Load : 75 ton Max. Temp. : 700°C	1	Electric Furnace Type
Biaxial Fatigue Testing Machine (Tortion–Push/Pull)	Max. Axial Load : ± 20 ton Max. Tortional Load : 200 kg·m	1	Induction Heating Type
Biaxial Creep Testing Machine (Tortion-Tension)	Max. Axial Load : 3 ton Max. Tortional Load : ± 10 kg·m	2	
Creep Crack Testing Machine (Uniaxial Tension)	Max. Load : 5 ton	4	Single Type : 4
Fatigue Crack Testing Machine (Uniaxial Push/Pull)	Max. Load : ± 5 ton : ± 10 ton	1 1	Load Control Type : 1 Strain Control Type : 1
Impact Testing Machine (Charpy)	Max. Absorption Energy : 30 kg·m	1	

■ LIST OF SODIUM LOOPS FOR STRUCTURAL MATERIAL TESTS

Facilities / Particulars	Material Test Sodium Loop-1	Material Test Sodium Loop-2	Structural Materials Sodium Exposure Test Pots	Carbon Transfer Test Loop	Fatigue Test Loop-1	Fatigue Test Loop-2	Sodium Exposure Test Loop-1	Sodium Exposure Test Loop-2	Creep Test Loop	Self-Welding & Wearing Test Loop	Carbon Behavior Test Apparatus	Sodium Thermal Fatigue Test Apparatus
Maximum Using Temperature (°C)	700	700	750	600	700	600	700	550	600	700	700	600
Main Piping Diameter (in.)	3/4	3/4	1/2	1/2	1/2	3/4	3/4	3/4	3/4	3/4	3/4	2 and 3/4
Maximum Flow Rate (ℓ/min.)	30	30	10	9.8	30	35	38	38	35	About 5	0.5	160
Sodium Inventory (ton)	About 1.0	About 1.8	0.4	0.3	1.3	0.4	0.4	0.4	0.52	About 0.8	0.03×2	0.75
Loop Material	SUS 304 SUS 316	SUS 304 SUS 316	SUS 304 SUS 316	SUS 304 2¼Cr−1Mo	SUS 304	SUS 304	SUS 304 SUS 316	SUS 304 2¼Cr−1Mo	SUS 304	SUS 304 SUS 316	SUS 304 SUS 316	SUS 304 SUS 316
Test Items Concerning Studies on Material Behavior	Test of Materials in Sodium (Mass-Transfer, Creep, etc.)	Test of Materials in Sodium (Mass-Transfer, Creep, etc.)	Sodium Compatibility Test of Materials in Sodium	Test on Carbon Transfer between Austenitic Stainless Steel and Ferritic Steel	Fatigue Test in Flowing Sodium	Fatigue Test in Flowing Sodium	Sodium Exposure, Simulating the Primary System	Sodium Exposure, Simulating the Secondary System	Creep Test in Flowing Sodium	Self-Welding & Wearing Test in Flowing Sodium	Test on Carbon Transfer between Structural Material and Sodium	Thermal Fatigue Test in Sodium

■ OUTLINE OF IN-SODIUM TEST MACHINES FOR STRUCTURAL MATERIALS

Testing Machine		Specification	Unit
Tensile Testing Machine	Single Type	Max. Load : 1.5 ton Max. Temp. : 650°C	8
	Multiple Type	Max. Load : 1.5 ton Max. Temp. : 600°C 6 Levers	6×1
Fatigue Testing Machine (Uniaxial Push/Pull)		Max. Load : ±10 ton Max. Temp. : 650°C Wave Form : Triangle, Sine, etc.	2
Creep-Fatigue Testing Machine		Max. Load : ±10 ton Max. Temp. : 650°C Wave Form : Trapezoid, Saw-Tooth, etc.	2
Friction and Wear Testing Machine		Max. Load : 0.5 ton Max. Temp. : 650°C Slide Velocity : 0.1~100 mm/sec.	3
Self-Welding Testing Machine		Max. Load : 1 ton Max. Temp. : 700°C	3
Alkaline Cracking Testing Machine		Max. Load : 1 ton Max. Temp. : 550°C Strain Rate : 0.0005~ 0.01 mm/mm	1
Alkaline Corrosion Testing Pot		Max. Temp. : 650°C Liquid Quantity : 1.5 ℓ	4
Sodium Thermal Fatigue Testing Machine		Max. Temp. : 600°C Max. ΔT : 400°C	1

■ LIST OF SODIUM LOOPS FOR CORE MATERIAL TESTS

Particulars \ Facilities	Material Test* Sodium Loop-1	Material Test* Sodium Loop-2	Core Material Exposure Test Pots	Self-Welding and* Wearing Test Loop
Max. Using Temperature (°C)	700	700	730	700
Main Piping Diameter (in.)	3/4	3/4	3/4	3/4
Max. Flow Rate (ℓ/min.)	30	30	About 1	About 5
Sodium Inventory (ton)	About 1.0	About 1.8	About 0.4	About 0.8
Loop Material	SUS 304, 316	SUS 304, 316	SUS 304, 316	SUS 304, 316
Test Items Concerning Studies on Material Behavior	Tests of Materials in Flowing Sodium Corrosion & Mass-Transfer Test, Creep & Creep-Rupture Test	Tests of Materials in Flowing Sodium Corrosion & Mass-Transfer Test, Creep & Creep-Rupture Test	Sodium Compatibility Test of Materials in Flowing Sodium	Tribology Tests of Hard-Facing Materials in Flowing Sodium Self-Welding, Friction and Wear Test

* Common Use to Structural Material Tests

■ OUTLINE OF TEST MACHINES FOR CORE MATERIALS

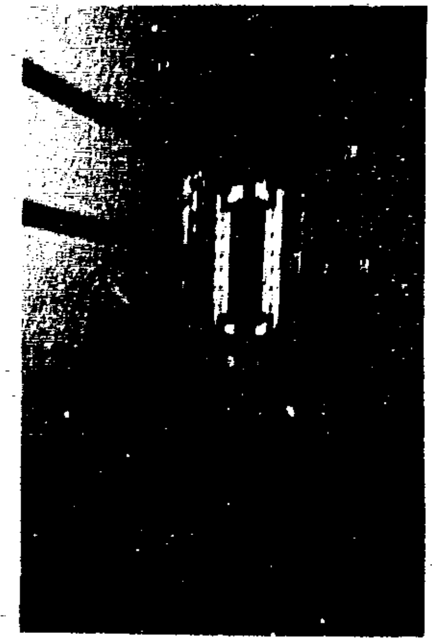
Environment	Testing Machine	Specification	Unit	Remark
In-Air	Tensile Testing Machine	Max. Load : 25 ton Max. Temp. : 900°C Instron Type	3*	5 ton×1 25 ton×2
	Biaxial Creep/Creep Rupture Testing Machine (Internal Pressure Type)	Max. Pressure : 700 kgf/cm² Max. Temp. : 800°C Pressure Line (system) Electric Furnace Type	5	
	Fatigue/Creep-Fatigue Testing Machine (Uniaxial Push/Pull)	Max. Load : ± 10 ton Max. Temp. : 800°C Strain Rate : 10^{-3} sec^{-1}	1*	
	Biaxial Creep Rupture Testing Machine	Max. Pressure : 700 kgf/cm² Max. Sodium Temp. : 700°C Pressure Line (system) : Total 60	4	
In-Sodium	Corrosion and Mass-Transfer Test Section	Max. Sodium Flow Velocity : 700 cm/sec Max. Sodium Temp. : 700°C	4	
	Sodium Exposure Test Section	Max. Sodium Temp. : 730°C Sodium Flow Rate : about 300 cm/sec Vessel Type	5	
	Friction and Wear Testing Machine	Max. Load : 0.2 ton Max. Sodium Temp. : 650°C Sliding Velocity : 0.1 ~ 100 mm/sec Angle of 120°C Oscillating Rotation and Vertically Reciprocating Sliding Motion, Pin & Plate Type	3*	
	Self-Welding Testing Machine	Max. Load : 1 ton Max. Sodium Temp. : 700°C Ring & Disc Type	3*	
Caustic	Alkaline Corrosion Testing Pots	Max. Temp. : 100°C(4 Pots), 200°C(1 Pot) Liquid Quantity : 2ℓ	5	

* Common Use to Structural Material Tests

■ GENERAL APPEARANCES OF TESTING MACHINES FOR STRUCTURAL MATERIALS

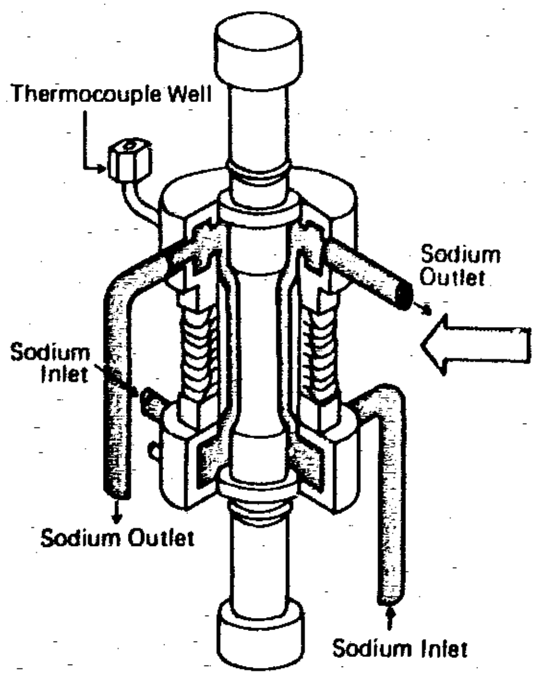
In-Air Creep Testing Machine (99 Machines)

In-Air Multi Axial Fatigue Testing Machine
(Torsion - Push/Pull)



In-Air Biaxial Creep Testing Machine
(Torsion - Tension)

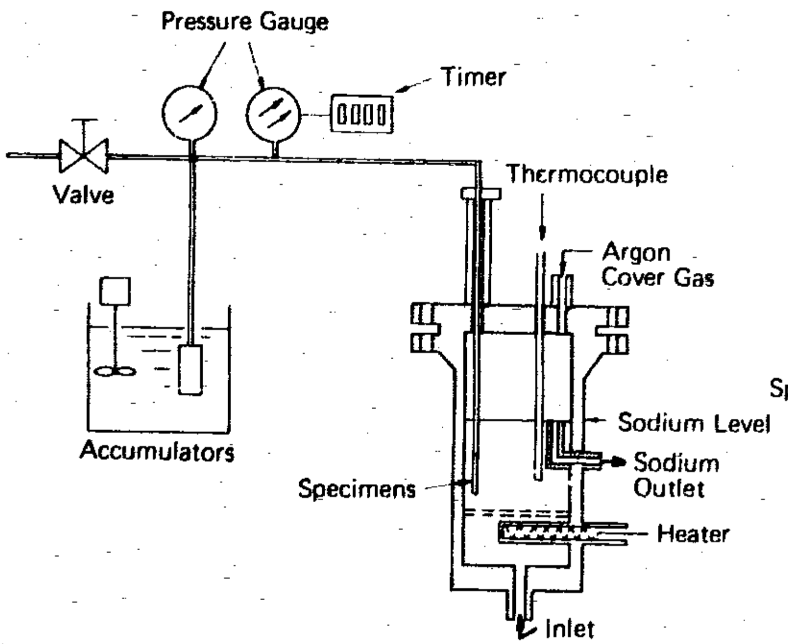
In-Sodium Creep Testing Machine



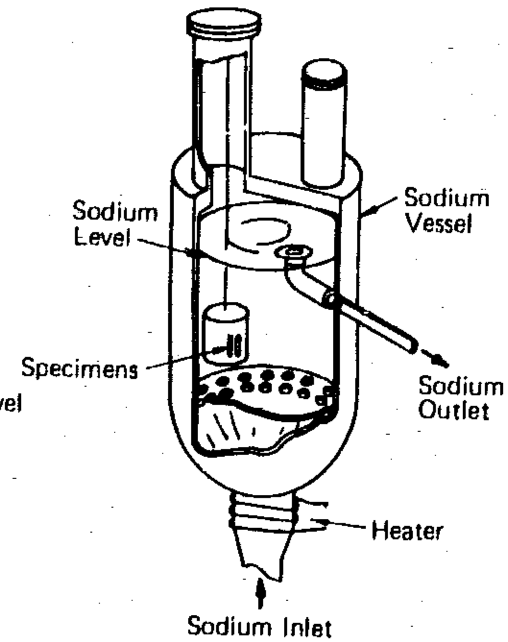
Bellows Type Test Specimen

In-Sodium Fatigue Testing Machine

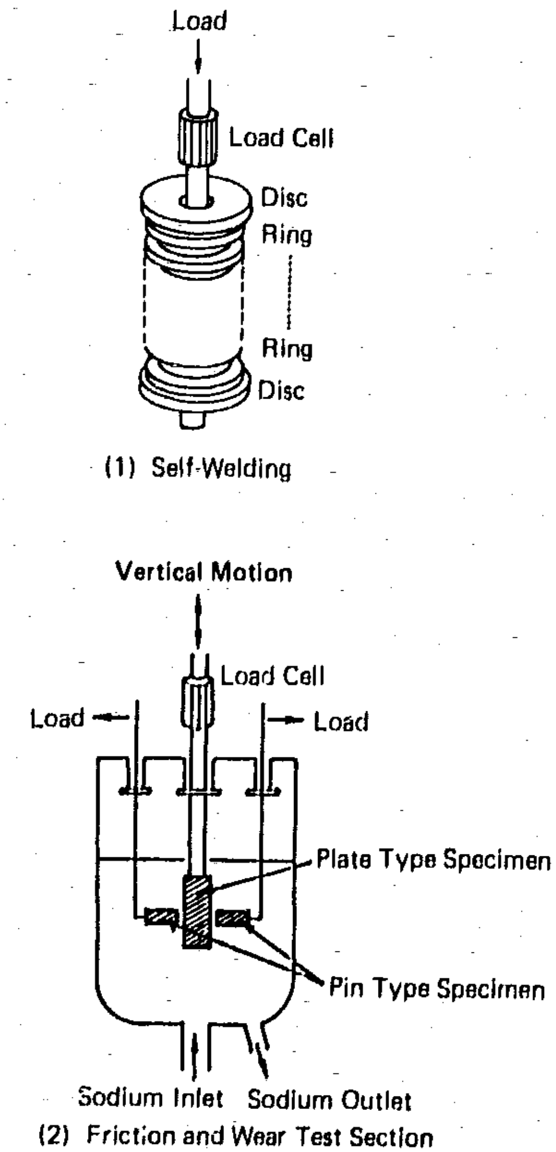
■ SCHEMATIC DRAWINGS OF TEST SECTIONS FOR CORE MATERIALS



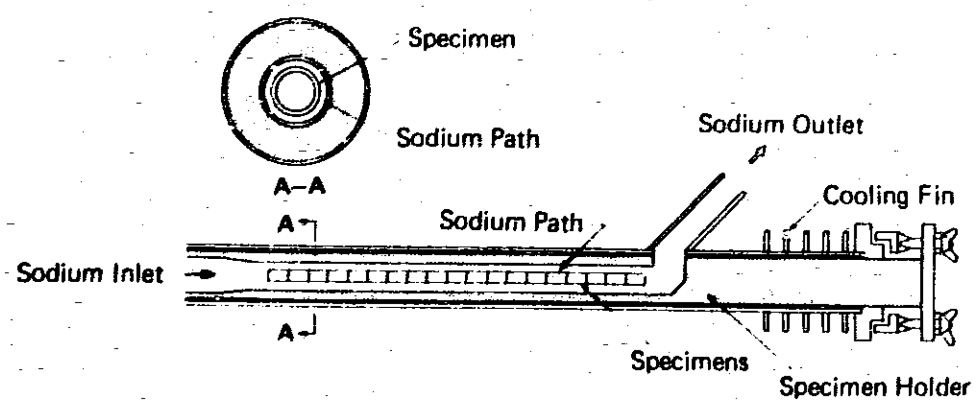
Internal Pressure Creep Rupture Test Section



