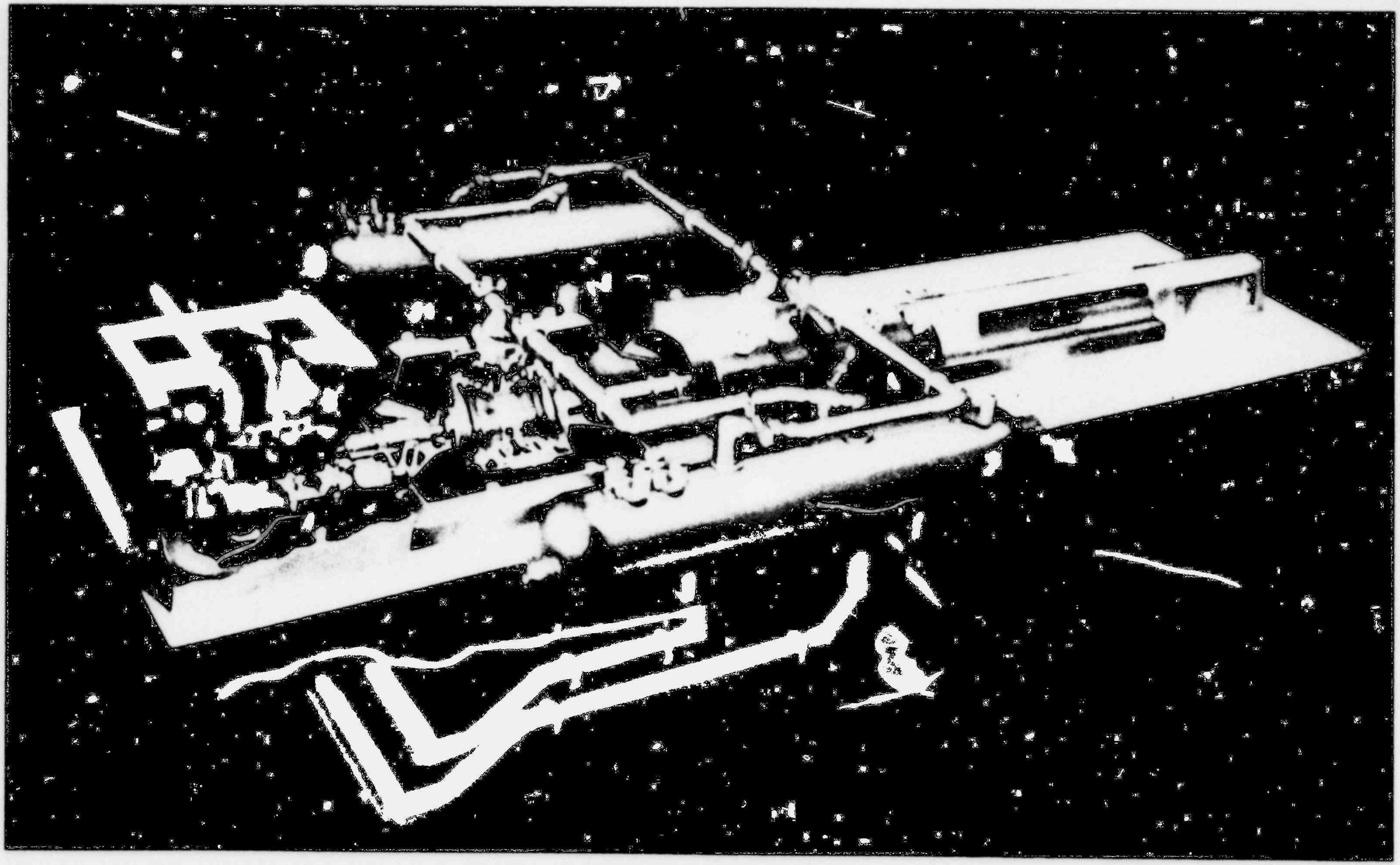
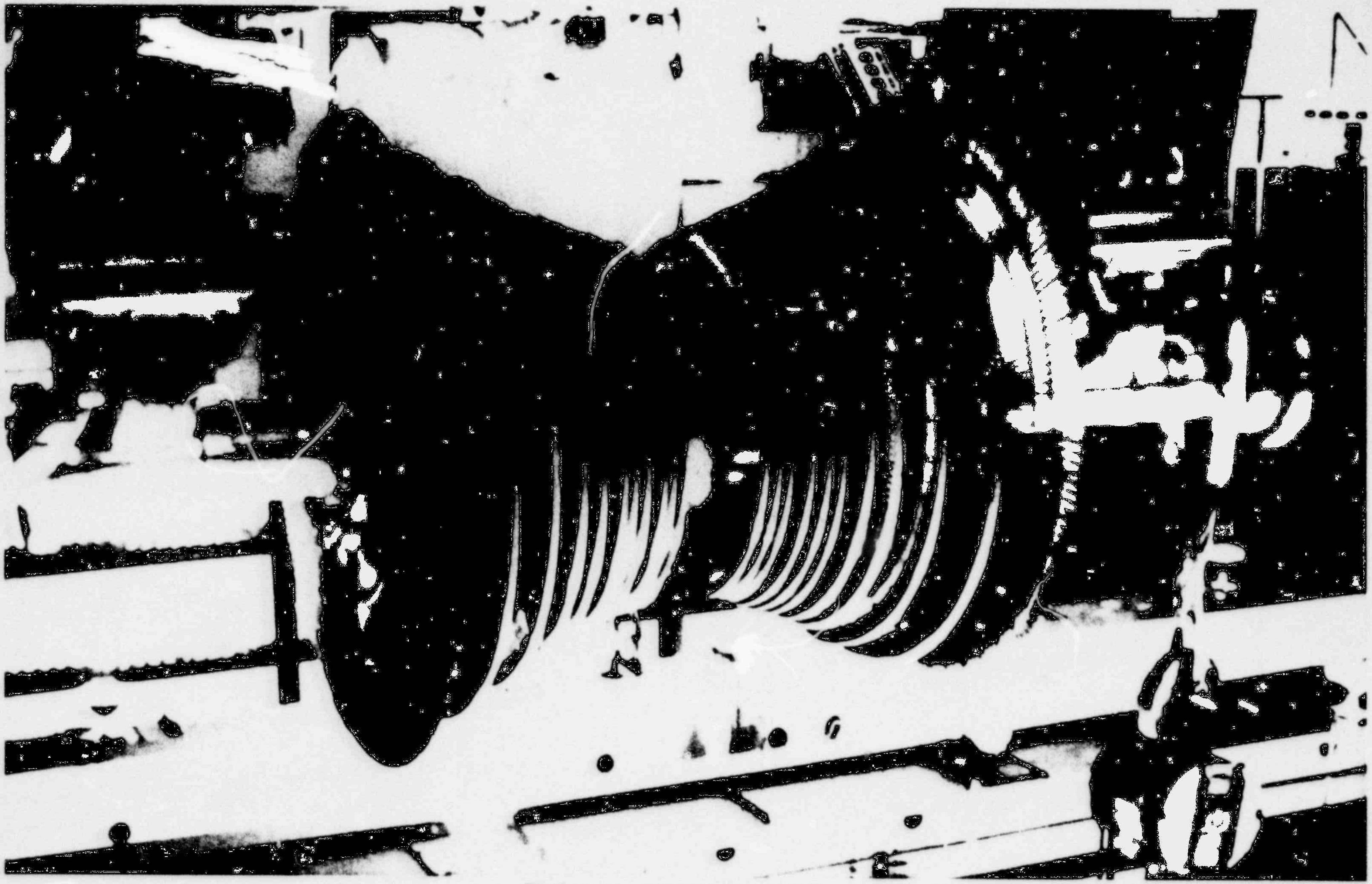
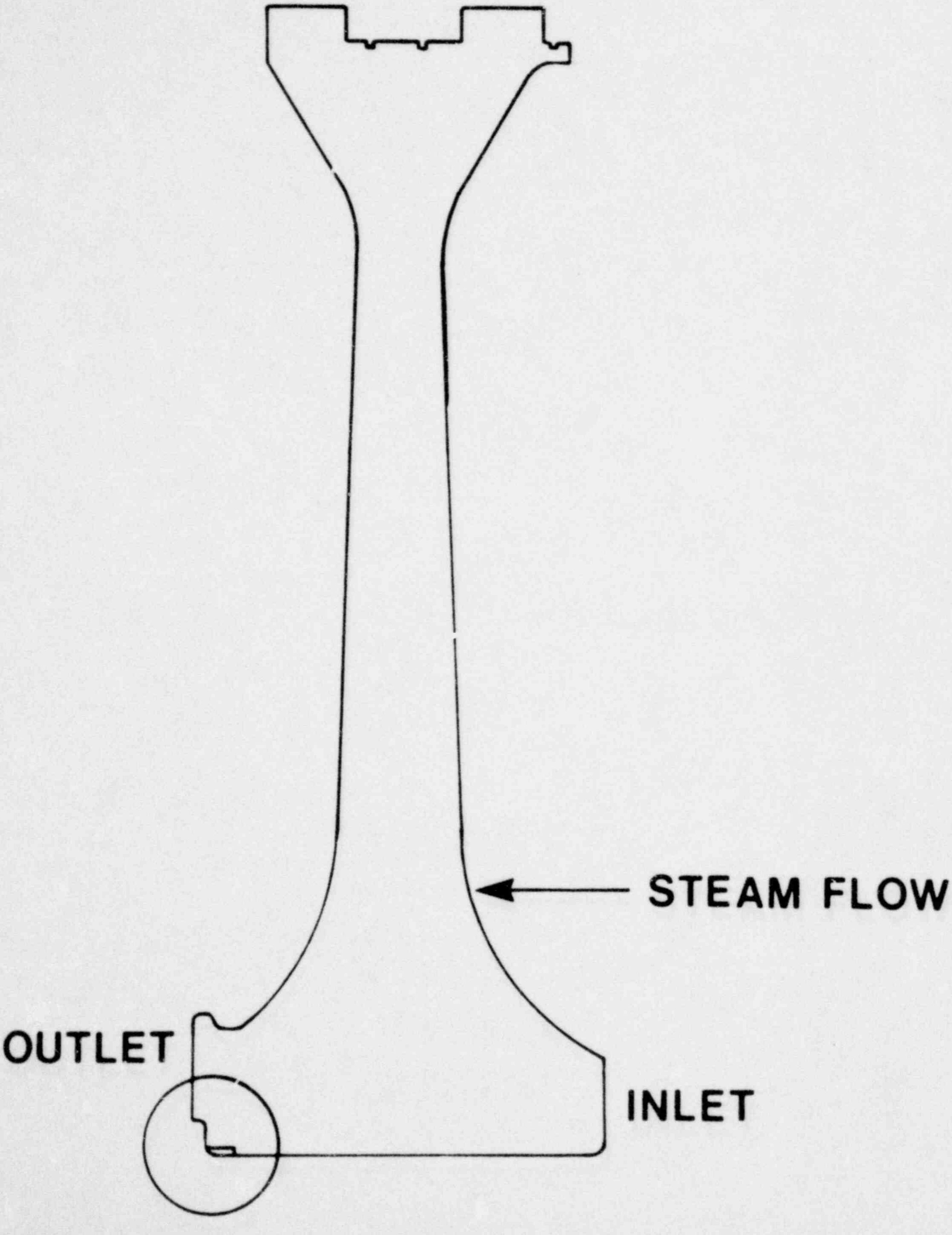
INTRODUCTION