Sodium Exposure Test Pot



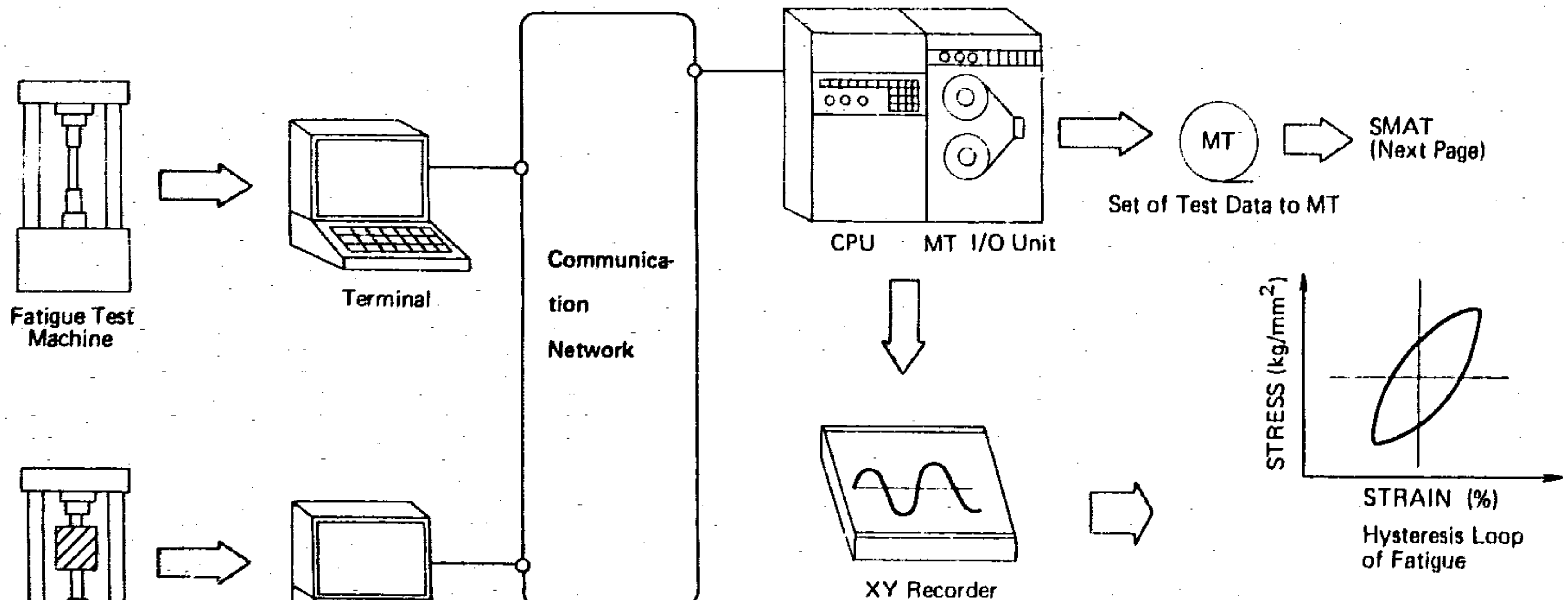
Self-Welding and Friction & Wear Test Section

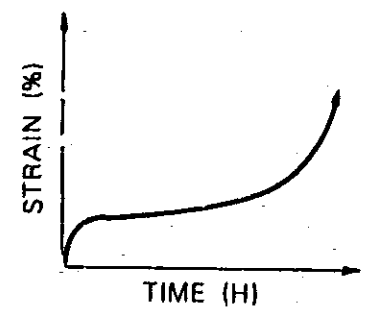


Corrosion and Mass-Transfer Test Section

■ PREPARATION OF MATERIALS DATA BASE AND SUMMARIZATION TO MATERIALS DATA HAND BOOK (1)

Real Time System for Compilation of Materials Strength Data



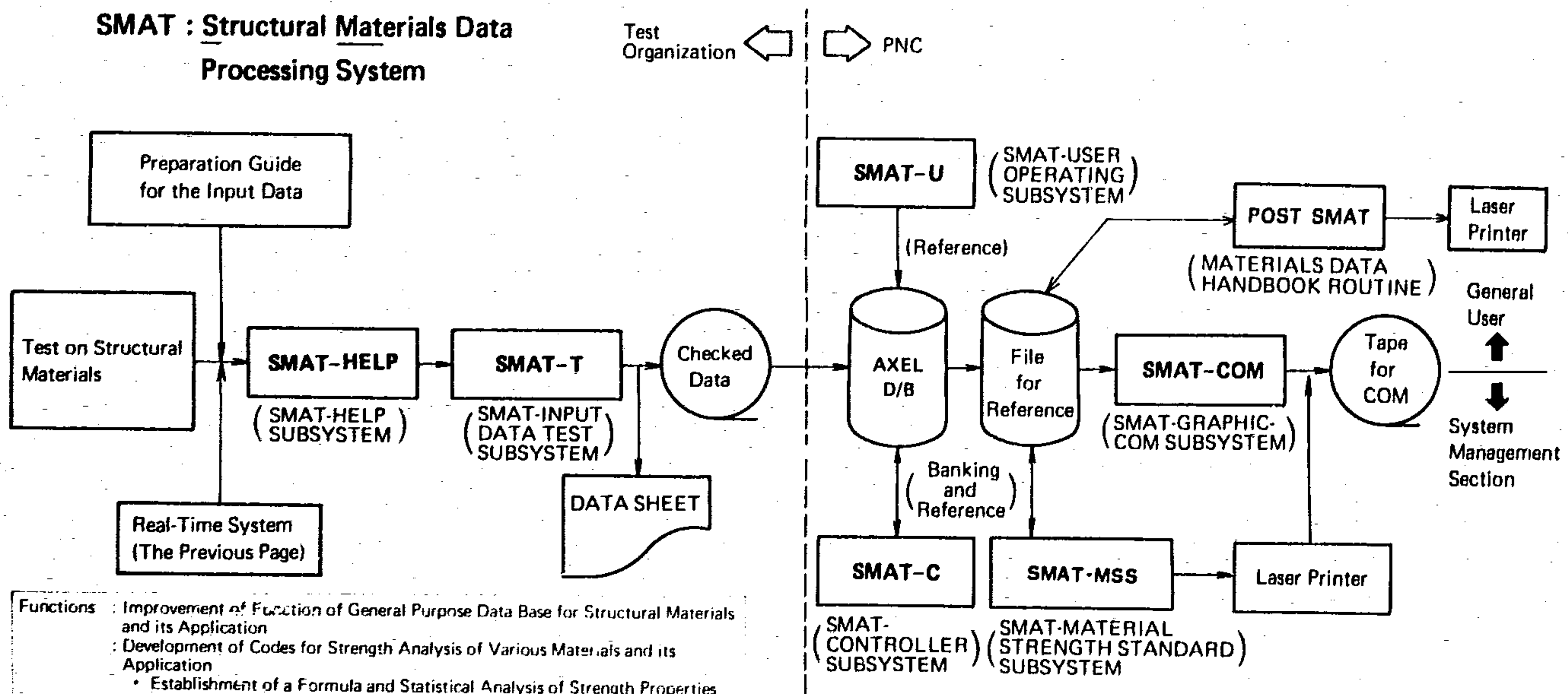


Creep-Strain Curve

Functions : On-Line Data Acquisition from All the Fatigue Testing Machines (Stress, Strain)
: On-Line Data Acquisition from All the Creep Testing Machines (Strain, Time)
: Edition of Acquisited Data and Preparation of File
: Analysis of Acquisited Data
: Edition of Input Data for SMAT System
: Monitoring of Testing Machines
: Data Required to Conduct Material Tests (Control of Test Plan, History of Materials, Information of Test Specimens, Test Results)

■ PREPARATION OF MATERIALS DATA BASE AND SUMMARIZATION TO MATERIALS DATA HAND BOOK (2)

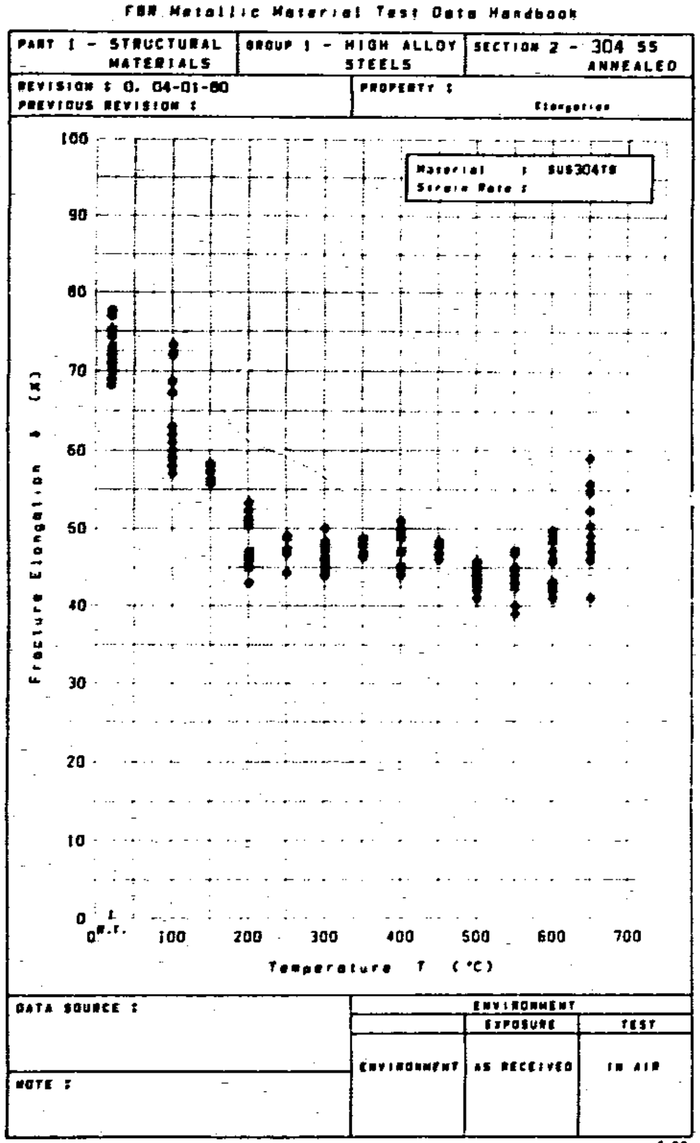
SMAT : Structural Materials Data Processing System

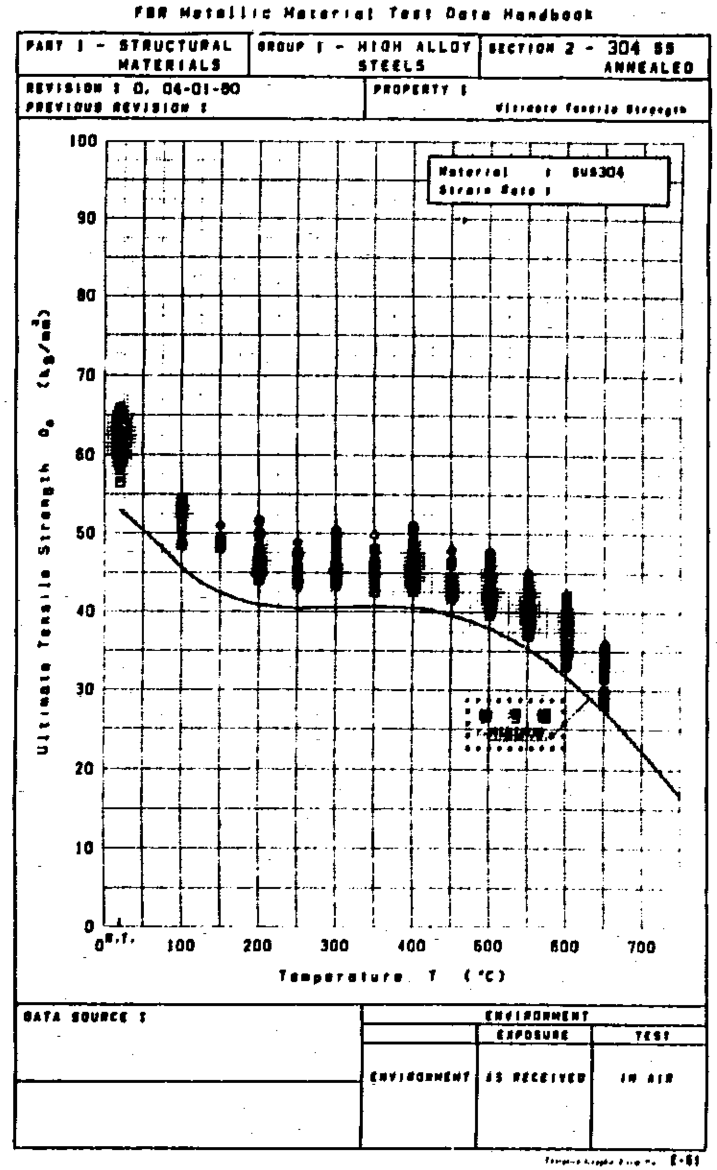


Functions
: Improvement of Function of General Purpose Data Base for Structural Materials and its Application
: Development of Codes for Strength Analysis of Various Materials and its Application
  - Establishment of a Formula and Statistical Analysis of Strength Properties on Base Metals and Weld Metals
  - Analysis of Deformation Behavior and Life Prediction
: Development of Code for Analysis of Environmental Effect and its Application
  - Carbon Transfer Behavior, Creep-Fatigue Behavior of Carburized Materials, etc.
: Development of Code for Strength Analysis of Welded Joint and its Application
  - Simplified Inelastic Analysis of Stress/Strain Distribution in Welded Joint and Life Prediction
: Development of Code for Analysis of Crack Growth Criteria and its Application
  - Establishment of a Formula and Statistical Analysis on Base Metals and Weld Metals
: Development of Code for Analysis of Inelastic Constitutive Equation and its Application
  - Construction of Model of Inelastic Constitutive Equation and Inelastic Analysis
: Edition of Materials Data Hand Book and Output of Figures and Tables