V. S. Andersen

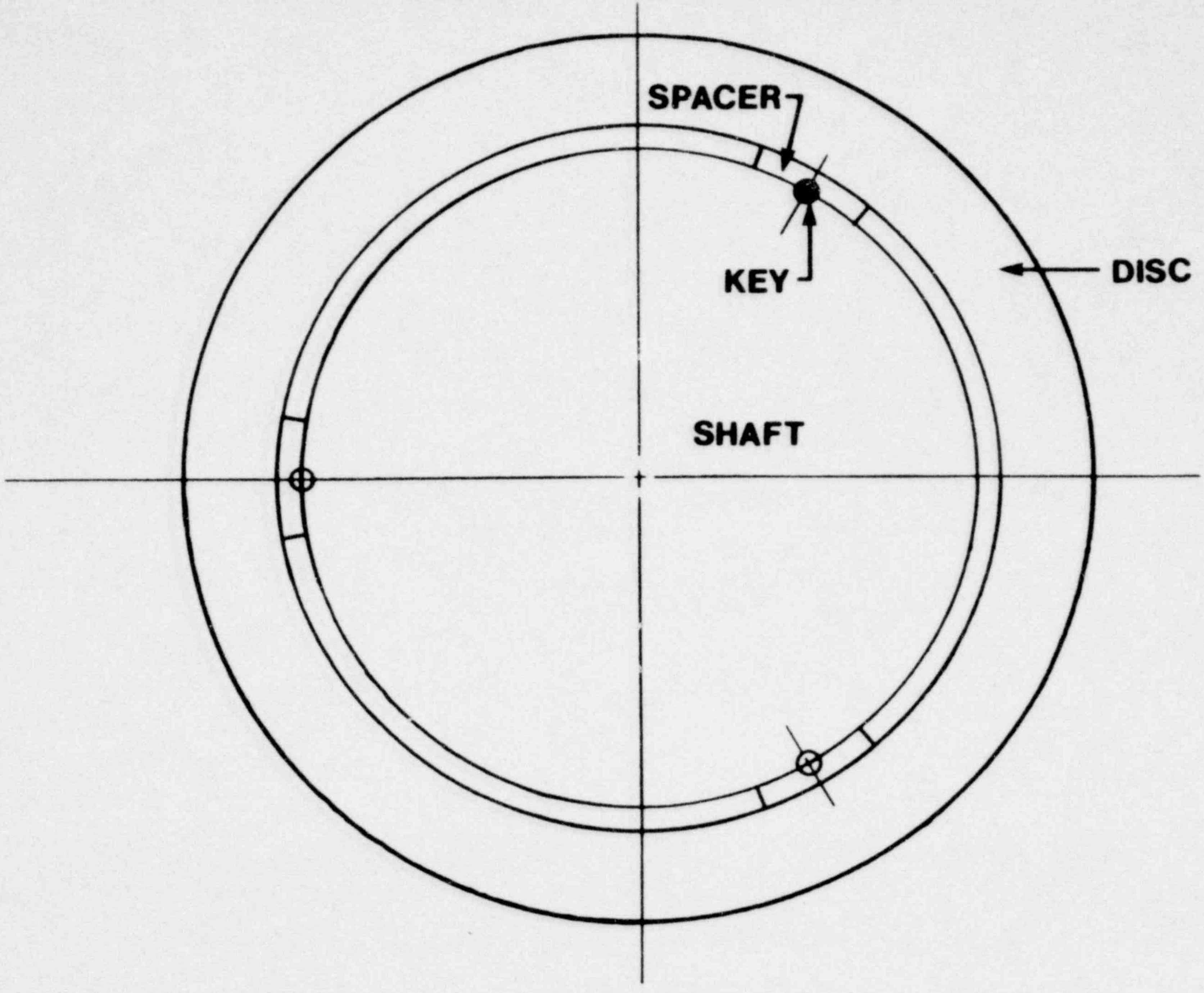




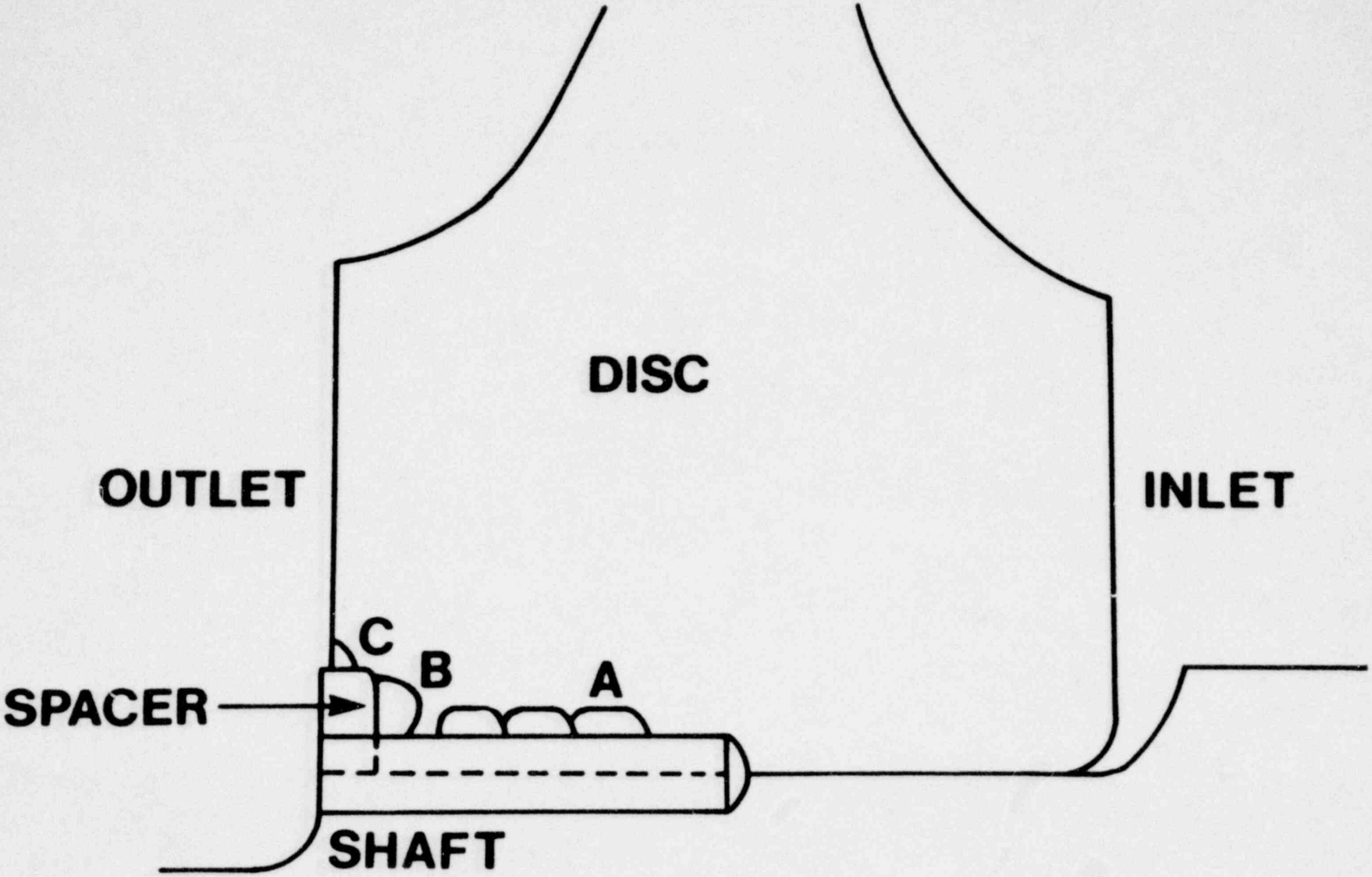
DISC CRACK AREA

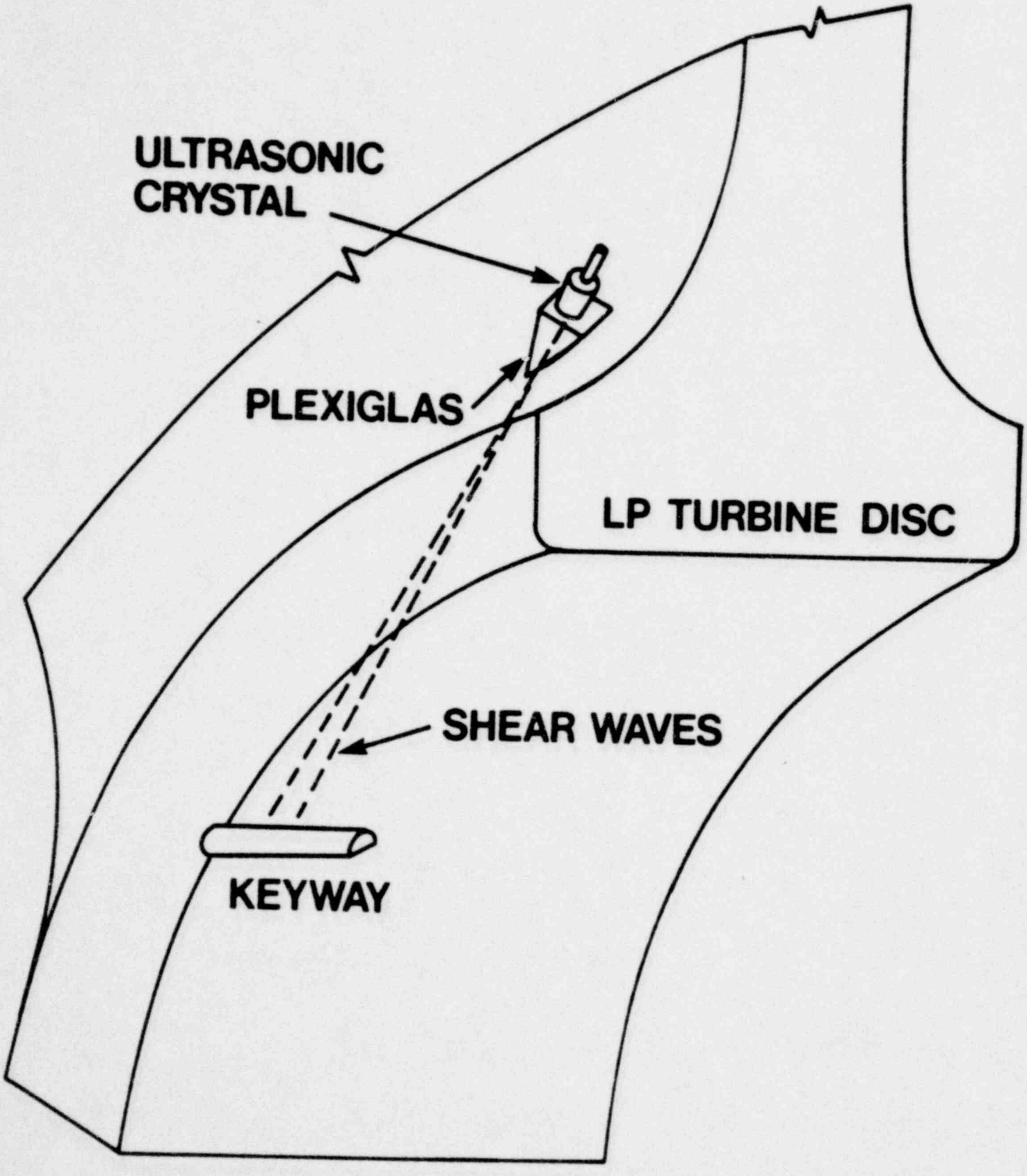


END VIEW OF DISC SHAFT



DISC CRACK LOCATIONS




ULTRASONIC CRYSTAL
PLEXIGLAS
LP TURBINE DISC
SHEAR WAVES
KEYWAY

PRIORITY CATEGORIES

AA – NUCLEAR WITH MORE THAN FIVE YEARS IN-SERVICE PERIOD OR SIGNIFICANT CORROSION

A – NUCLEAR WITH LESS THAN FIVE YEARS IN-SERVICE PERIOD

B – FOSSIL WITH ROUND KEYWAYS

C – FOSSIL WITH RECTANGULAR KEYWAYS

CORRECTIVE ACTION OPTIONS

- LIMITATIONS ON RUN TIME
- CRACK REMOVAL
- DISC REPLACEMENT
  - IN-KIND
  - NEW DESIGN
- ROTOR ASSIGNMENT

MISSILE PROBABILITY

- PREVIOUS P_1 PROBABILITIES NOW BEING REVISED TO INCLUDE CORROSION-ASSISTED CRACKING MECHANISMS
- METHODOLOGY BEING REVISED TO ELIMINATE UNNECESSARY CONSERVATISMS
- EFFECT OF PERIODIC INSPECTIONS ON P_1 BEING EVALUATED
- REVISED CALCULATIONS NOT EXPECTED TO INVALIDATE P_1 VALUE OF 10^{-4} USED BY NRC