Computer Room

■ FORMAT OF MATERIALS DATA HAND BOOK (EXAMPLES)

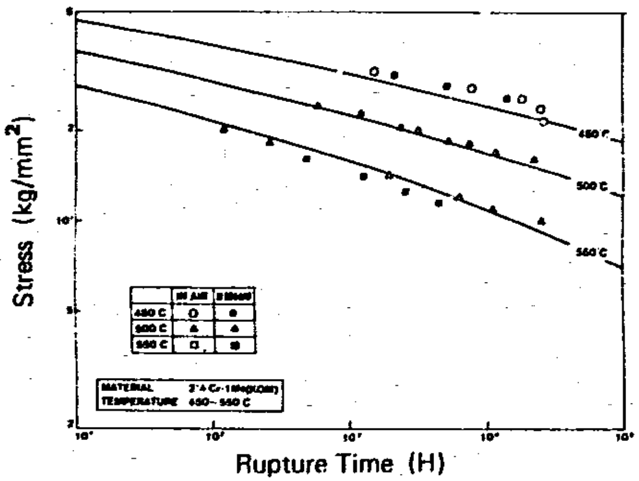




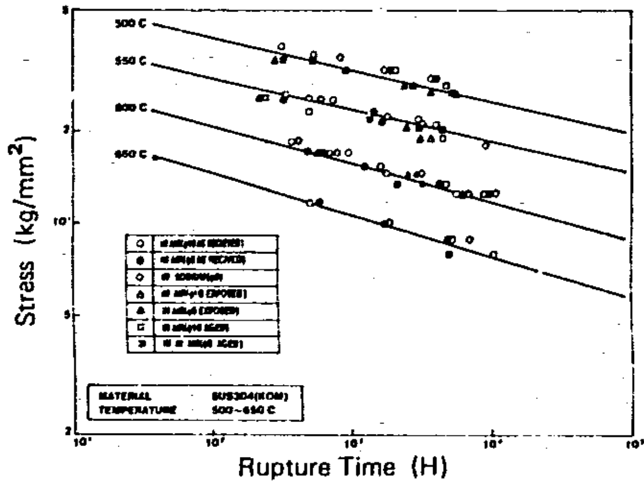
■ EQUIPMENT FOR METALLURGICAL EXAMINATION AND INSTRUMENTAL ANALYSIS

Apparatus	Main Specification	Unit	Remark
Scanning Electron Microscope	Resolution; 60 Å, Max. Magnification; X180,000, Max. Accelerating Voltage; 39 KV	1	JSM-35C
Scanning Electron Microscope	Resolution; 60 Å, Max. Magnification; X80,000, Max. Accelerating Voltage; 30 KV	1	S-450 Only for Radioactive Material Test
Transmission Electron Microscope	Resolution; 2.04 Å, Max. Magnification; X300,000, Max. Accelerating Voltage; 200 KV	1	JEM-200C
Energy Dispersive Spectro-Scopy	Si(Li) Detector, Resolution; 146 eV, Energy; $_{11}Na \sim _{92}U$	1	Addition to JSM-35C
Energy Dispersive Spectro-Scopy	Si(Li) Detector, Resolution; 146 eV, Energy; $_{11}Na \sim _{92}U$	1	Addition to S-450
Energy Dispersive Spectro-Scopy	Si(Li) Detector, Resolution; 148 eV, Energy; $_{11}Na \sim _{92}U$	1	Addition to JEM-200C, Equipped with CPU
Wave Dispersive Spectro-Scopy	Energy Resolution; Less than 15 eV Range of Measurable Wave Length; 5.8 ~ 88 Å, $_5B \sim _{15}P$	1	Addition to JSM-35C
Ion Microanalyzer	Diameter of Minimum Beam; 2 μm, Detectability; 50 ppb (for Si/B) $_1H \sim _{92}U$	1	IMA-2, Equipped with CPU, be Possible to Automatic Analysis
X-ray Diffraction Apparatus	Resolution; Δ(2θ) Less than 0.12° for Si (220)	1	Equipped with Micro Diffractmeter
Metallurgical Microscope	Max. Magnification; X 2,000, Automatic Exposure Meter	1	In Addition, 3 Ones
High Temperature Micro Vickers Hardness Tester	Max. Temperature; 1600°C, Load; 50 ~ 1000 g	1	In Addition, a Micro Vickers Hardness Tester
Rockwell Hardness Tester	Automatic Load; 60, 100 and 150 kg	1	
Vickers Hardness Tester	Load; 10 to 1,000 g, Min. Measurable Scale; 0.5 μm	1	
Surface Roughness Gauge	Range of Measurement; 0.01 ~ 600 μm, Max. Magnification; X 100 ~ 100,000	1	
Precision Balance	Range of Measurement; 1 μg, Standard Error; 1 μg	2	In Addition, Four Direct-Reading Balances
Inert-Gas Heating Furnace	Max. Heating Temperature; 600°C, Standard Error; ±5°C	5	

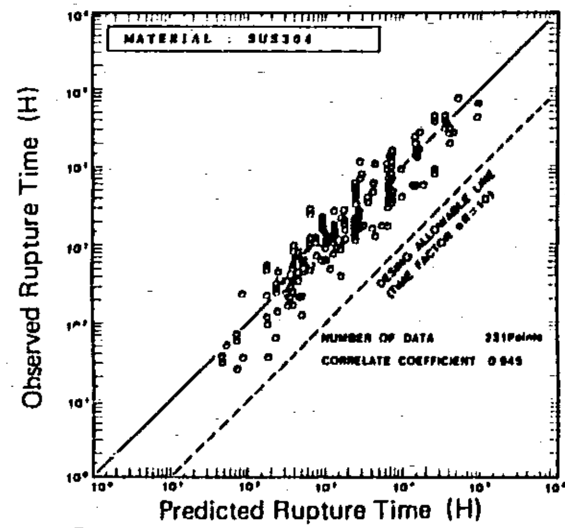
■ REPRESENTATIVE TEST RESULTS——FBR STRUCTURAL MATERIALS (1)



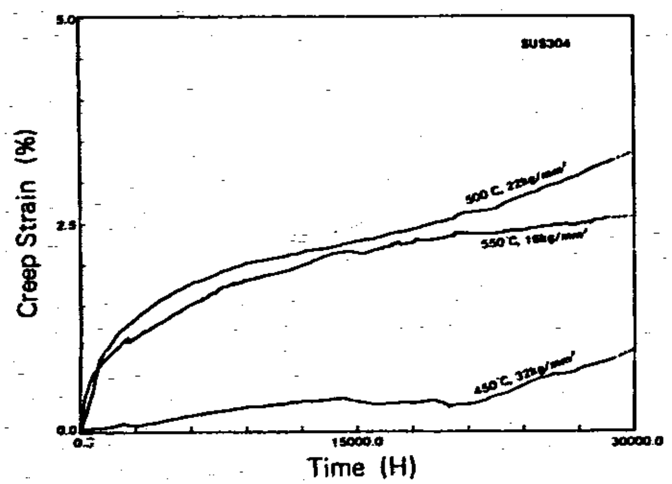
Comparison of Creep Rupture Data with Creep Rupture Equation for 2¼ Cr-1Mo Steel



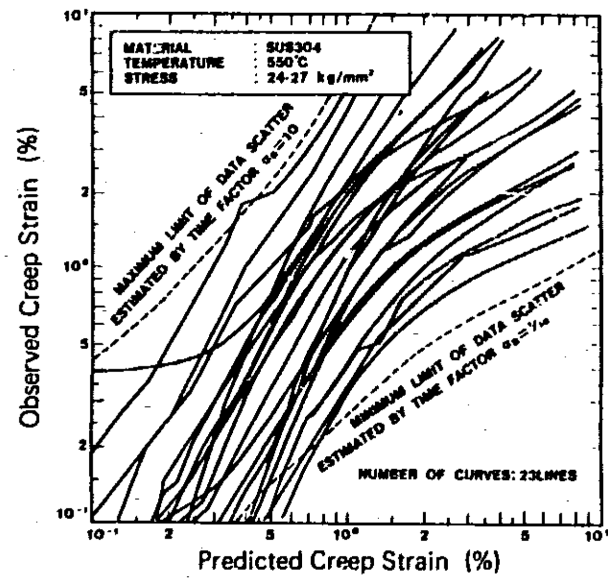
Comparison of Creep Rupture Data with Creep Rupture Equation for SUS 304 Steel



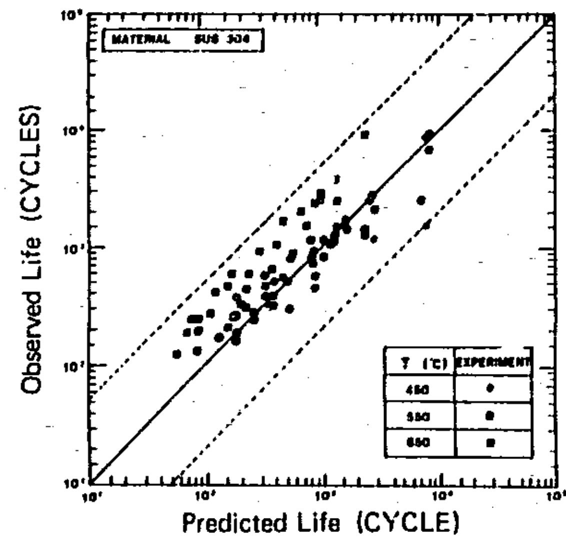
Correlation between Predicted and Observed Values of Time to Rupture for SUS 304 Steel



Long Term Creep Curves for SUS 304 Steel

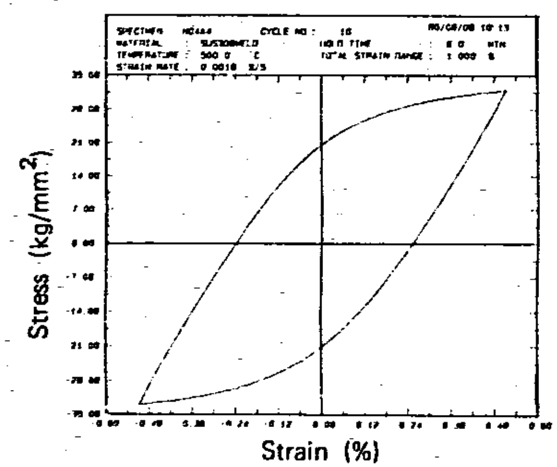


Correlation Between Predicted and Observed Creep Strain Behavior

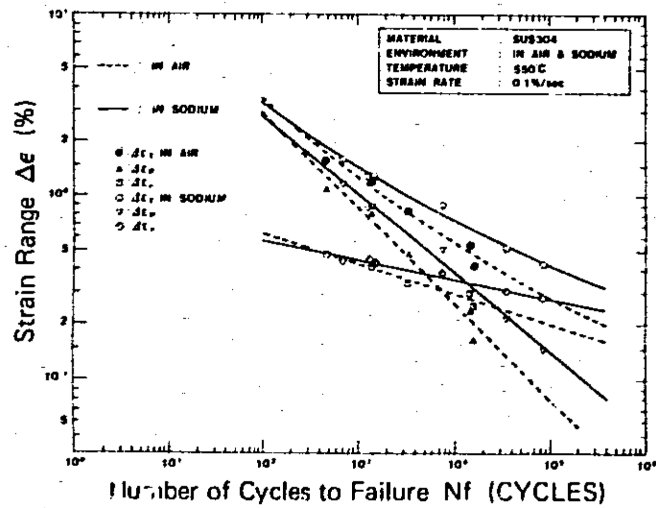


Correlation Between Predicted and Observed Creep-Fatigue Lives for SUS 304 Steel

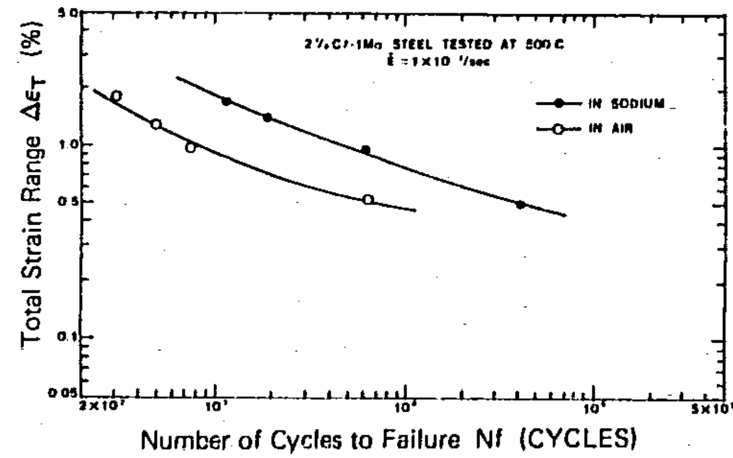
■ REPRESENTATIVE TEST RESULTS——FBR STRUCTURAL MATERIALS (2)