MISSILE ENERGY

- NEW TEST WORK RESULTED IN NEW ANALYTICAL APPROACHES
- ENERGIES REPORTED PREVIOUSLY EXPECTED TO CHANGE
- RECALCULATION OF ENTIRE NUCLEAR UNIT POPULATION NOW UNDERWAY
- REVISED REPORTS WILL BE ISSUED COMMENCING JANUARY 1980

STEAM CHEMISTRY CONSIDERATIONS

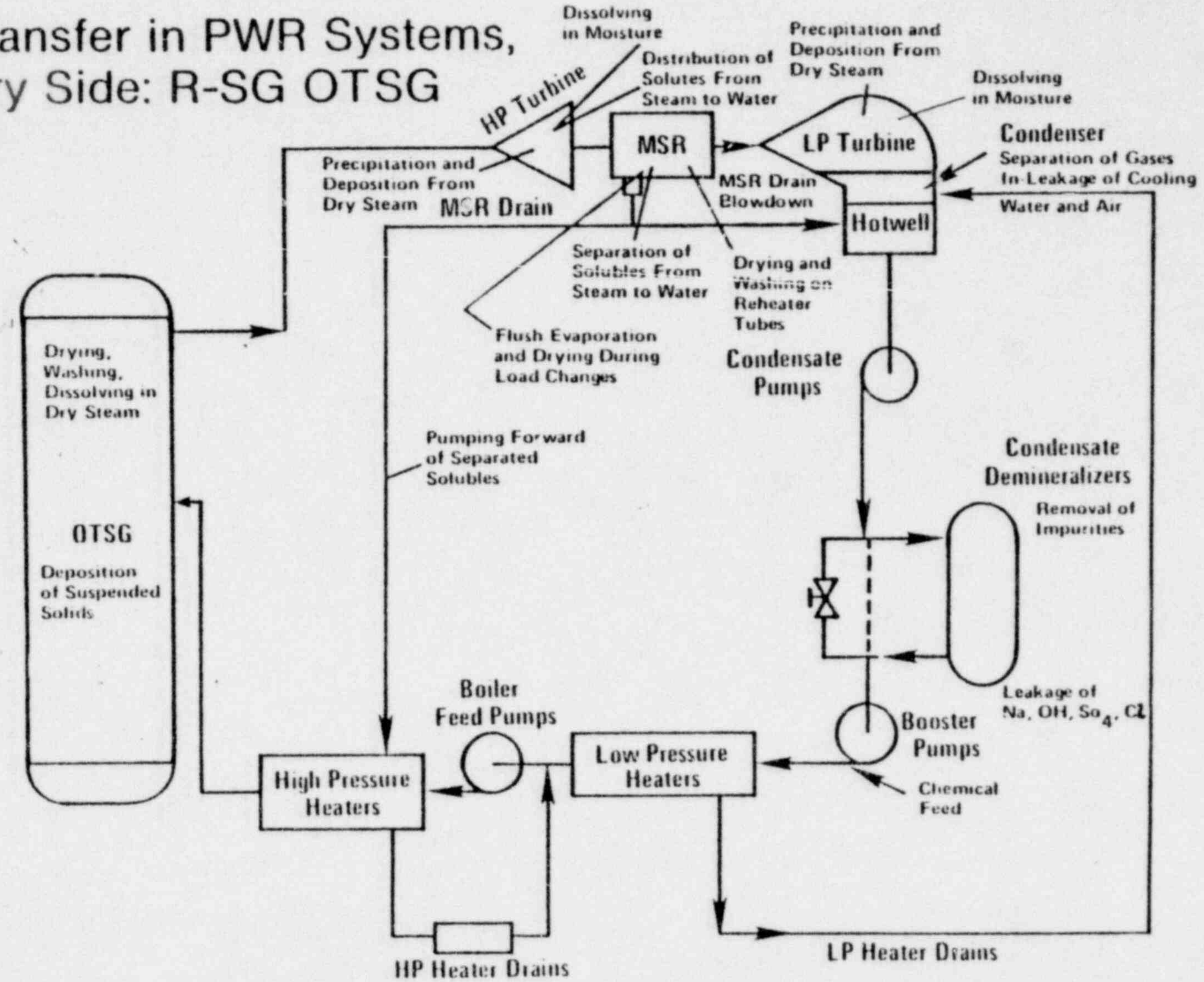
O. Jonas

SECONDARY WATER AND STEAM CHEMISTRY

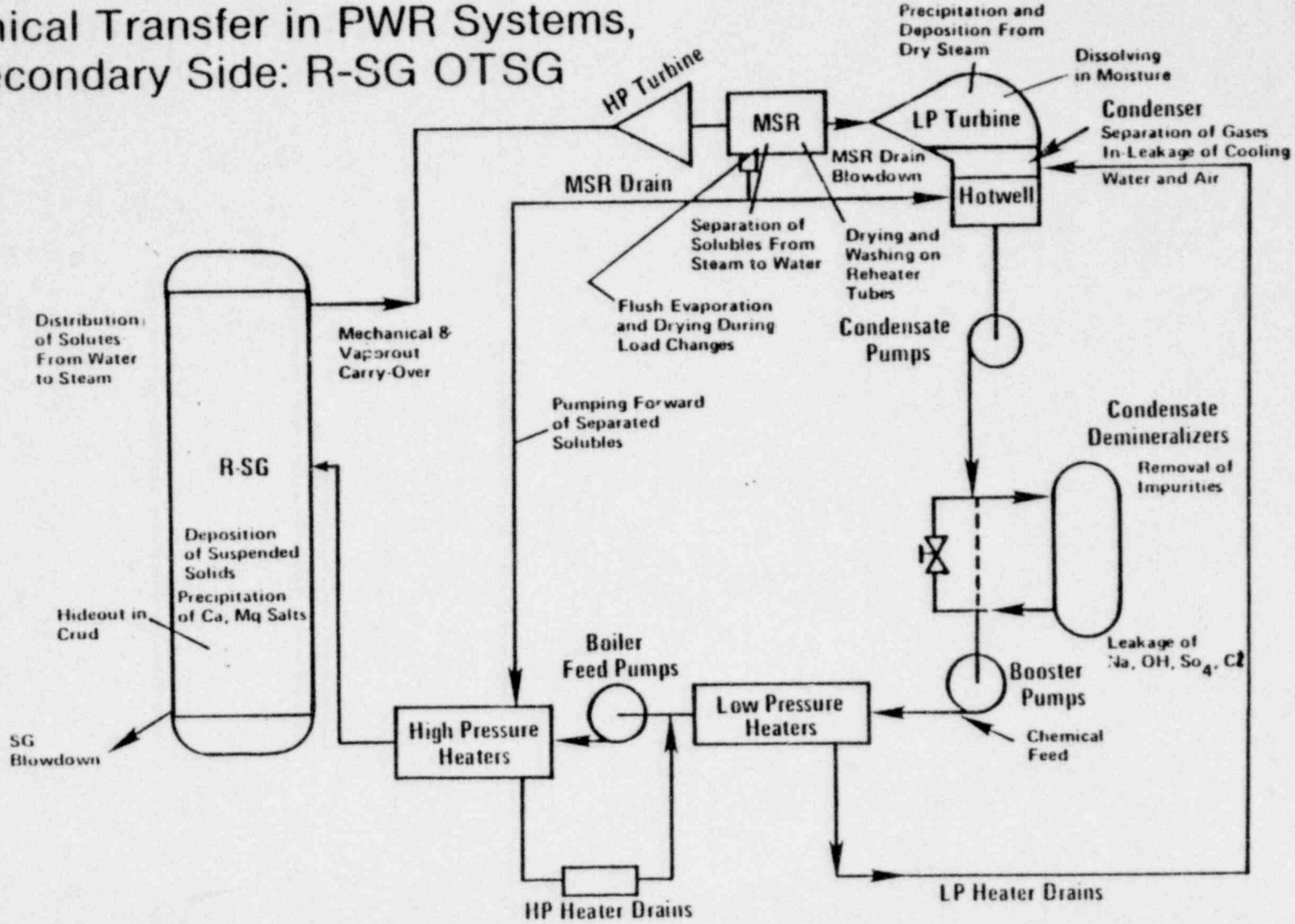
VERSUS

TURBINE CORROSION

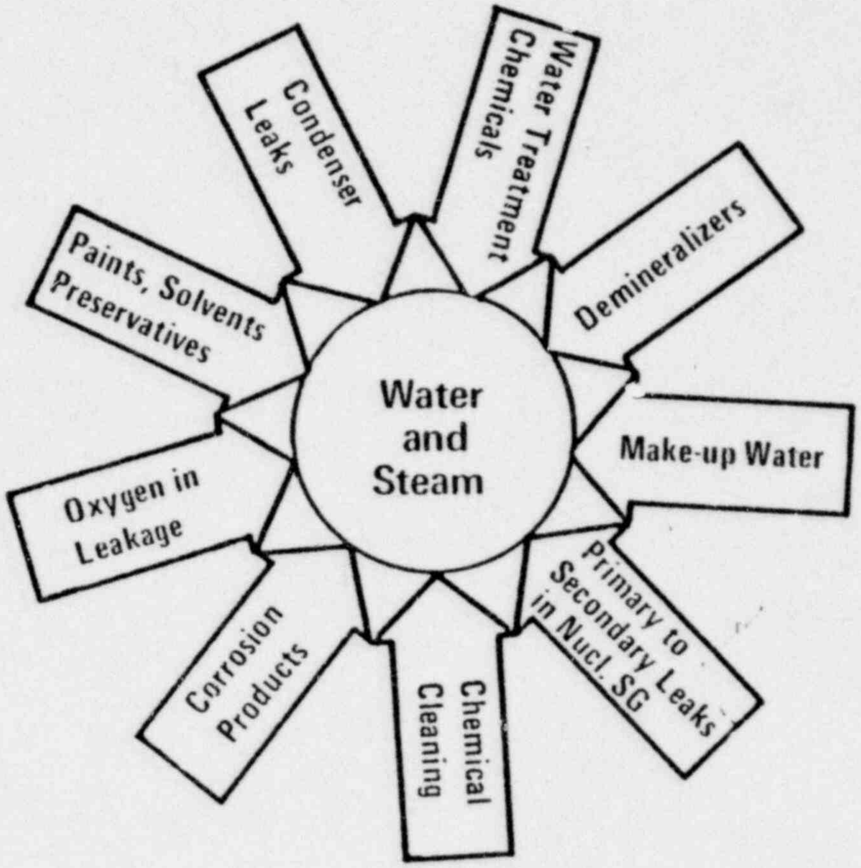
Chemical Transfer in PWR Systems, Secondary Side: R-SG OTSG



Chemical Transfer in PWR Systems, Secondary Side: R-SG OTSG



Sources of Contaminants



INFORMATION AVAILABLE

- BLOWDOWN CHEMISTRY: MOST UNITS WITH RECIRCULATION STEAM GENERATORS
- FEEDWATER CHEMISTRY: PARTIAL FOR UNITS WITH ONCE THROUGH STEAM GENERATORS
- HP STEAM CHEMISTRY: RECALCULATED FROM BLOWDOWN OR FEEDWATER
- DEPOSIT CHEMISTRY: 12 UNITS
- CHEMISTRY WITHIN CRACKS (SIMS): PART OF EACH FAILURE ANALYSIS

INTEGRATED STEAM CHEMISTRY, PWR RECIRCUL. S.G.

(To be provided later)

SIMS ANALYSES OF CHEMISTRY WITHIN CRACKS

UNIT	NSSS	CRACK LOCATION	MAJOR	MINOR	TRACE
A	Recirc.	Disk OD Blade Root	Na,K,Ca,Cl Cr,Fe,V,Al Na,K,Si,Ca	P Cl,C,	B
B	Recirc.	Disk Keyway	Fe,Na,Cl,K	Si,C	OH
C	Recirc.	Disk OD	Fe,Cr		
D	Recirc.	Disk Bore	Cl	Fe	Na,Ca,K,OH
E	Recirc.	Disk OD	Fe,Cr Cl,C_2	Na,Al,Ni	Si,K,Ca
F	Once Through	Disk OD	Cl,Cr	Na,C,K	Al,Si,Ca

SUMMARY OF CHEMICAL INFORMATION FOR TWO SIMILAR UNITS WHICH EXPERIENCED DISK CRACKING.

o TYPICAL PROBLEMS: FREQUENT CONDENSER LEAKS (BRACKISH WATER),
HIGH AIR INLEAKAGE, PARTICULARLY AT LOW LOAD

STRESS CORROSION AND DENTING IN STEAM GENERATORS,
AT LEAST ONE INCIDENT OF H_2SO_4 INGRESS

	UNIT 1	UNIT 2
• REVIEW OF RECORDS	HIGH Cl, Na, CONDUCTIVITY	
LP STEAM ANALYSIS 1974	HIGH Cl, Na	
• WATER TREATMENT QUESTIONNAIRE	X	X
• TURBINE DEPOSITS	MOSTLY OXIDES TRACES OF Cl, Na	-
• DIMA CHEMICAL ANALYSIS	DISK: Na, K, Ca, Cl	U-BEND: Cl, OH
• SODIUM ANALYSIS	-	10ppb TYPICAL 25PPb MAX.
• ION CHROMATOGRAPHY 7-14-78	Na, Cl, SO_4	-
• FIELD CORROSION TEST	-	PITTING, SCC

PRELIMINARY CONCLUSIONS

- SAME CORRODENTS CAN BE IDENTIFIED IN WATER, STEAM, DEPOSITS AND WITHIN CRACKS
- CRACK INITIATION BY PITTING INDICATES PRESENCE OF CORRODENTS
- IN MOST CASES, THERE IS CORROSION IN SEVERAL COMPONENTS OF THE SECONDARY SYSTEM
- $NaOH$, $NaCl$, Na_2SO_4, Na_2CO_3, $NaHCO_3$ AND POSSIBLY HIGH OXYGEN, NH_4Cl, $(NH_4)_2SO_4$, $(NH_4)_2CO_3$, UNIDENTIFIED SULPHUR AND ORGANIC COMPOUNDS, AND COMBINATIONS OF THE ABOVE ARE THE CORRODENTS

FRACTURE MECHANICS ANALYSIS
AND EXPERIMENTAL VERIFICATION

W. G. Clark, Jr.

ANALYTICAL AND EXPERIMENTAL EVALUATION OF STRESS INTENSITY FACTORS FOR CRACKS AT THE BORE OF ROTATING DISCS

- PRESENTATION OUTLINE -

1. INTRODUCTION: THE PROBLEM AND PRIMARY CONSIDERATIONS

2. AN ANALYTICAL APPROACH: THE SUPERPOSITION METHOD OF DETERMINING K_I (LANDES)

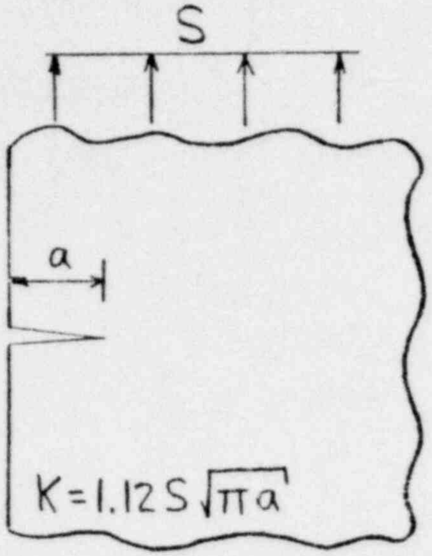
3. EVALUATION OF STRESS GRADIENT + KEYWAY NOTCH EFFECTS:

4. A SIMPLIFIED APPROACH: COMBINED SHORT CRACK, LONG CRACK SOLUTION (DOWLING)

5. EXPERIMENTAL VERIFICATION: SPIN BURST TESTING (SANKEY)
   CRACKED NOTCH K_{Ic} (NOVAK & BARSOM)
   CRACKED NOTCH DA/DN (BROEK)

6. REQUIRED ACCURACY OF K-EXPRESSION: MATERIAL PROPERTIES
   STRESS INFORMATION
   BRANCHED CRACKS (LO)
   MULTIPLE CRACKS

7. SUMMARY:

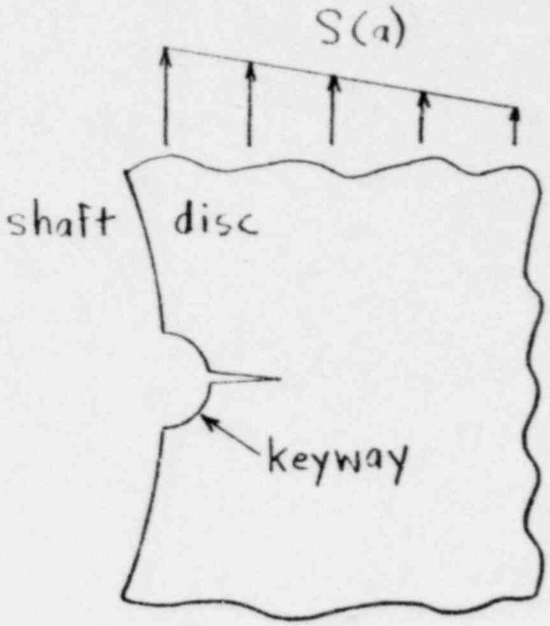


Edge-Cracked
Semi-Infinite Plate

⇒

correct for
- notch
- remote stress gradient
- crack shape
- notch plasticity

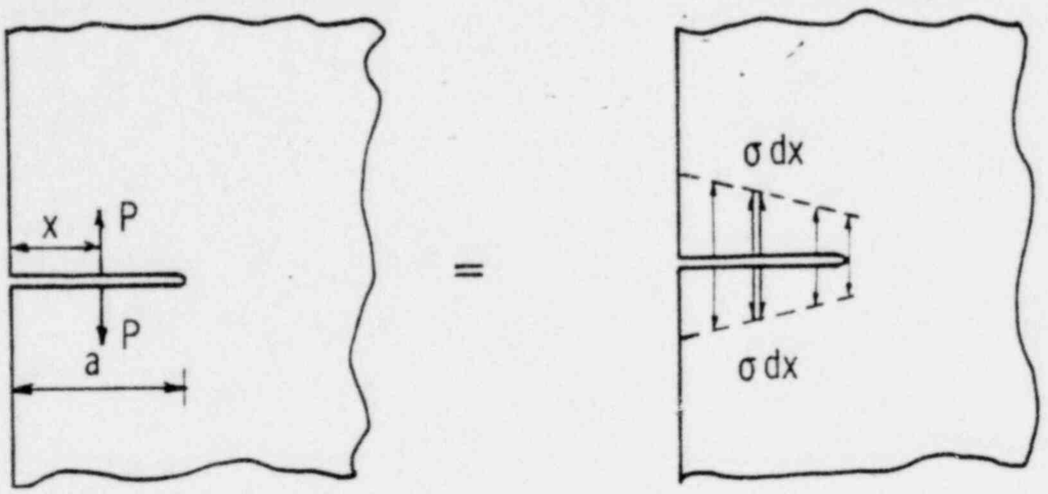
⇒



Disc Keyway
with Crack

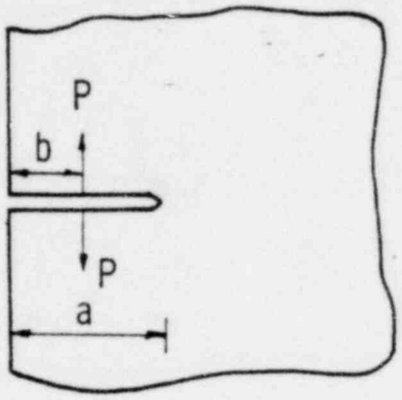
Use of Edge-Cracked Plate K-Solution
for Turbine Disc Keyway Crack