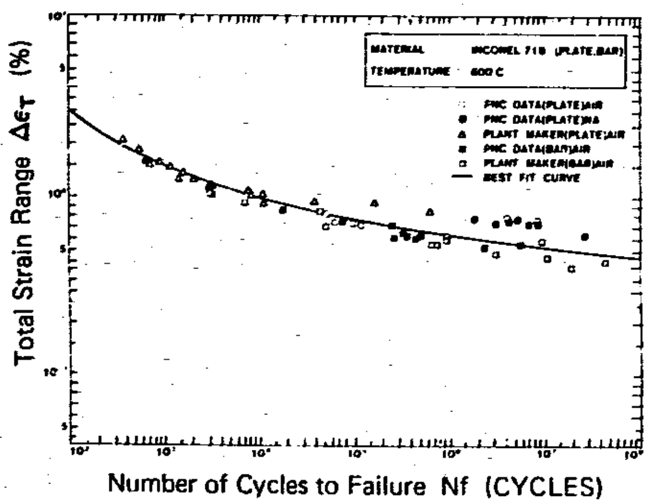
Output of On-line Sampling Data from Fatigue Testing Machine



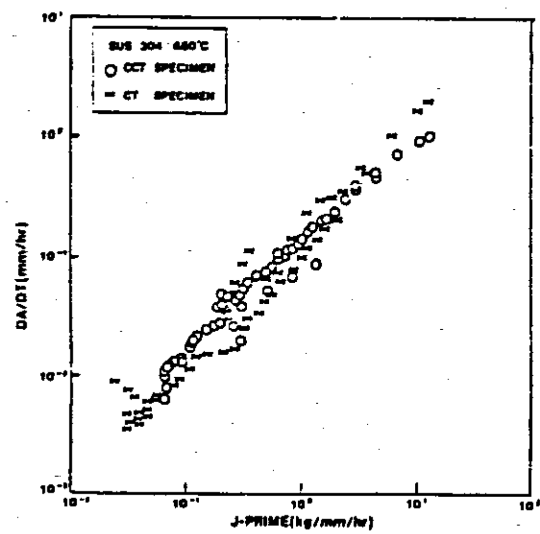
Relation Between Strain Range and Number of Cyles to Failure for SUS 304 Steel in Air and Sodium at 550°C



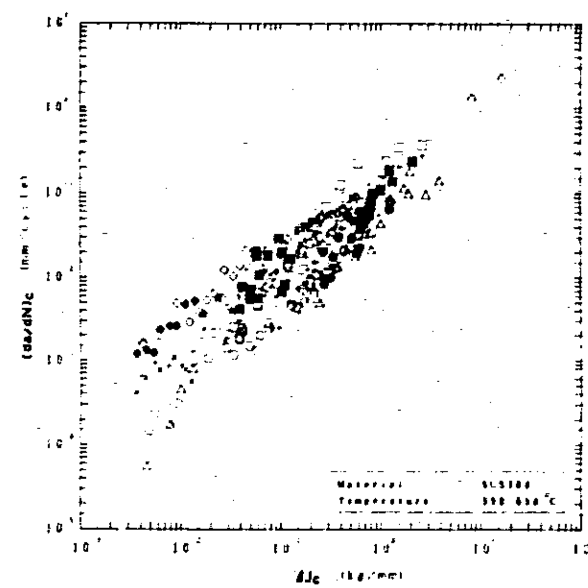
Relation Between Strain Range and Number of Cycles to Failure for 2¼Cr-1Mo Steel in Air and Sodium at 500°C



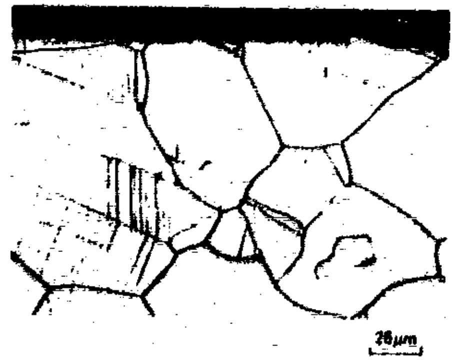
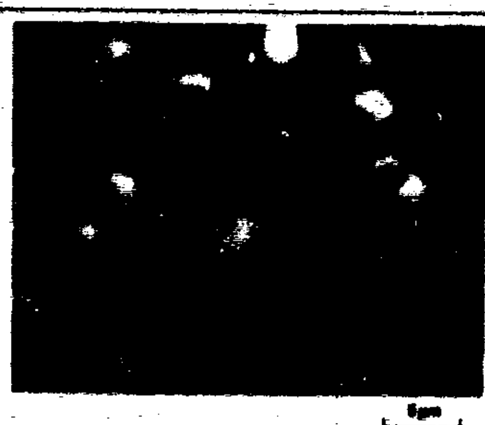
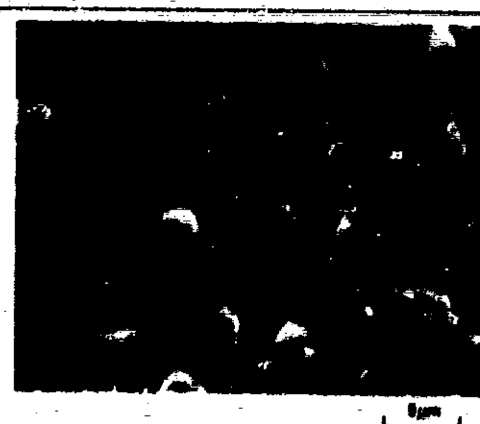
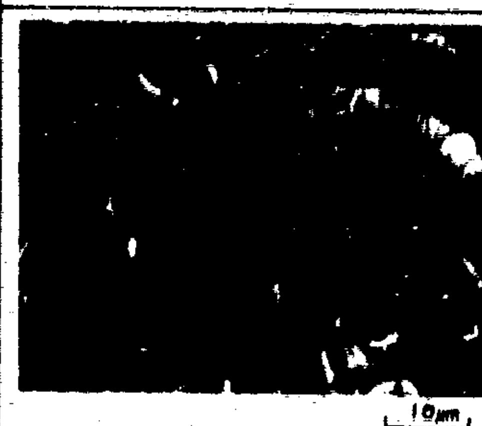
High-Cycle Fatigue Test Results for Inconel 718 Plate and Bar in Air and Sodium



Creep Crack Growth Test Results for SUS 304 Steel


Creep-Fatigue Crack Growth Test Results for SUS 304 Steel

■ REPRESENTATIVE TEST RESULTS FBR STRUCTURAL MATERIALS (3)

Materials	2¼Cr-1Mo Steel	SUS 304	Mod. 9Cr-1Mo Steel
Heat Treatment	Normalizing; 920～940°C Tempering ; 710～730°C	Solution Treatment; 1100°C	Normalizing; 1040°C Tempering ; 780°C
Cross-Sectional Micro Structures of Sodium Exposed Materials 550°C, 5000 H	 Bainite	 Austenite	 Tempered Martensite
Surface Micro Structures of Sodium Exposed Materials (SEM Image) 510°C, 10100 H			

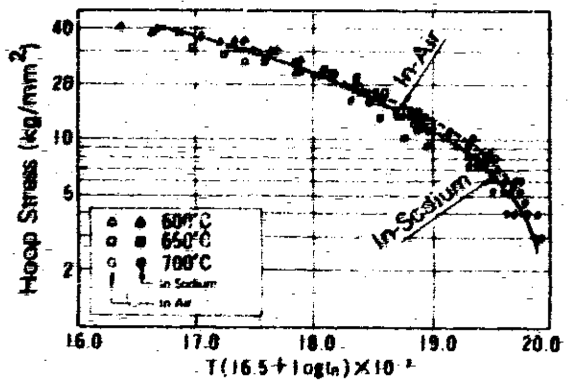
Chemical Compositions

2¼Cr-1Mo Steel	C	Si	Mn	P	S	Cr	Mo
	0.15	0.28	0.55	0.010	0.005	2.38	0.98

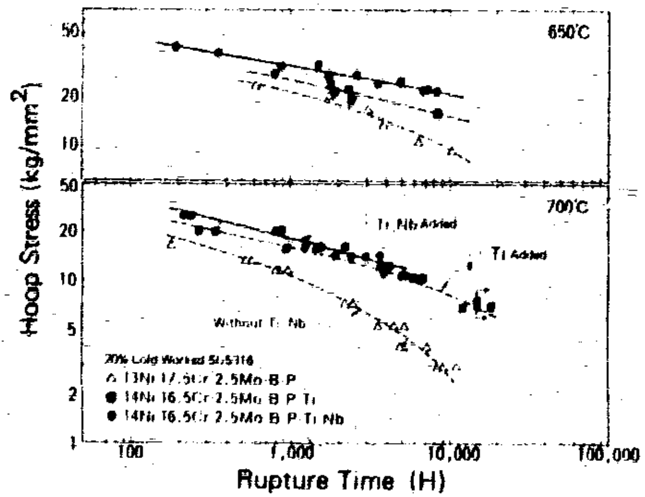
SUS 304	C	Si	Mn	P	S	Ni	Cr
	0.05	0.59	0.87	0.027	0.003	8.98	18.47

Mod. 9Cr-1Mo Steel	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	N
	0.10	[illegible]	0.41	0.007	0.004	0.07	8.37	[illegible]	0.21	[illegible]	0.046

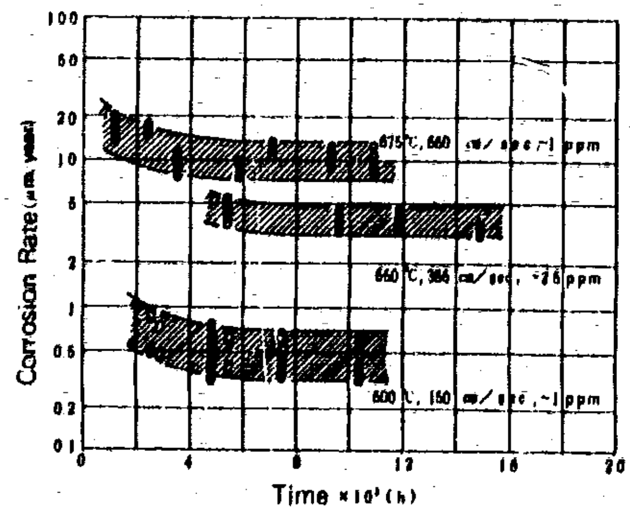
■ REPRESENTATIVE TEST RESULTS——FBR CORE MATERIALS (1)



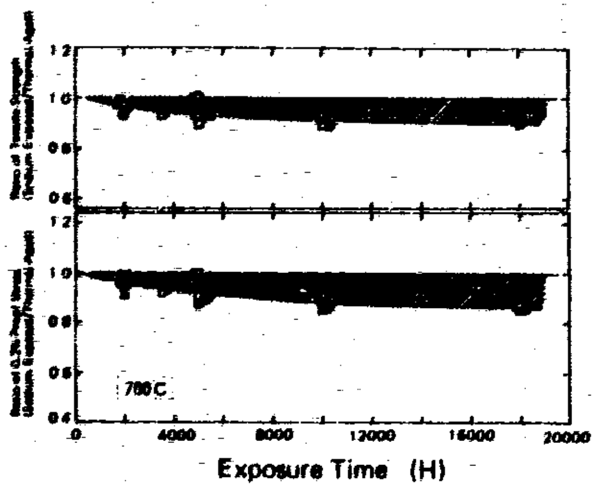
Master Internal Pressure Creep Rupture Data for SUS 316 Cladding Tube



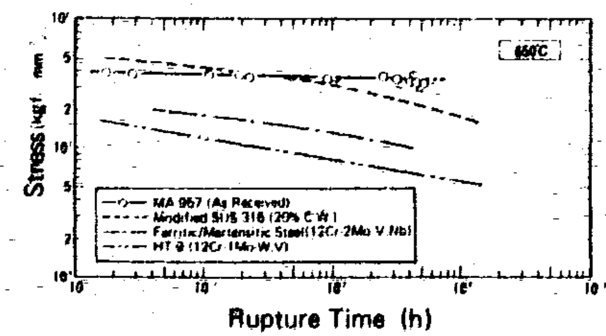
Effect of Ti and Nb on Internal Pressure Creep Rupture Strength in Sodium



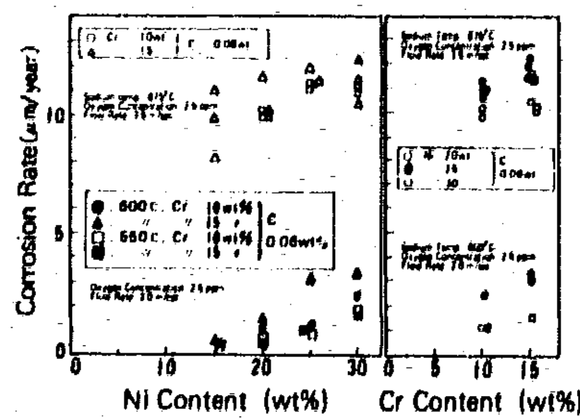
Relation between Corrosion Rate and Sodium Exposure Time for Mod. SUS 316 Cladding Tube



Effect of Sodium Exposing Time on Tensile Strength for Mod. SUS 316



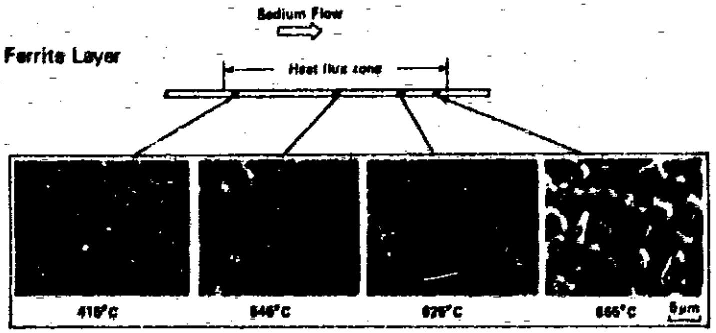
The Property of Creep Rupture of ODS Ferritic Steel in Air (Incoloy MA957)



Effect of Ni and Cr Contents on Corrosion Rate for Advanced Austenitic Stainless Steels

■ REPRESENTATIVE TEST RESULTS——FBR CORE MATERIALS (2)

Cross-sectional Microstructures of Mod. SUS 316 Cladding Tube after Exposure to Flowing Sodium (675°C, 6.6m/sec, 3600h)