Dwg. 6375A09

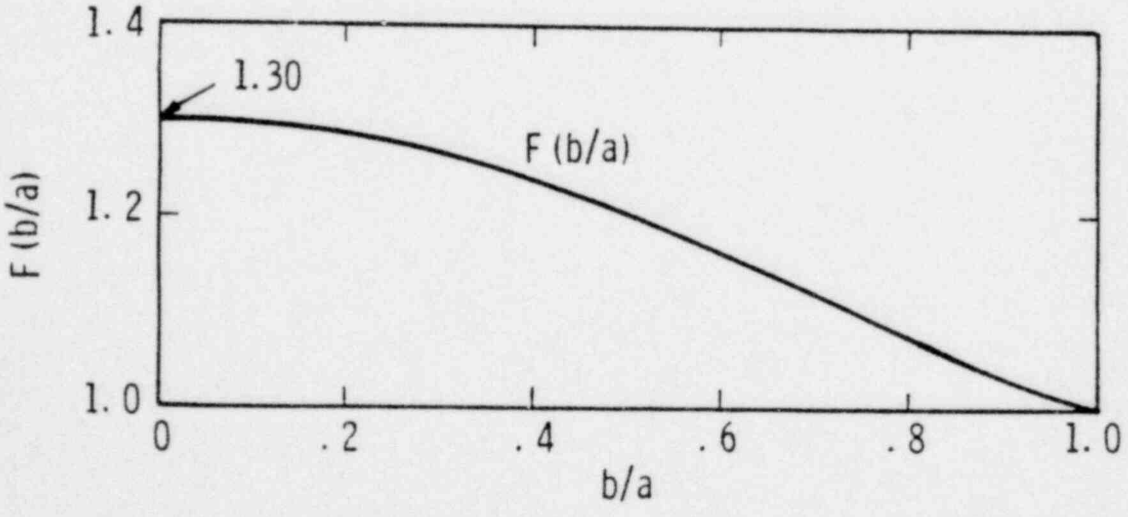


Point load on an edge crack surface

Curve 684210-A



$$K = 2\sqrt{\frac{a}{\pi}}\ \frac{P}{\sqrt{a^2 - b^2}}\ F(b/a)$$



K Solution for an edge crack with a point force on the crack surface

Dwg. 6375A06

Method

$$K = 1.12\, \sigma \sqrt{\pi a}$$

C1) σ_{C1} = Keyway Maximum Stress

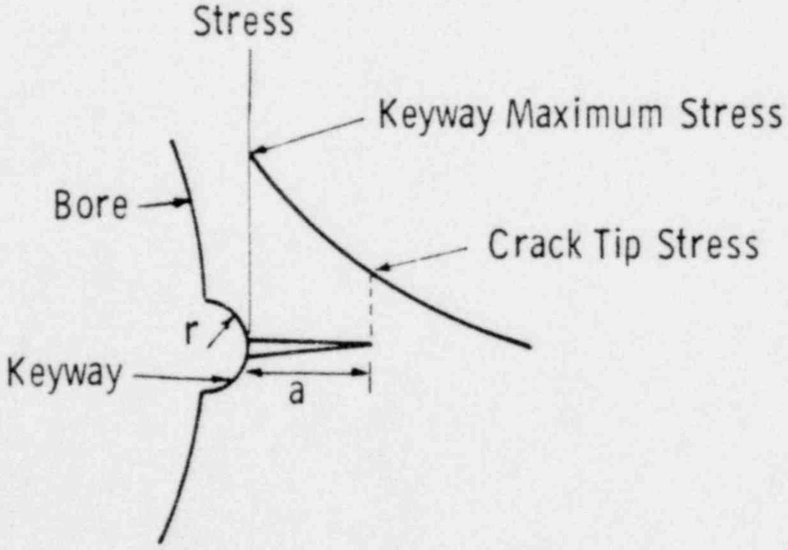
C2) σ_{C2} = Crack Tip Stress

C3) σ_{C3} = Numerical Average Stress

C4) $K = 1.12\, \sigma_{bore} \sqrt{\pi (a + r)}$

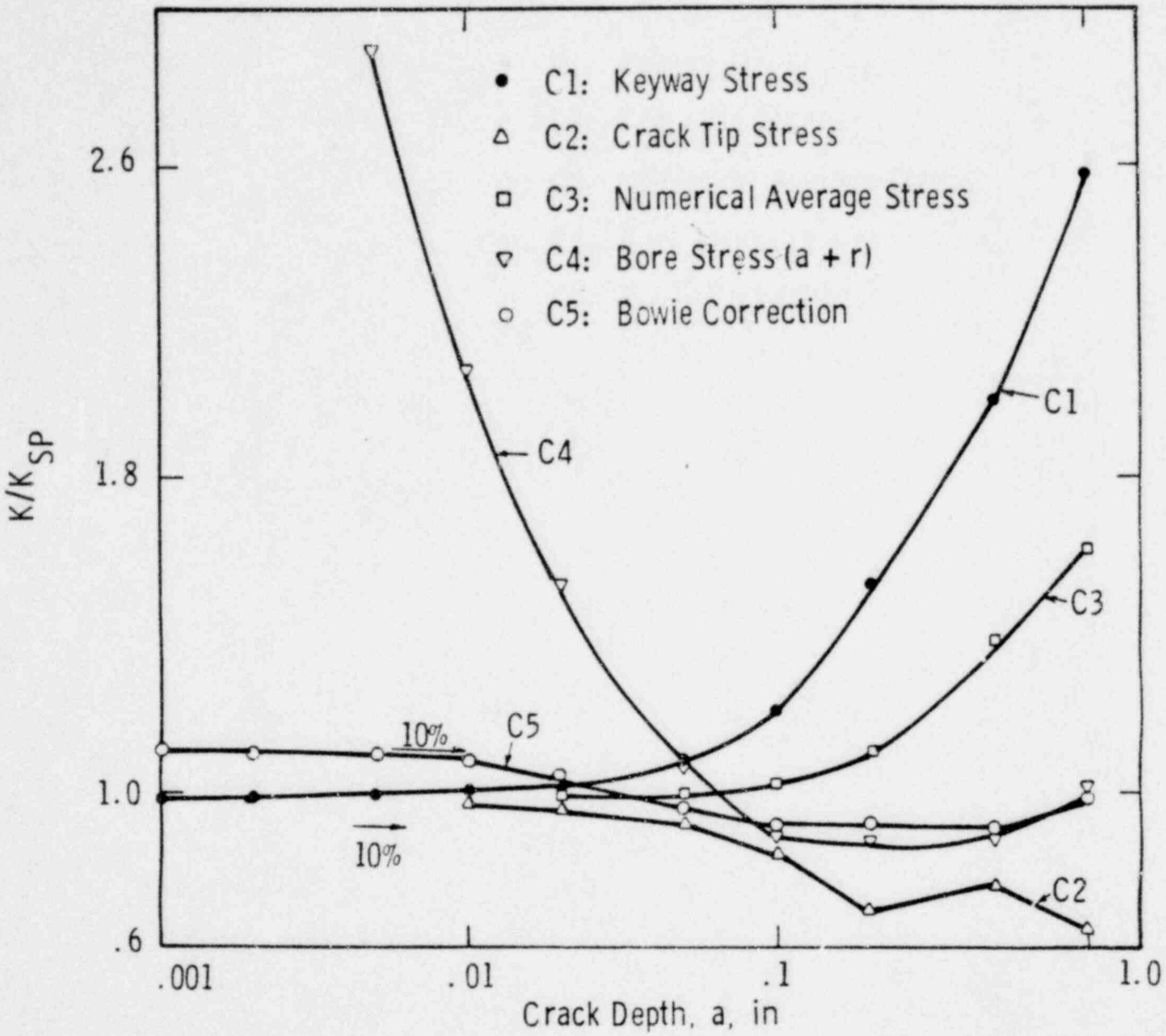
C5) Bowie Correction

$K = 1.12 \sigma_{bore} \sqrt{\pi a} \quad F(a/r)$



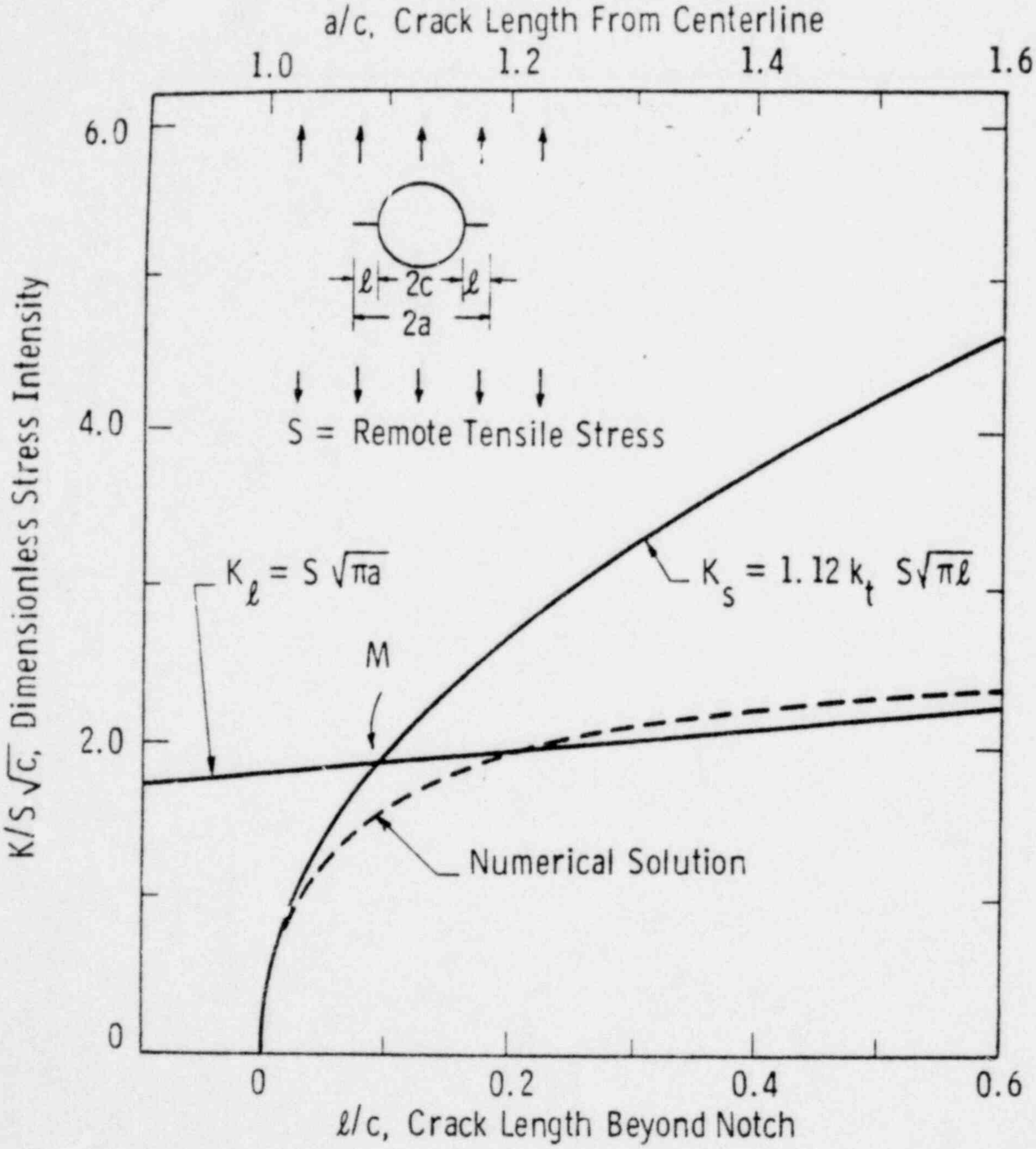
Five methods used to estimate K for a crack coming from a keyway on BB81, Disc 1

Curve 684211-A



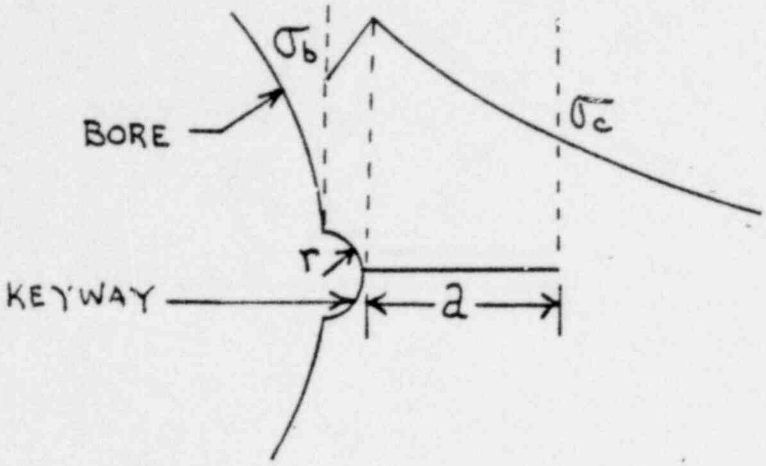
Comparison of K solutions from estimation procedures with the superposition solution — crack coming from a keyway on a BB81, Disc 1

Curve 695713-A



Short and long crack limiting cases and numerical solution, for cracks growing from a circular hole in an infinite plate (Newman)

SUMMARY OF APPLICABLE K-EXPRESSIONS



WHEN: $a > \frac{1}{4} r$ AND $\sigma_b < 1.1\, \sigma_c$

USE: $K_I = 1.12\, \sigma_b \sqrt{\pi(a+r)}$ *

WHEN: $a > \frac{1}{4} r$ AND $\sigma_b < 1.5\, \sigma_c$

USE: $K_I = 1.12\, \sigma_{AVE} \sqrt{\pi(a+r)}$ * ; $\sigma_{AVE} = \dfrac{\sigma_b + \sigma_c}{2}$

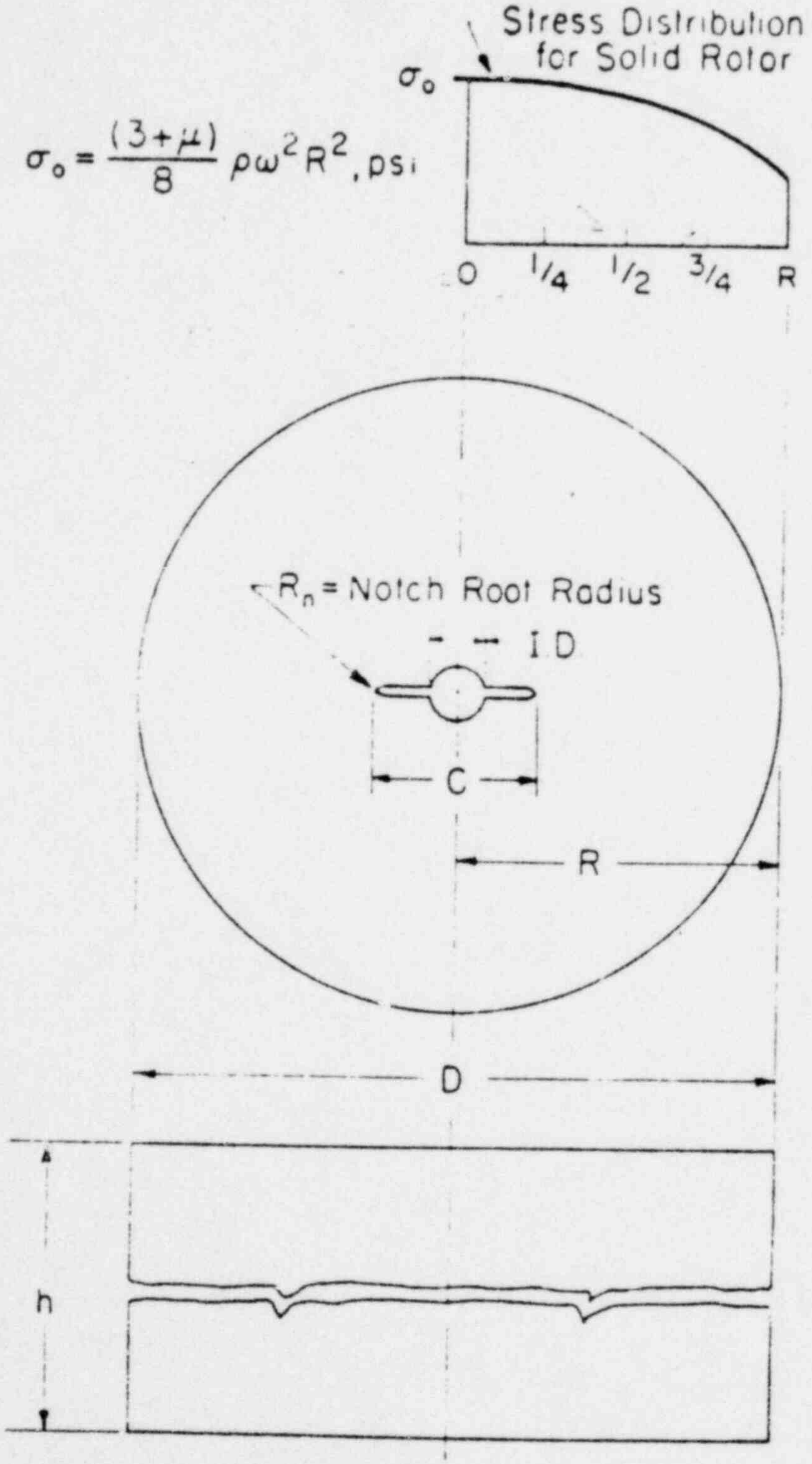
Q FACTOR CAN BE USED TO ACCOUNT FOR SHAPE