Test Condition : Max. Temp. ~676°C
Sodium Flow Rate ~1.2m/sec
Heat Flux 200w/cm²

Scanning Electron Micrographs of the Cladding Surface

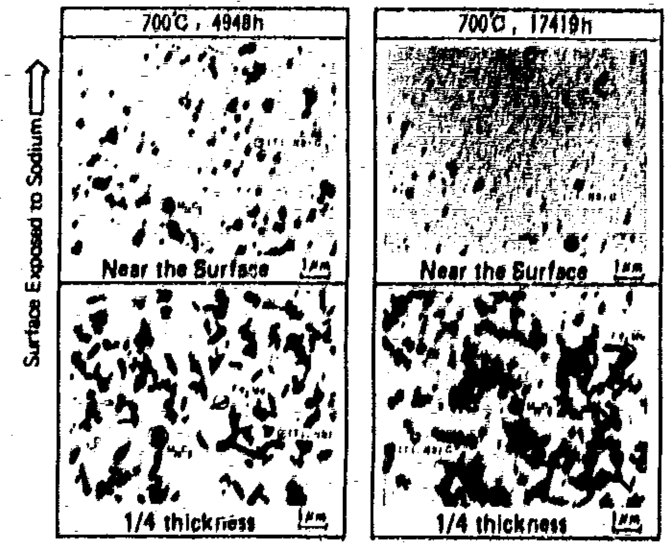
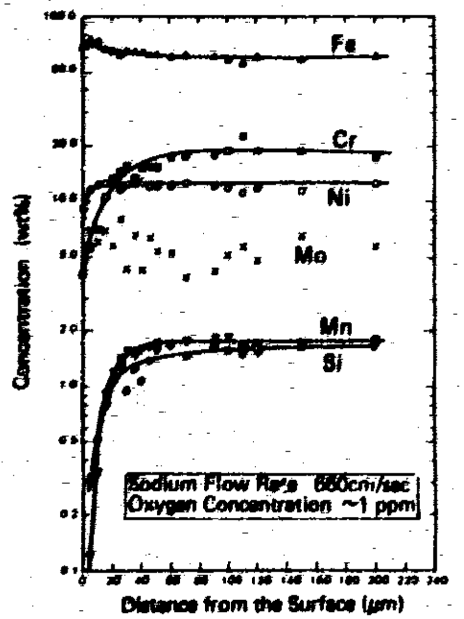
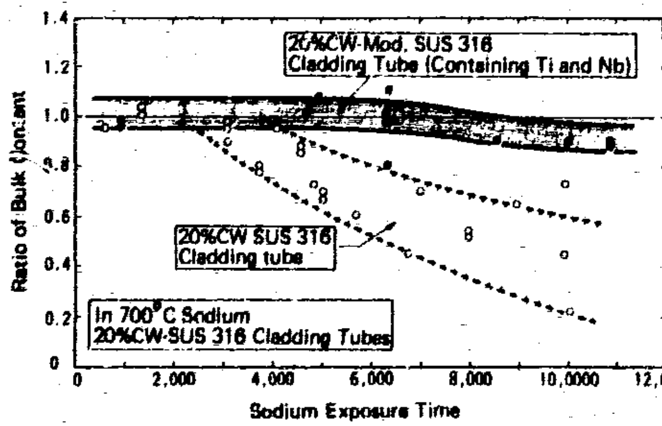


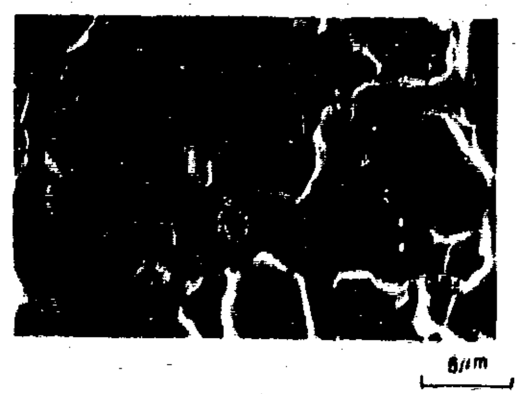
Image of Extraction Replica of Internal Pressure Creep Rupture Test Specimen in Sodium (Mod. SUS 316)



Profiles of the Major Elements of Mod. SUS 316 Cladding Tube after Exposure to Flowing Sodium (675°C, 6.6m/sec, 16800h, EDS Analysis)

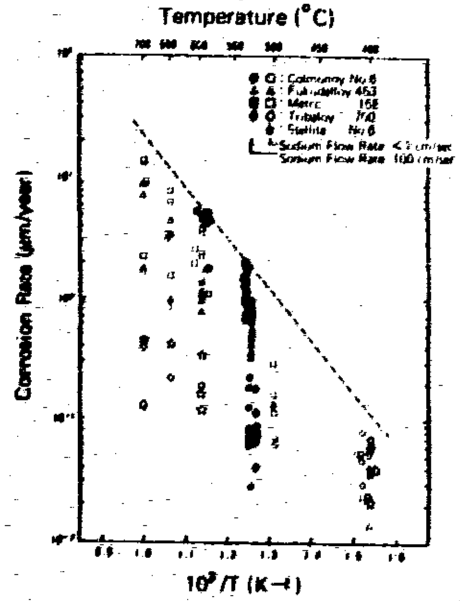


Change in Bulk Carbon Contents after Creep-Rupture Tests for SUS 316 and Mod. SUS 316 in 700°C Sodium

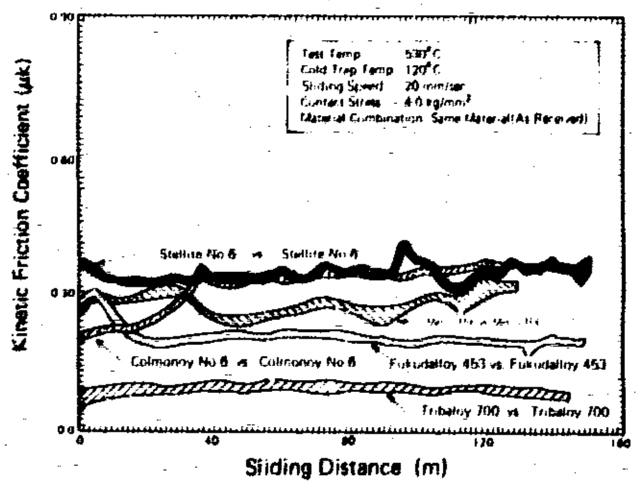


A Surface Microstructure of ODS Ferritic Steel Exposed in Flowing Sodium (675°C, 6.6m/sec, 2000h, Incoloy MA957)

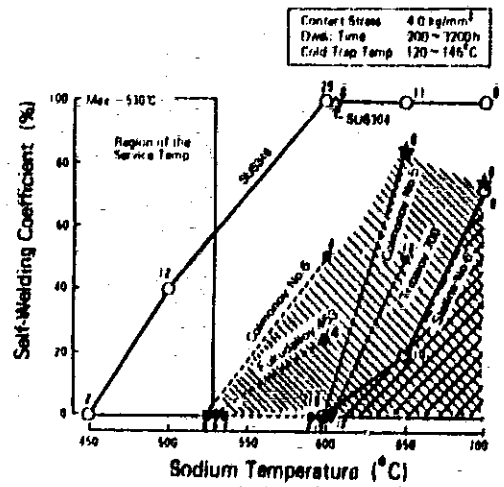
■ REPRESENTATIVE TEST RESULTS — HARD FACING MATERIALS



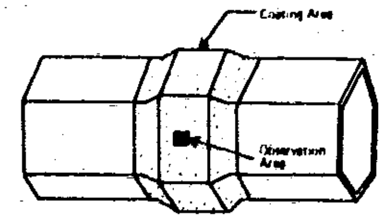
Effect of Sodium Temperature on Corrosion Rate for Hard-Facing Materials in Sodium



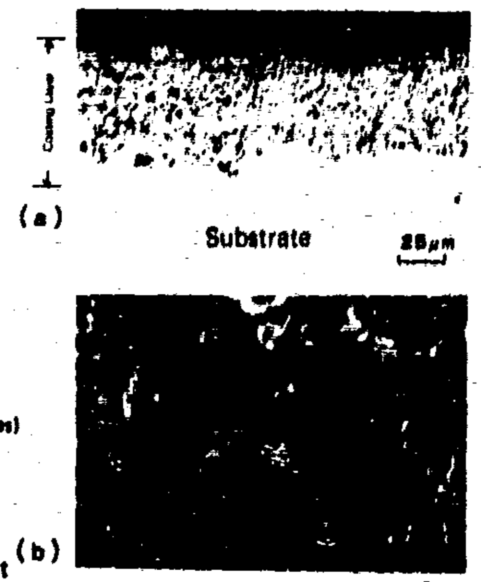
Friction Behavior of Cobalt-Free Hard-Facing Materials in Sodium



Self-Weldability of Hard-Facing Materials in Sodium (Combination between Same Materials)

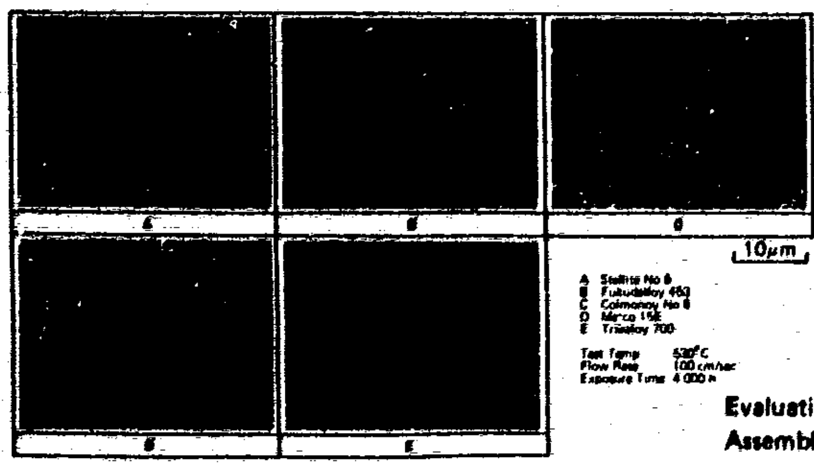


Schematic Illustration of Duct Load Pad



(a) A Cross-Sectional Microstructure after Thermal Cycling Test in Sodium. (420°C~600°C, Max. 30°C/s, 100 cycles)
(b) A Surface Microstructure after Sodium Exposure Test (600°C, 7800h)

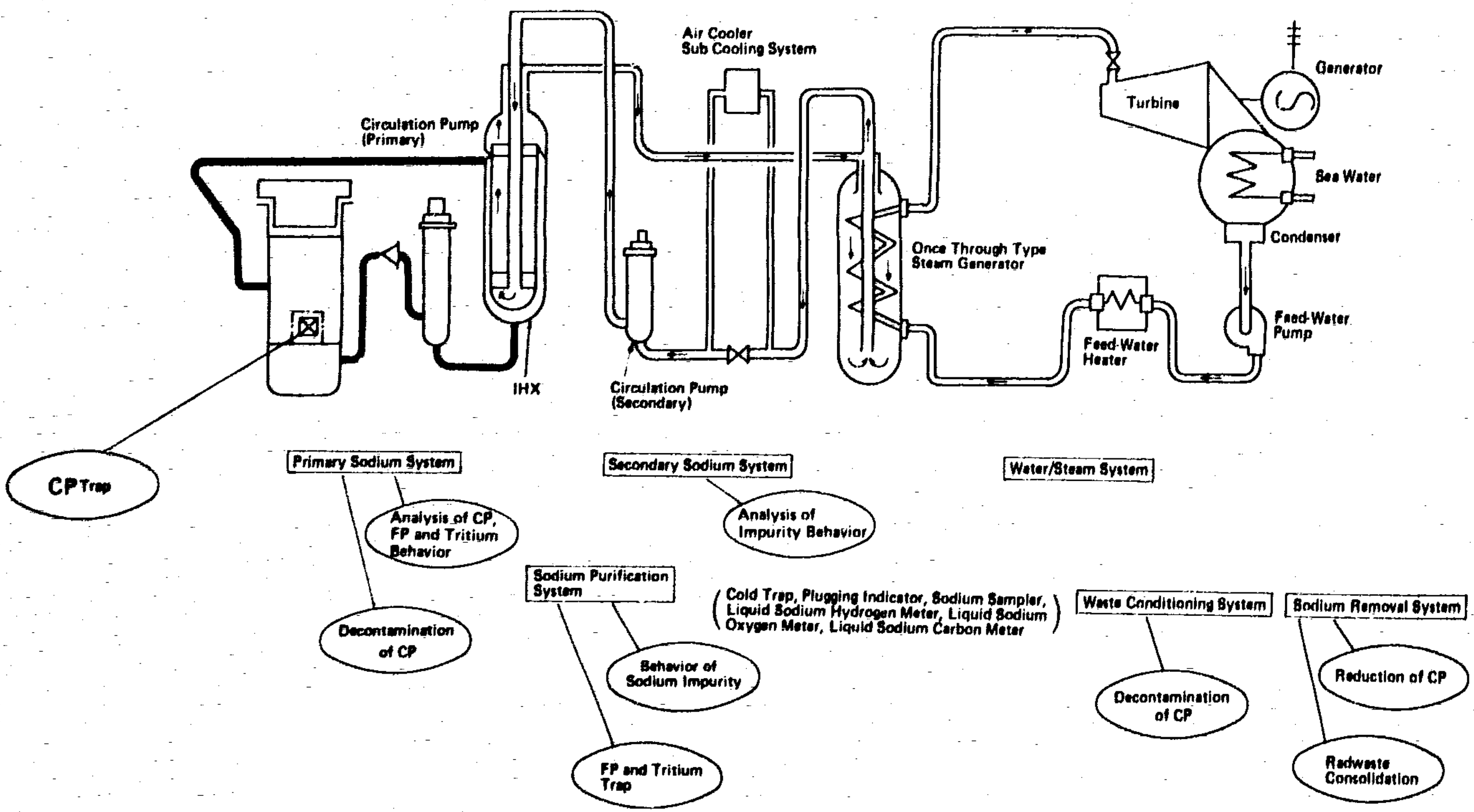
Evaluation of Tribological Coatings for the Fuel Assembly Duct Load Pads in Sodium Environment



Surface Microstructures of Hard-Facing Materials after Flowing Sodium Exposure

■ SODIUM TECHNOLOGY AREA—SODIUM AND RADIOACTIVE IMPURITY

An Example of FBR Plant System



■ CHARACTERIZATION OF SODIUM TECHNOLOGY AREA

Radioactive Material Test in Sodium		(CP)	(FP)
	Concerned Region	o Primary System and Sodium Removal Facility from Exchanged Fuel Assemblies	o Primary System and Gasuous Processing System
(CP & FP)	Operational Phase	o During Normal Operation	o During Operation with Failed Fuel
• To Decrease Radiation Exposure to Plant Personnel	Source	o Activation of Core Materials/Corrosion in Sodium	o Nuclear Fission/Cladding Failure
• To Prevent Contamination in FBR Primary System	Nuclide	o ^{54}Mn, ^{60}Co, ^{58}Co	o Such many Kinds as ^{137}Cs, Rare Gase and Rare Earth etc.
	Decreasing Method	o CP Trap, Decontamination of Radioactivity	o FP Trap, Decontamination of Radioactivity

Sodium Impurity Measurement and Control Test		(Oxygen)	(Carbon)	(Hydrogen)	(Tritium)
Chemical Impurities & Tritium	Concerned Region	o Primary and Secondary System	o Primary and Secondary System	o Secondary System	o Primary, Secondary and Water/Steam System and Environment of Plant
To Assure Reliability of Core and Structural Material in Sodium	Operational Phase	o During Normal Operation	o During Normal Operation and In-leak of Pump Oil	o During Normal Operation and Failure of Heat Transfer Tube of SG	o During Normal Operation
• To Assure Reliability FBR Plant Operation	Source	o Air Contamination	o Carbon Transfer of Structural Material in Sodium and In-leak of Pump Oil	o Corrosion in SG / Diffusion of Nascent Hydrogen and Sodium-Water Reaction	o Fast Neutron Induced Reaction in Control Rod and Ternary Fission in Fuel Diffusion
	Control Method	o Cold Trap	o Cold Trap (maybe)	o Cold Trap	o Cold Trap or Tritium/Hydrogen Chemical Trap
	Measurement Method	o Sampler o Plugging Indicator Vanadium Equilibration Method (Oxygen Meter)	o Sampler o Carbon Meter Specimen Equilibration Method	o Hydrogen Meter (Plugging Indicator)	

■ DOCUMENT OF RADIOACTIVE MATERIAL TEST IN SODIUM

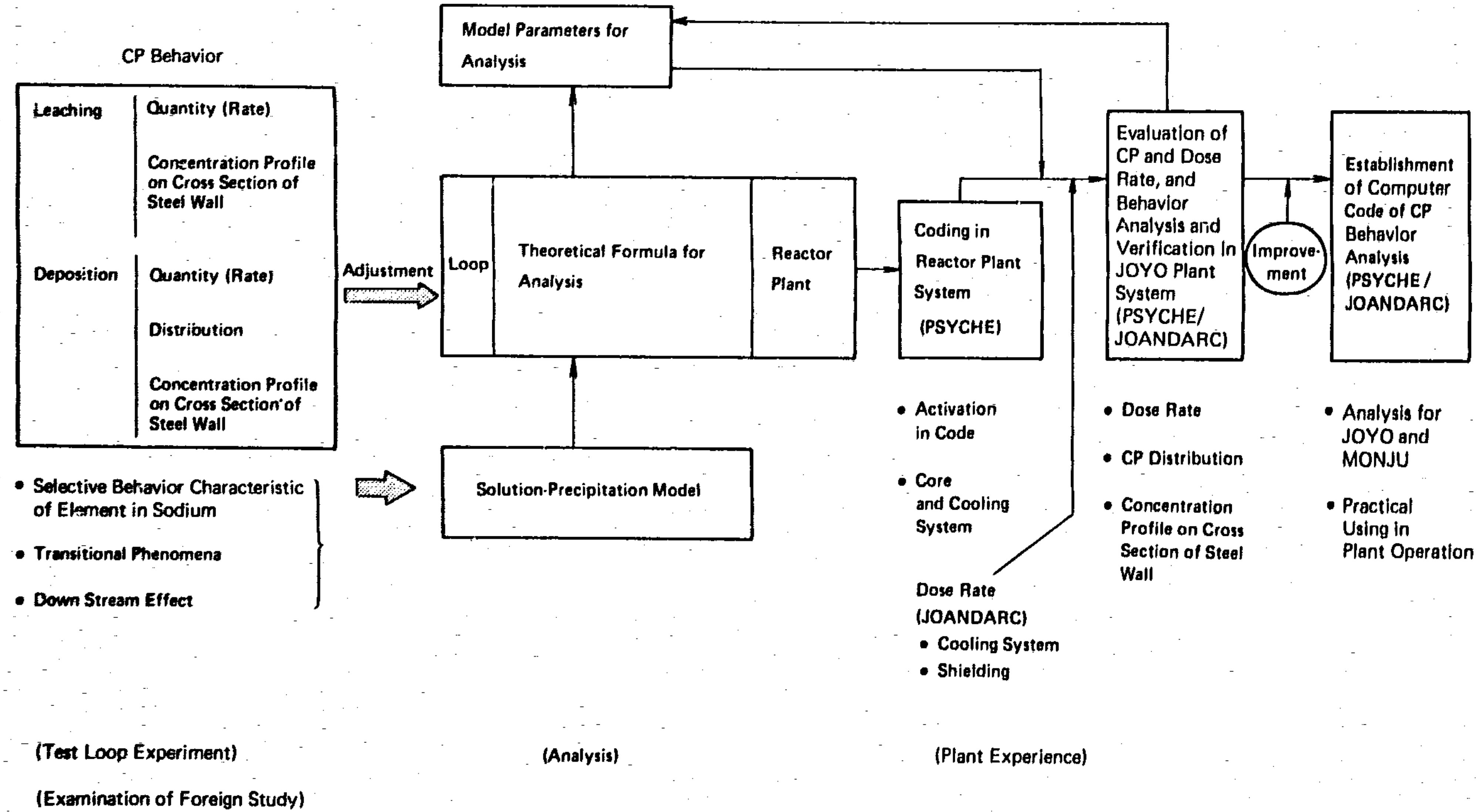
Test Item	Type or Method	Result and Subject
CP Behavior Test	Out-Pile Loop Experiment	Understanding and Quantifying of Characteristics of CP Behavior (Selectivity Characteristics of Elements, Transitional Phenomena, Down Stream Effect) was finished. Characterization of Particulate Mechanism of CP Behavior is required, especially with Progress of Advanced Core Materials.
Development of Computer Code for CP Behavior Analysis	Formulation of Solution-Precipitation Model and its Coding (PSYCHE) and Combining with Dose Rate Analysis Code (JOANDARC)	Formulation of Theoretical Formula for Analysis, and Determination of Model Parameters by Using Results from the Test Loop Experiment and JOYO Operation was finished. Coding of CP Source Term (PSYCHE) and Combining with Dose Rate Analysis in Reactor Plant Systems (JOYO and MONJU) was finished. Verification of PSYCHE/JOANDARC by Evaluation of CP and Dose Rate in JOYO was finished. Analysis and Evaluation of CP Source Term and Dose Rate in MONJU was finished. Development of Its Availability in Plant Operation is required.
Development of CP Trapping	Nickel Getter Type Installed in Core Subassembly and Reflector	Development of Trapping Materials of High Efficiency Type is processing. Which is especially Effective on Decreasing of ^{54}Mn and Dose Rate. Characterization Test of Trapping Material (Dependency of Temperature, Sodium Flow, Shape, Exposure Time and Nickel Mass Transfer on Trapping Efficiency and Corrosion Problem) and Modelling for Design were finished. Demonstration Test of a Type of CP Trap is proceeding in JOYO.
Evaluation of Methods to Prevent or Control Source Rate of CP	Evaluation by Using Analytical Model	Evaluation of effects by Decreasing of Oxygen, Cobalt Impurity Level in Core Materials and using Cobalt Free Hard Facing Materials were in practical using in Plants.
Development of Cesium Trap	RVC Filled Type Installed in Sodium Purification System	Selection of RVC Material with Fine Struct, Characterization Test of Trapping Material (Effect of Temperature, Cesium Concentration, and Pre-processing on Trapping Efficiency), and Confirmation of Non-existence of Carburization Effect were finished. Practical using Program is proceeding in JOYO. Development of High Quality Type and its Test in Sodium are required.

■ DOCUMENT OF SODIUM IMPURITY MEASUREMENT AND CONTROL TEST

Test Item	Type or Method	Result and Subject
Development of Sodium Sampling Method	By-pass Flow Through Sampling Method	Used in the Primary and Secondary System of JOYO and the Test Loops for R&D.
Development of Plugging Indicator	Type of Precipitation and Solution at Orifice	Development of Plugging Indicator being able to Indentify Impurities.
Development of Liquid Sodium Hydrogen Meter and its Behavior Test	Diffusion Type with Nickel Membrane	Study on Oxygen and Hydrogen Interaction in Sodium.
Development of Liquid Sodium Oxygen Meter	Electrochemical Type	Development of Long-lived Oxygen Meter is required.
Development of Liquid Sodium Carbon Meter	Diffusion Type with Thin Membrane	Higher Sensitive Carbon Meter and Quantifying is required.
Impurity Measurement in Sodium with Specimen Equilibration Method	Specimen Equilibration Method	• Development of Specimen Equilibration Device. • Establishment of Measurement Method of Oxygen with Vanadium Wire Method. • Development of Carbon Measurement Method with Fe-12Mn and SUS304L is proceeding.
Development of Regeneration Method of Cold Trap in Secondary Sodium System	Method of Thermal Decomposition of Hydride and Sweeping Gas from Liquid Surface	Completion of Conceptual Design.
Development of New Method for Removal and Storage of Tritium and Hydrogen in Sodium System	Type of Metallic Alloy for Hydrogen Storage	Feasibility Study is required on Availability of Metallic Alloy for Hydrogen Storage in Sodium System.

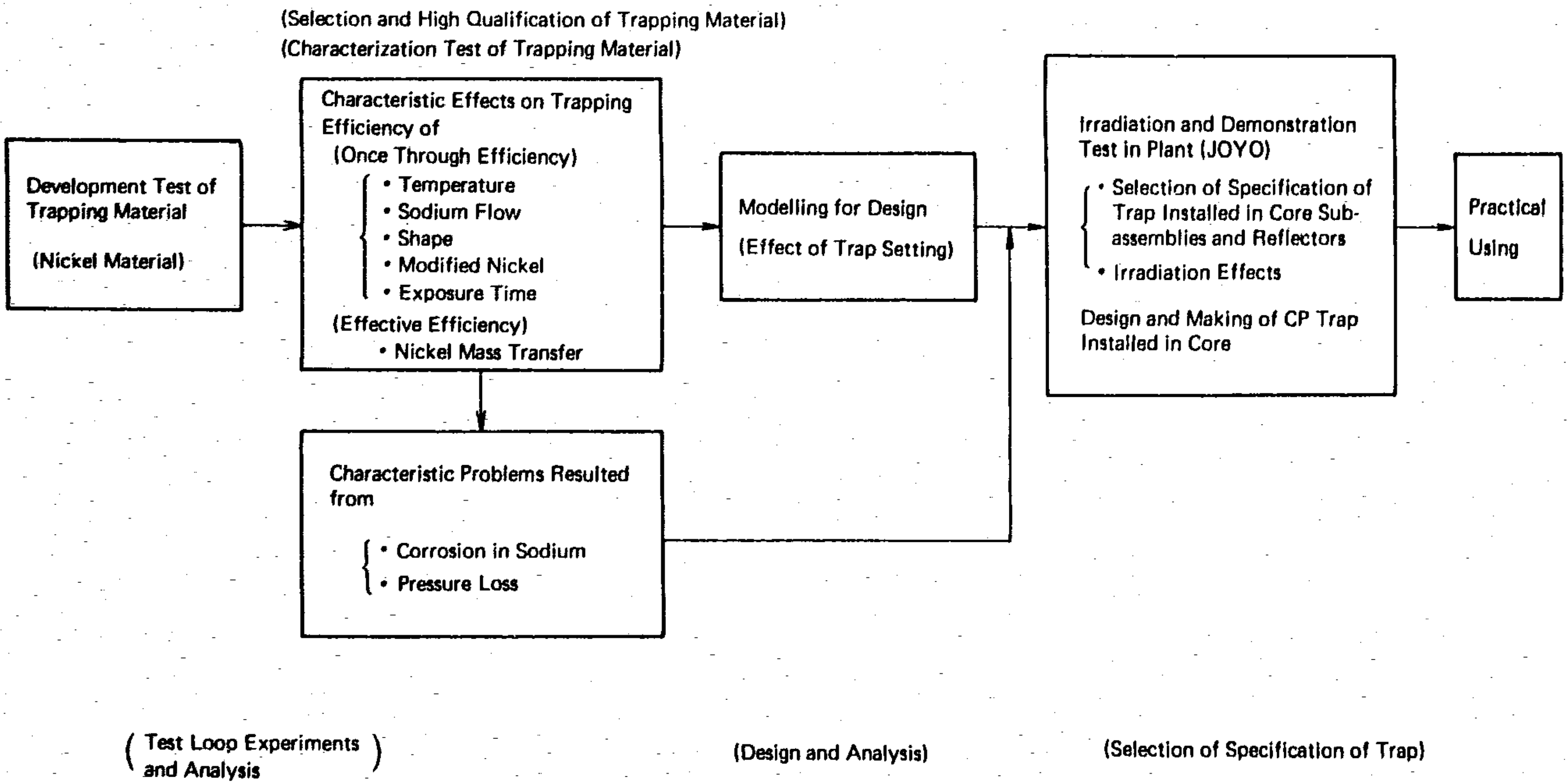
■ DEVELOPMENT OF COMPUTER CODE FOR CP BEHAVIOR ANALYSIS

(PSYCHE/JOANDARC)