* ACCURACY - WITHIN 5% TO 10%

WHEN: $a < \frac{1}{4} r$

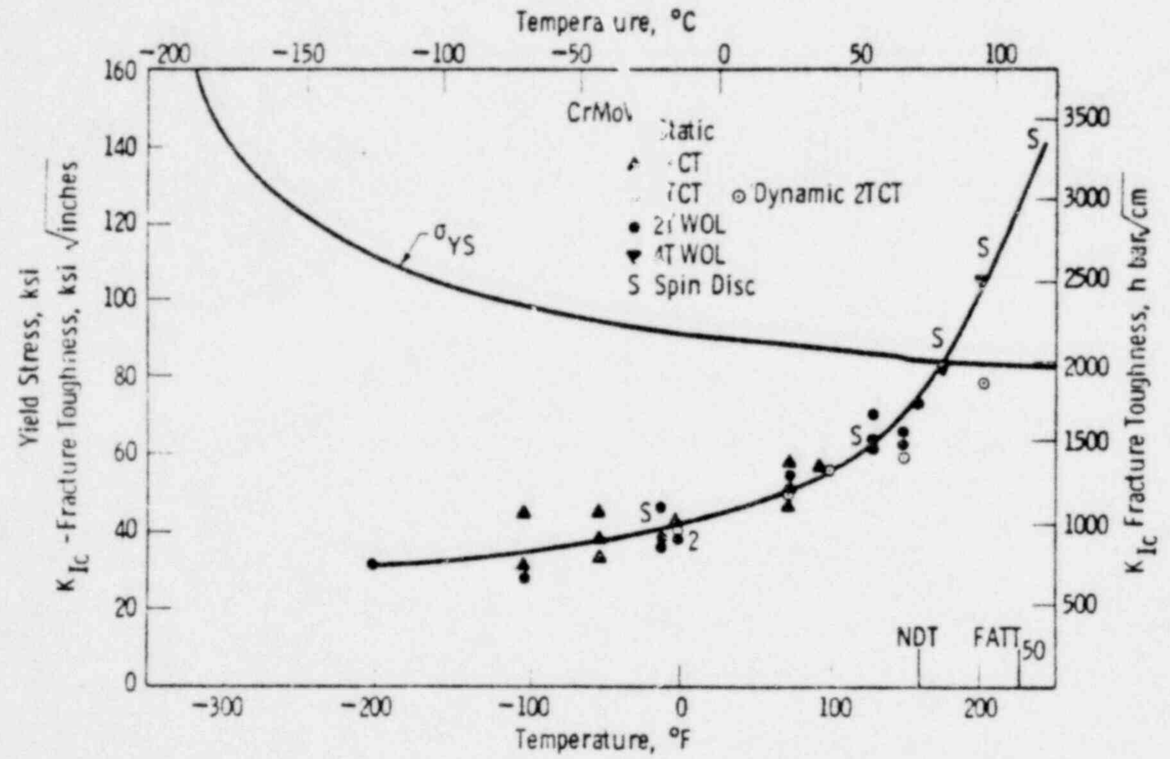
USE: $K_I = 1.12\, K_t\, \sigma_b \sqrt{\pi a}$

ACCURACY - WITHIN 10%

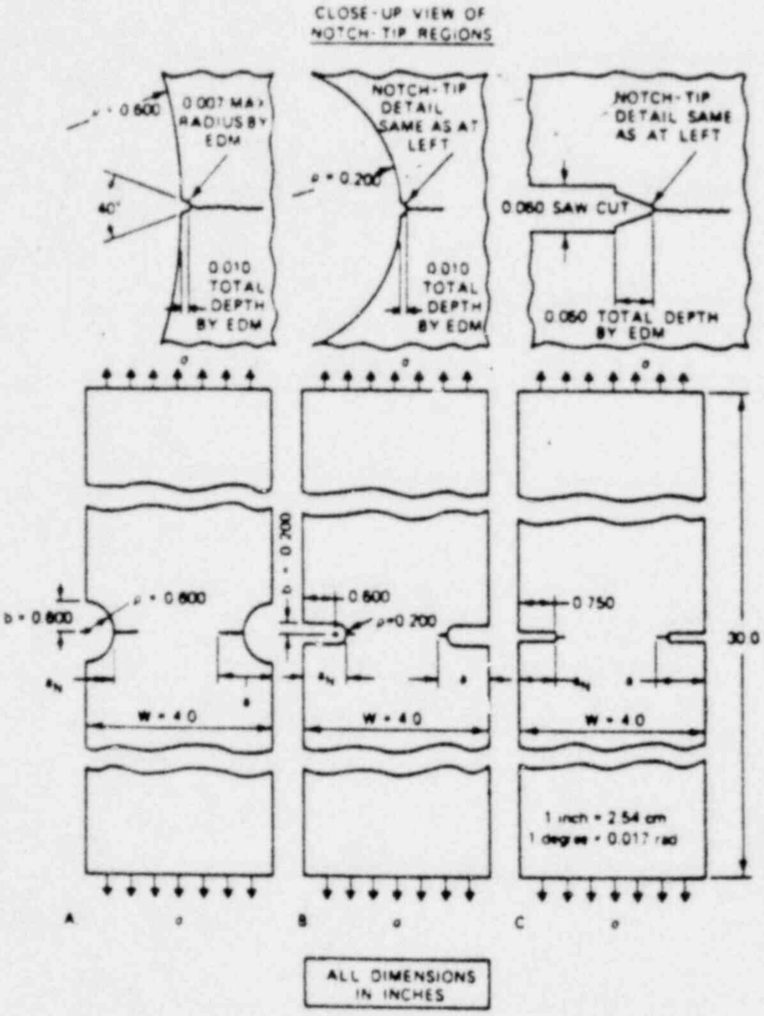


Test Rotor Details

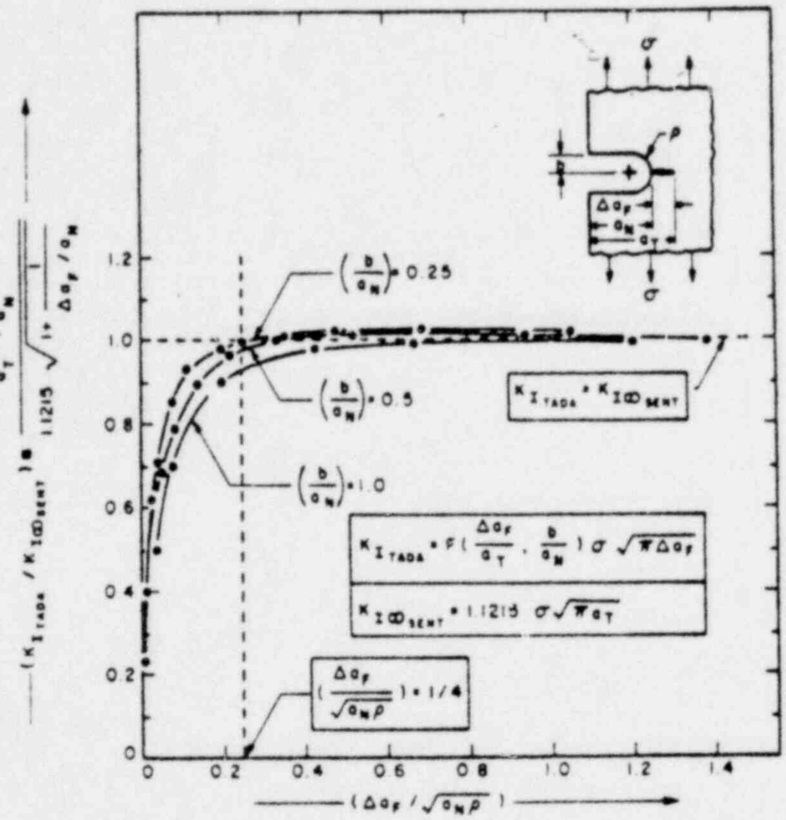
Curve 657507-A



Temperature dependence of the plane-strain fracture toughness (K_{Ic}) of a CrMoV alloy forging



Three basic types of double edge-notched tension (DENT) specimens tested.



K_I ratio for cracks emanating from various semi-elliptical notches contained in a semi-infinite SENT specimen subjected to uniform tension applied remotely.

the elastic-stress field at each crack tip caused by the presence of the opposing notch. These results indicate that the effects of a finite specimen width on the general analytical criterion developed are minimal, and further, that the corresponding effects of opposing notches for a finite-width DENT specimen can be neglected, or considered as second-order, until the notches become quite deep, $[2a/W) \geqq 0.40]$.

Fig.4

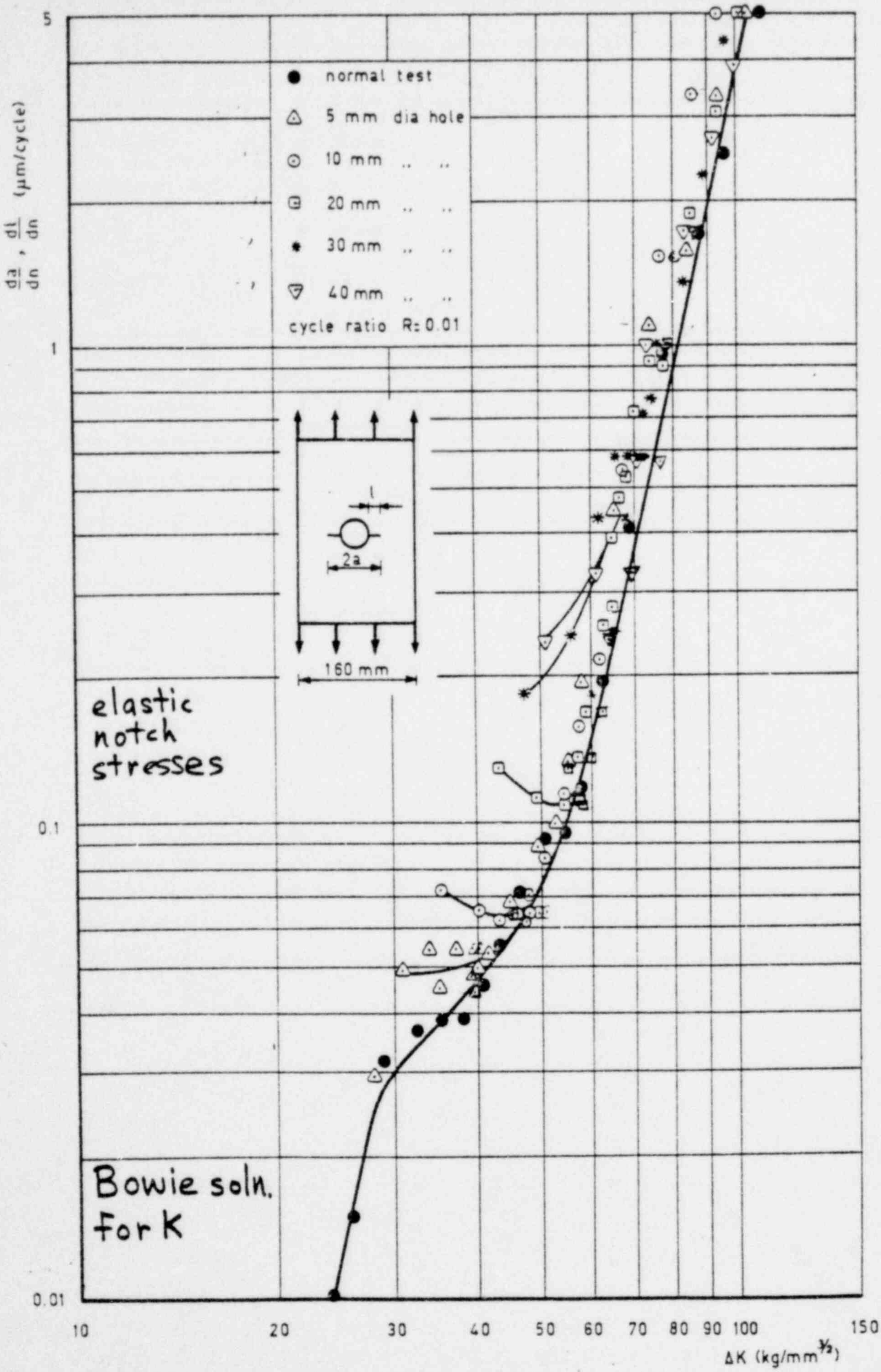


Fig. 4 Crack growth rates. Central crack; symmetric case (Broeck)