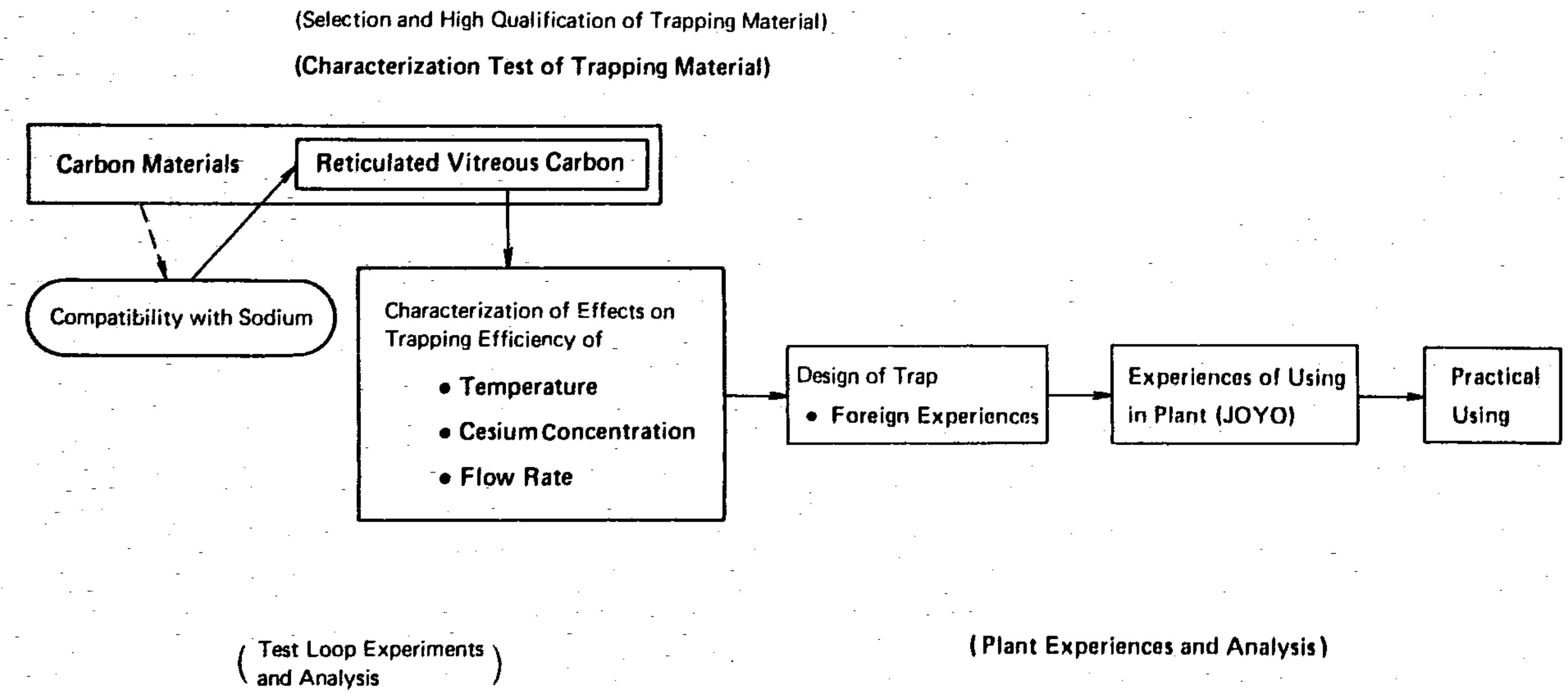
■ DEVELOPMENT OF RADIOACTIVITY CONTROL METHOD ——DECREASING RADIATION EXPOSURE (1)

Development of CP Trapping Method



■ DEVELOPMENT OF RADIOACTIVITY CONTROL METHOD —DECREASING RADIATION EXPOSURE (2)

Development of FP Trapping Method — Cesium Trap.



■ APPARATUS FOR RADIOACTIVE MATERIAL TEST IN SODIUM

Utilization ; To Study CP Behavior and Develop Methods of CP and Cesium Trapping.

Characteristics ;

Constitution : Main and Purification Circuit (One System for Each of Them)

Materials : SUS316 (Heater, Cooler, Hot-Leg Piping)
SUS304 (Cold-Leg Piping, Other Components and Piping)

Sodium Inventory : 20 ℓ

Maximum Temperature : 650°C

Maximum Flow Rate : 6.5 ℓ/min

Main Piping : 17.2 mm O.D.×2.0 mm thick.

Test Section ;

The main circuit has test sections: the corrosion test section (T-1) in which irradiated specimens are exposed, followed by hot-leg piping, the CP Trap test section (CPT), and a deposition test section (T-2) in cold-leg piping.

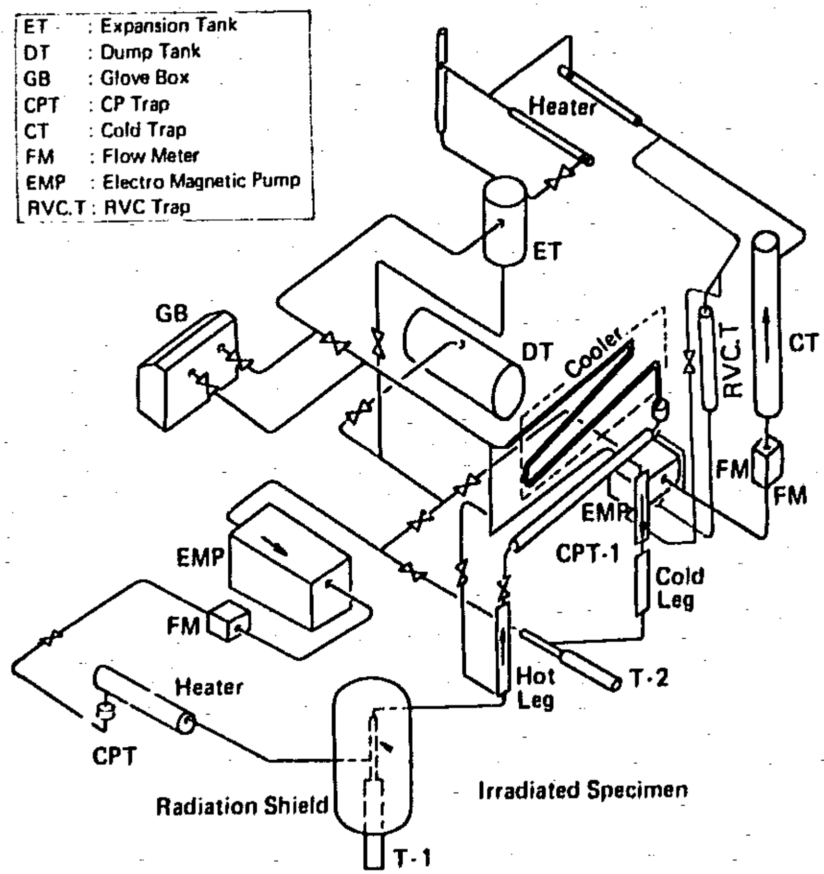
The purification circuit also has test sections : the cold trap and cesium trap, i.e. RVC trap (RVC).

Examples of Experimental Condition ;

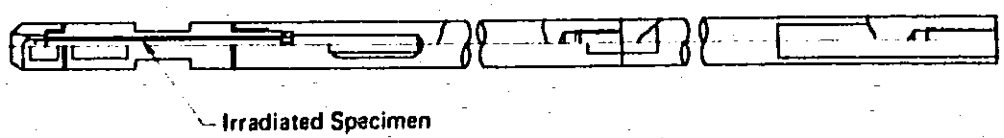
Temperature : 530°C (T-1), 530°C (CPT), 400°C (T-2), 120°C (CT) and 200°C (RVC)

Flow Velocity : 5.6 m/sec. (T-1)

Oxygen Level in Sodium : 2.5 ppm



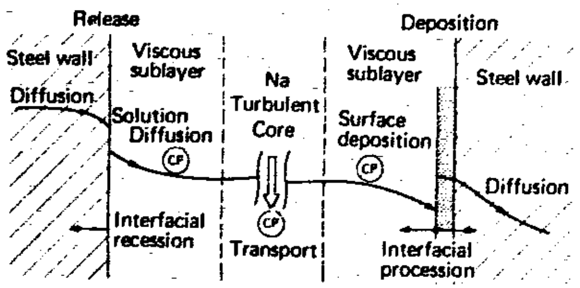
Schematic drawing of Activated Material Test Loop-II



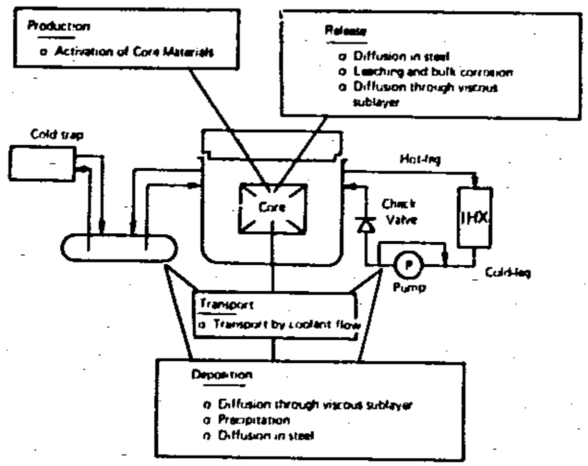
Test Specimen Holder (T-1)

■ MAIN RESULTS—RADIOACTIVE MATERIALS BEHAVIOR AND CONTROL IN SODIUM

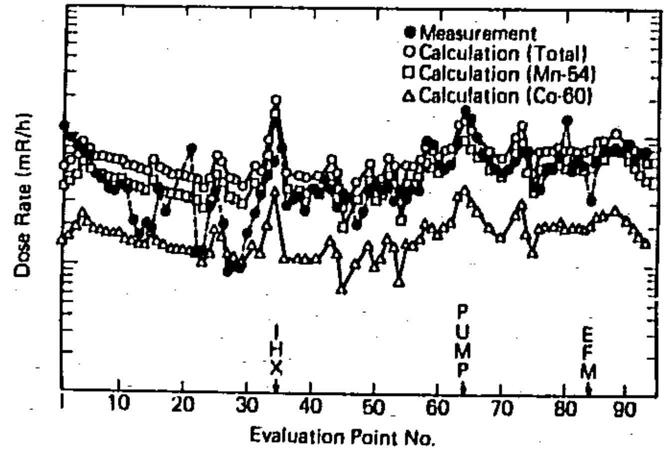
Development of Computer Code (PSYCHE) for CP Behavior Analysis



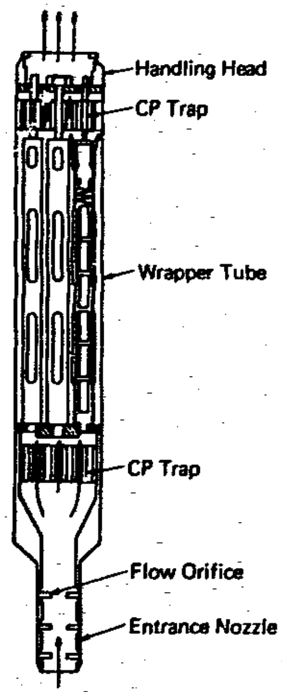
"Solution-Precipitation Model" for CP Behavior Analysis



Simulation System of CP Behavior in FBR Plant

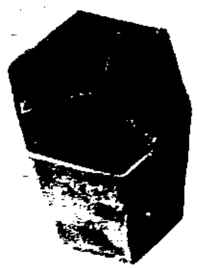


Comparison of Measured vs. Calculated Gamma Radiation Levels along JOYO Primary Main Circuit Piping (Cumulative Reactor Output, 8.4×10^4 MWd)

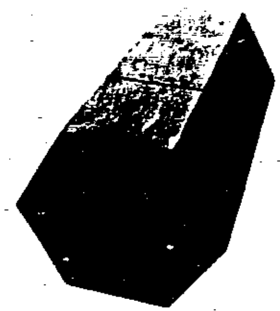


Core Subassembly and Reflector with CP Traps

Development of CP Trap

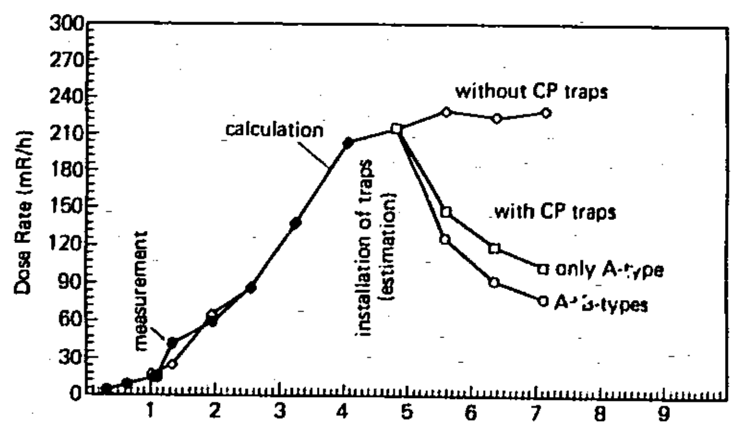


High Efficiency Trap Type (A)



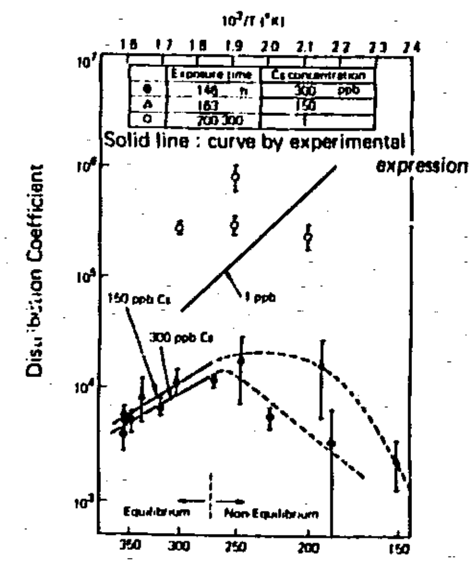
Reflector and Trap Type (B)

Core Region of Installing CP Traps
A-types: Inner and outer reflectors
B-types: 4th and 5th rows in core fuel assembly