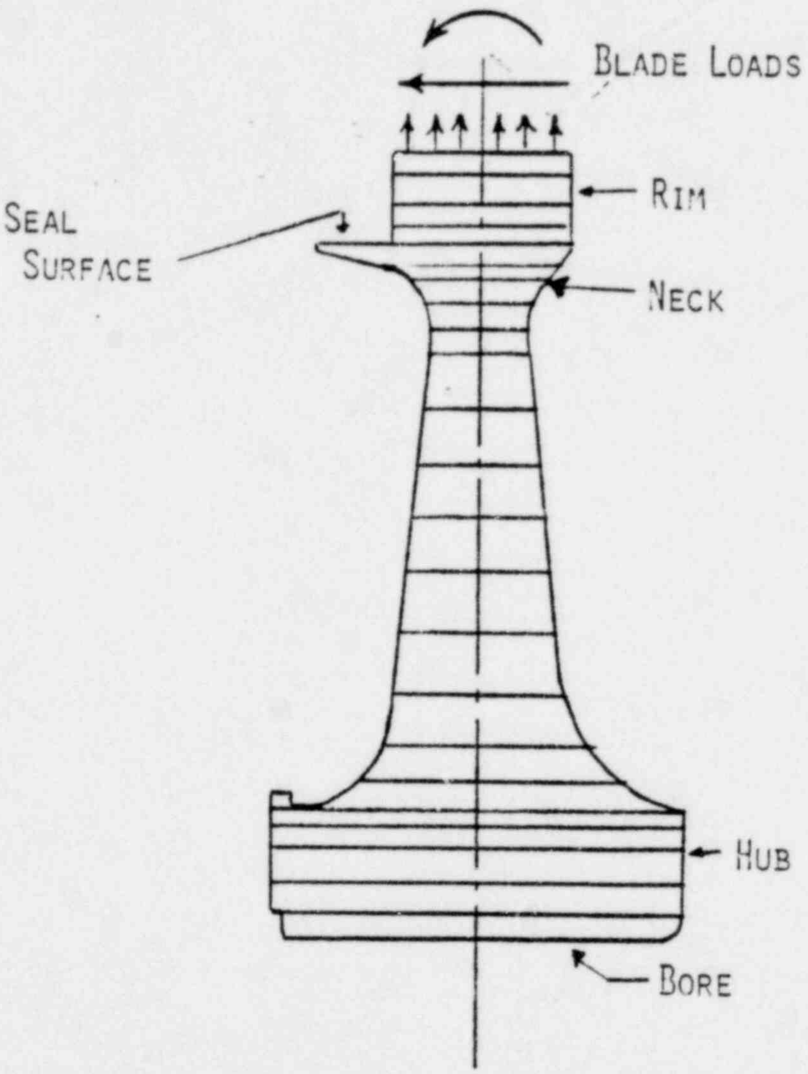
STRESS ANALYSIS TECHNIQUES

R. E. Warner

STRESS ANALYSIS TECHNIQUES

1. CLOSED FORM ANALYTICAL EXPRESSIONS
   - ELASTIC AND PLASTIC
2. FINITE DIFFERENCE TECHNIQUE
   - ELASTIC
3. FINITE ELEMENT
   - ELASTIC
   - ELASTIC/PLASTIC

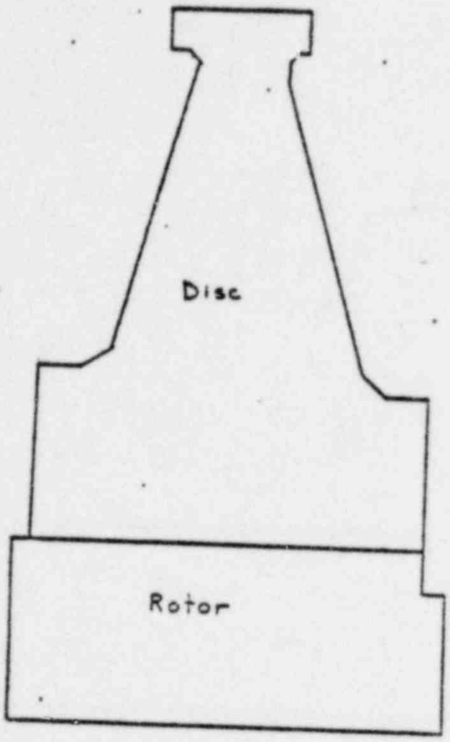
FINITE DIFFERENCE TECHNIQUE

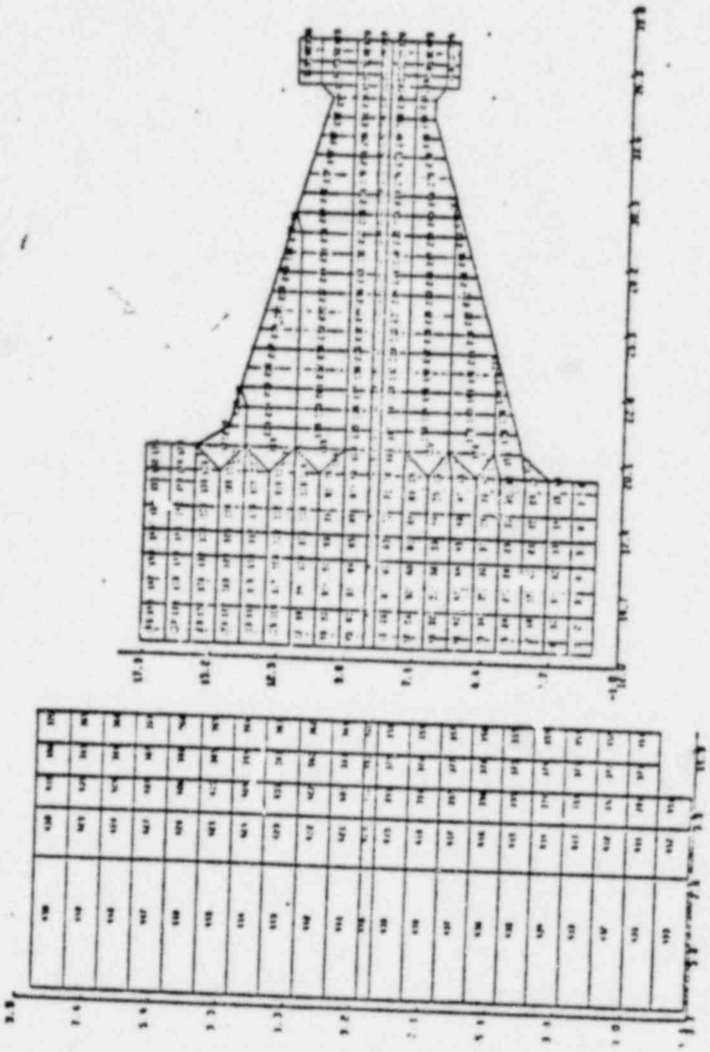


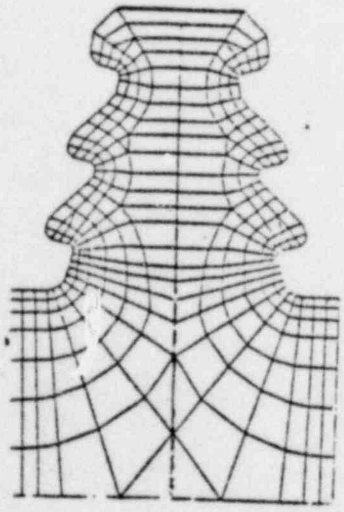
DISC PROFILE

FINITE ELEMENT TECHNIQUES

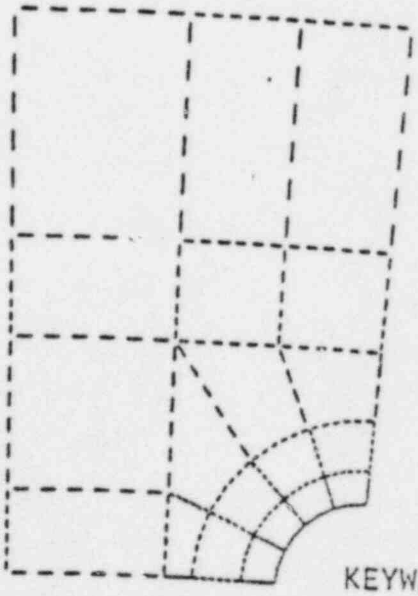
WECAN
NASTRAN
ANSYS







LUG



KEYWAY

STRESS ANALYSIS TECHNIQUES

RESULTS FROM MORE COMPLEX FINITE ELEMENT TECHNIQUES ARE CONSISTENT WITH SIMPLIFIED SOLUTIONS COMBINING THE USE OF ELASTIC - PERFECTLY PLASTIC RULES AND USING STRESS CONCENTRATION EFFECTS.

DISC LOADINGS

1. Blading centrifugal force (rim load).
2. Disc centrifugal force.
3. Shrink fit.
4. Thermal loading.
5. Torque loading.
6. Pressure loadings.

DESIGN CONSTRAINTS - ROTATIONAL LOADS

(RIM LOAD, DISC CF, SHRINK FIT)

Φ_1 - ω_f/ω_d - RATIO OF FAILURE SPEED TO DESIGN SPEED.

Φ_2 - ω_i/ω_d - RATIO OF SPEED FOR INCIPIENT BORE PLASTIC RESPONSE TO DESIGN SPEED.

Φ_3 - ω_l/ω_d - RATIO OF SPEED AT WHICH LOSS OF FIT OCCURS TO DESIGN SPEED.

Φ_4 - ω_m/ω_d - RATIO OF FACTORY OVERSPEED TO DESIGN SPEED.

Φ_5 - RATIO OF MAXIMUM SHAFT EFFECTIVE STRESS AT STANDSTILL TO SHAFT YIELD STRESS.