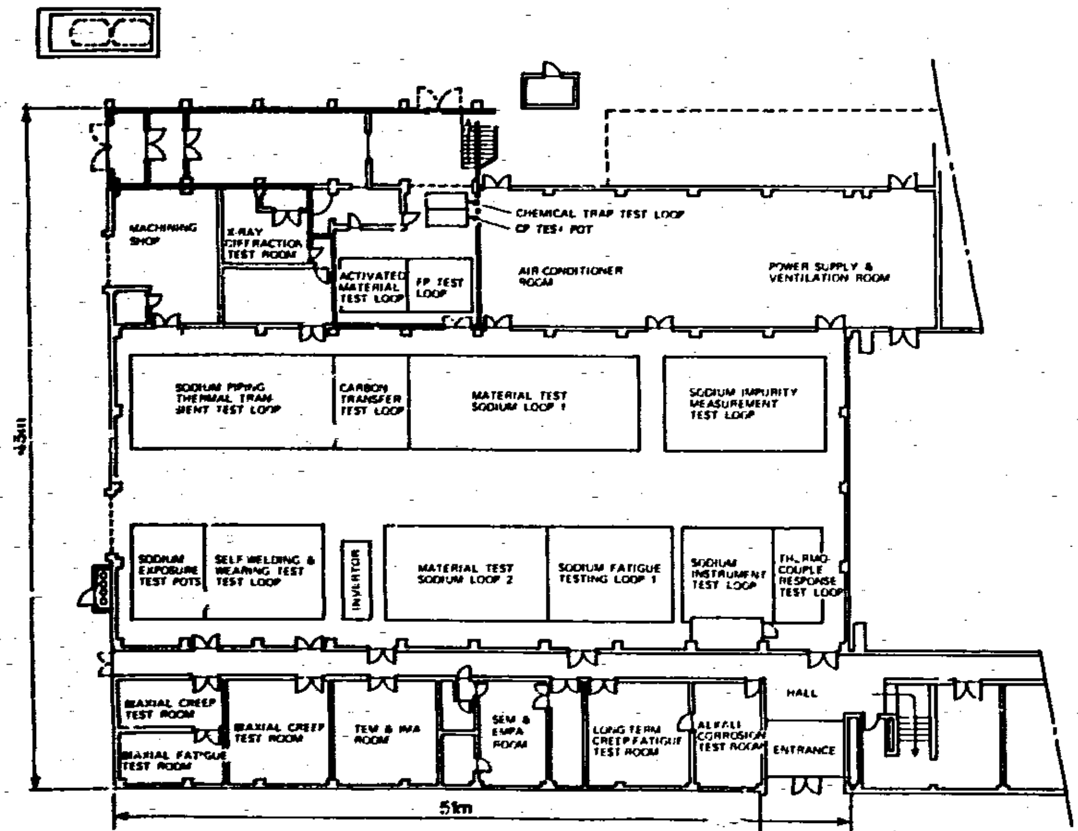
Prediction of Effect of Installing CP Traps in JOYO

Development of Cesium Trap



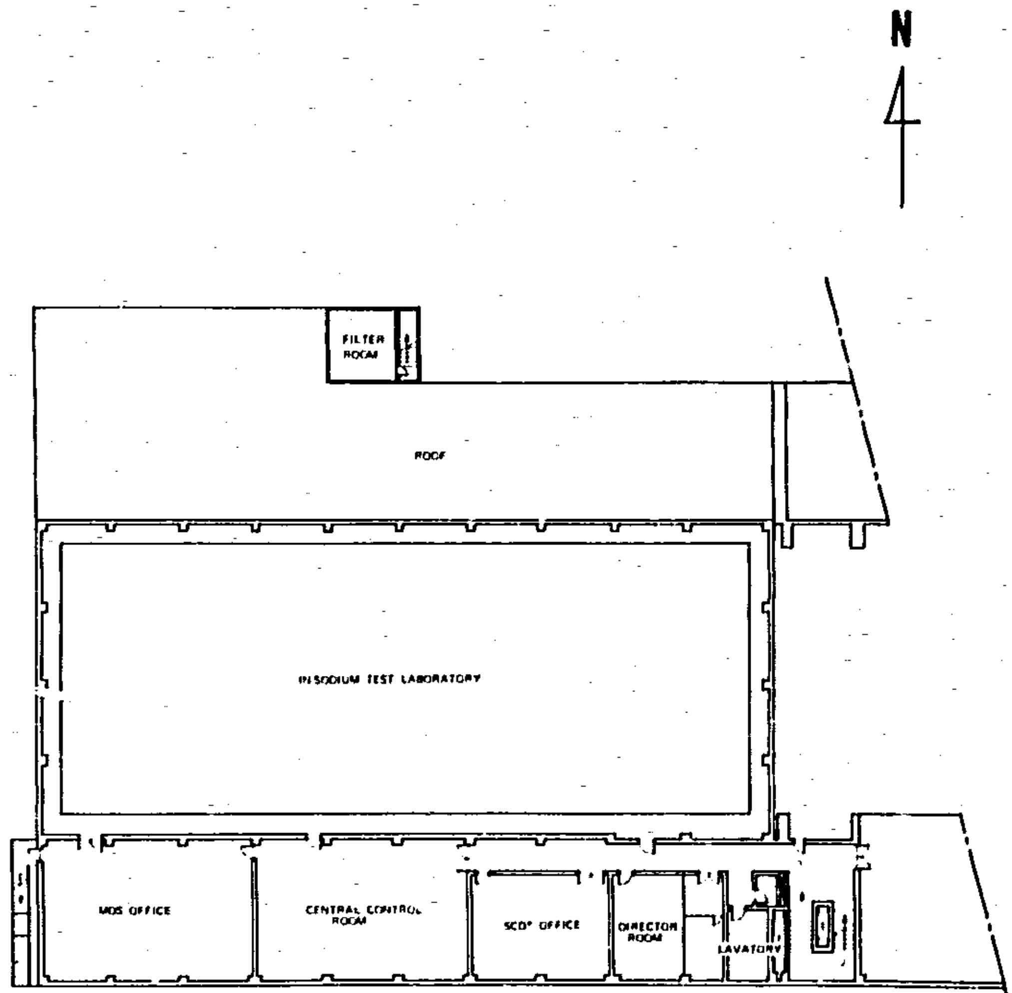
Distribution of Cesium between Trap Material (RVC) and Sodium

■ LAYOUT OF THE FIRST FACILITY OF THE MATERIALS DEVELOPMENT SECTION



RADIATION CONTROL AREA

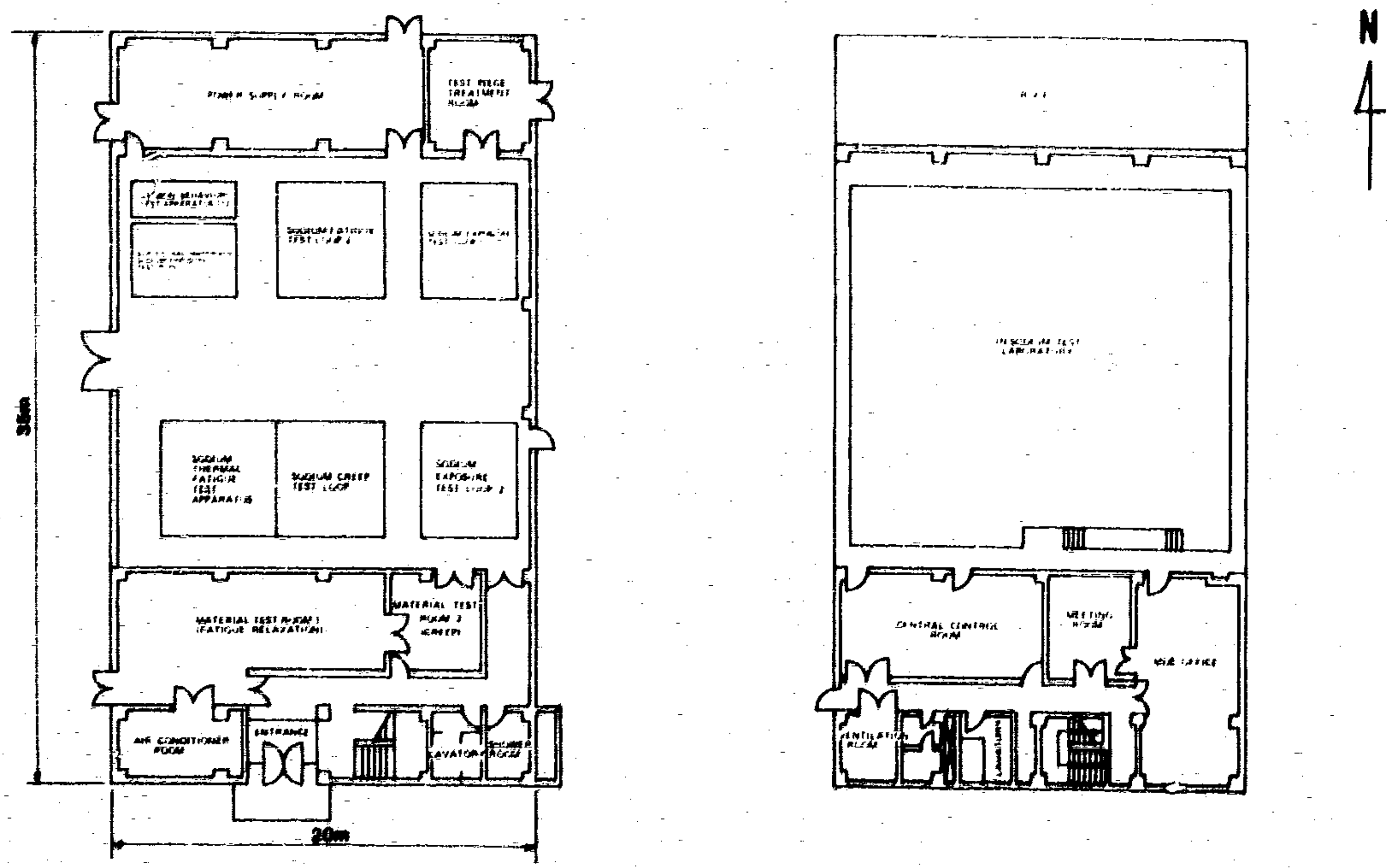
(1F)



SCD* : SYSTEMS & COMPONENTS DIVISION

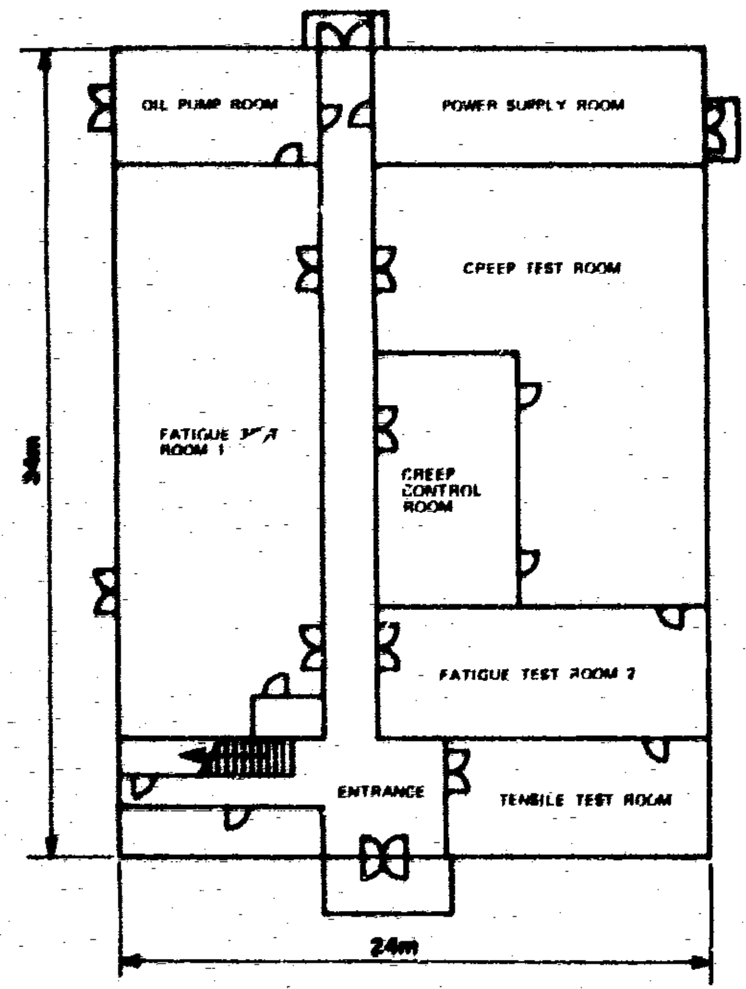
(2F)

■ LAYOUT OF THE SECOND FACILITY OF THE MATERIALS DEVELOPMENT SECTION



(1F)　　(2F)

■ LAYOUT OF THE THIRD FACILITY OF THE MATERIALS DEVELOPMENT SECTION



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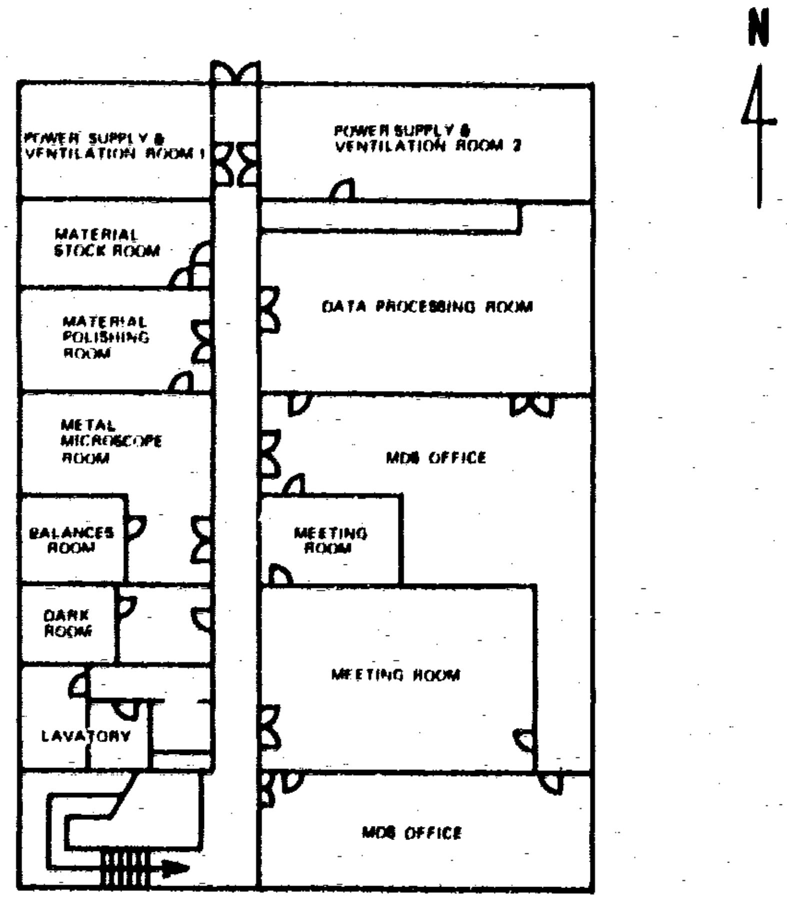

(2F)

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