DESIGN CONSTRAINTS

THERMAL STRESS

1. PREVENT LOSS OF FIT AT OPERATING SPEED.
    - PREVENT FRETTING
    - PREVENT CHANGE IN TORSIONAL NATURAL FREQUENCY AND RESPONSE
    - PREVENT CHANGE IN LATERAL NATURAL FREQUENCY AND RESPONSE
2. CONSTRAIN ROTATION OF DISC RIM.
    - PRESERVE BLADE PATH AXIAL CLEARANCES
    - DETERMINE PROPER COLD CLEARANCE SETTINGS

TORQUE LOADING

1. SHRINK FIT NOT RELIED UPON TO TRANSMIT TORQUE.
2. KEYS ARE DESIGNED TO TRANSMIT ENTIRE TORQUE LOAD.

MATERIALS RELATED FACTORS IN STRESS CORROSION INCLUDING BRITISH EXPERIENCE

B. B. Seth

MATERIALS RELATED FACTORS

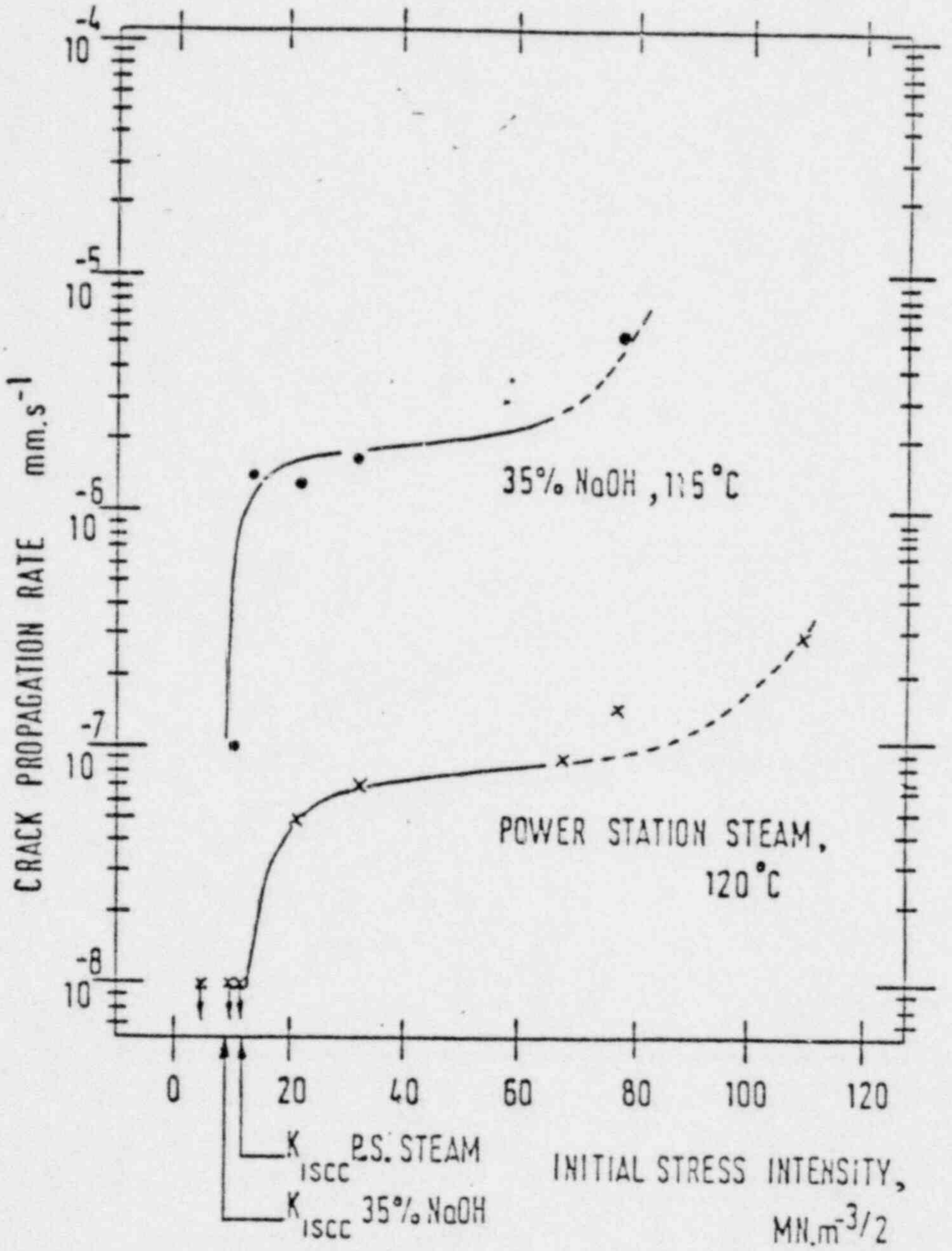
A. MAJOR

1. ENVIRONMENT
2. TEMPERATURE
3. COMPOSITION
4. MATERIAL STRENGTH

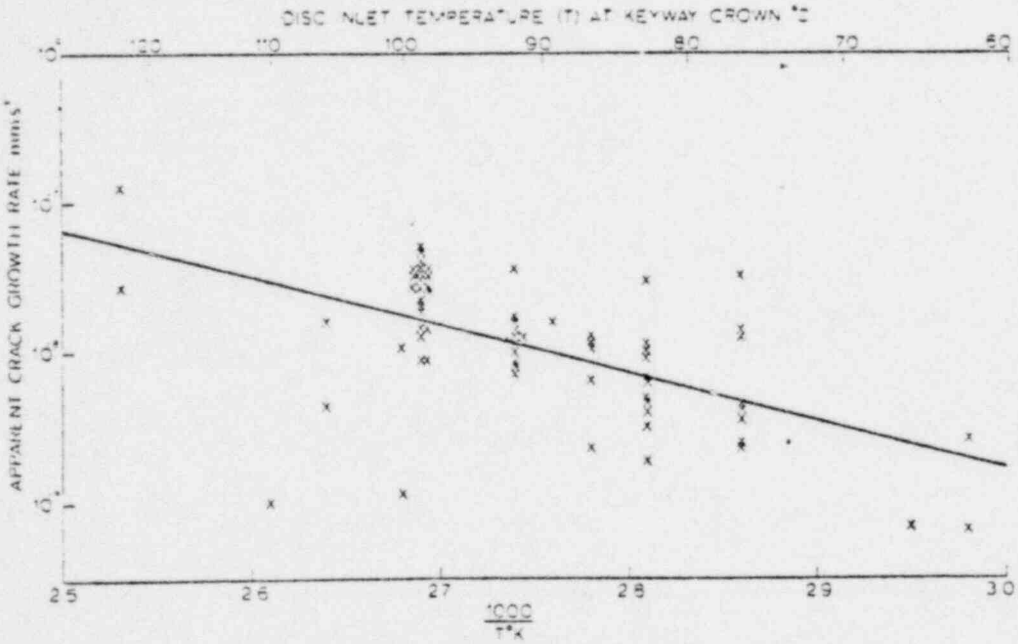
B. POSSIBLE OTHERS

1. EMBRITTLEMENT
2. PRIOR LOADING HISTORY
3. FATIGUE INTERACTION

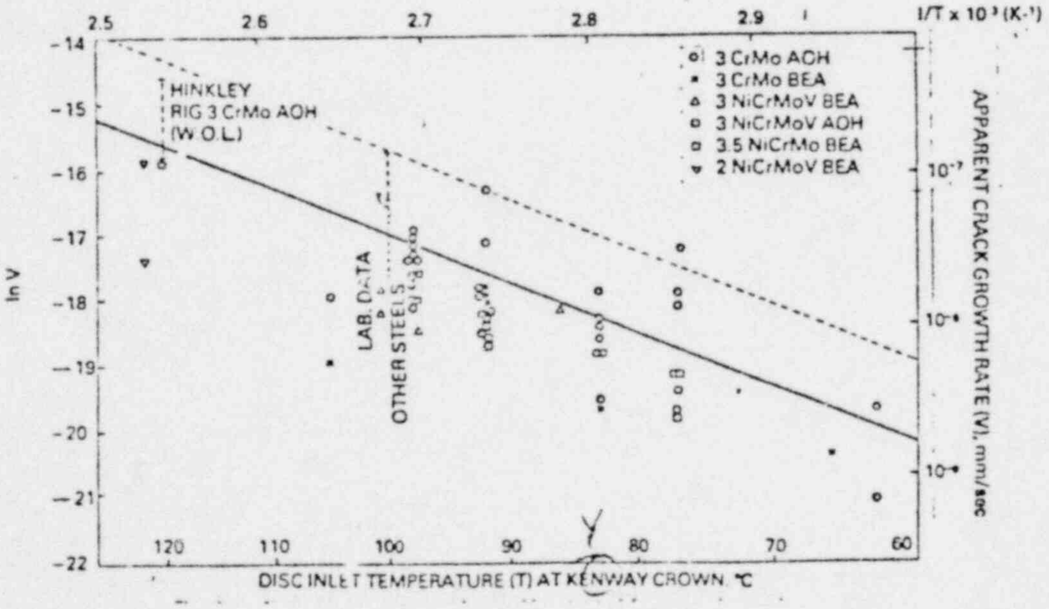
IGL - 140



J.ADAMS, R.HARRISON & J.PARKER.

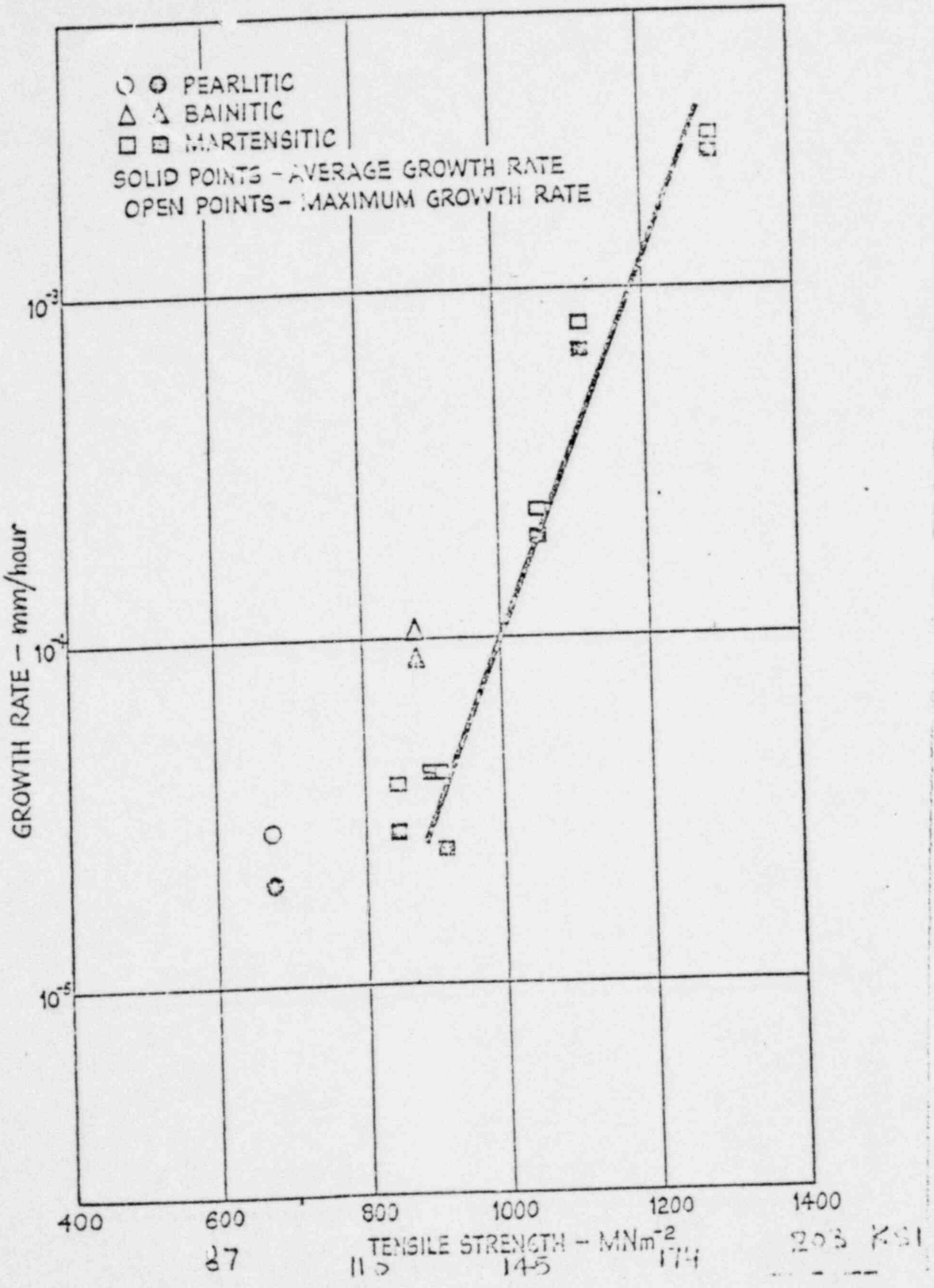


Apparent crack growth rate obtained from maximum crack depth and rotor life, plotted against disc operating temperature


2.5
2.6
2.7
2.8
2.9
1/T x 10³ (K⁻¹)
-14
-15
-16
-17
-18
-19
-20
-21
-22
ln V
HINKLEY
RIG 3 CrMo AOH
(W.O.L.)
LAB. DATA
OTHER STEELS
3 CrMo AOH
3 CrMo BEA
3 NiCrMoV BEA
3 NiCrMoV AOH
3.5 NiCrMo BEA
2 NiCrMoV BEA
10⁻⁷
10⁻⁸
10⁻⁹
APPARENT CRACK GROWTH RATE (V), mm/sec
120
110
100
90
80
70
60
Y
DISC INLET TEMPERATURE (T) AT KENWAY CROWN. °C

CRACK PROPAGATION RATES

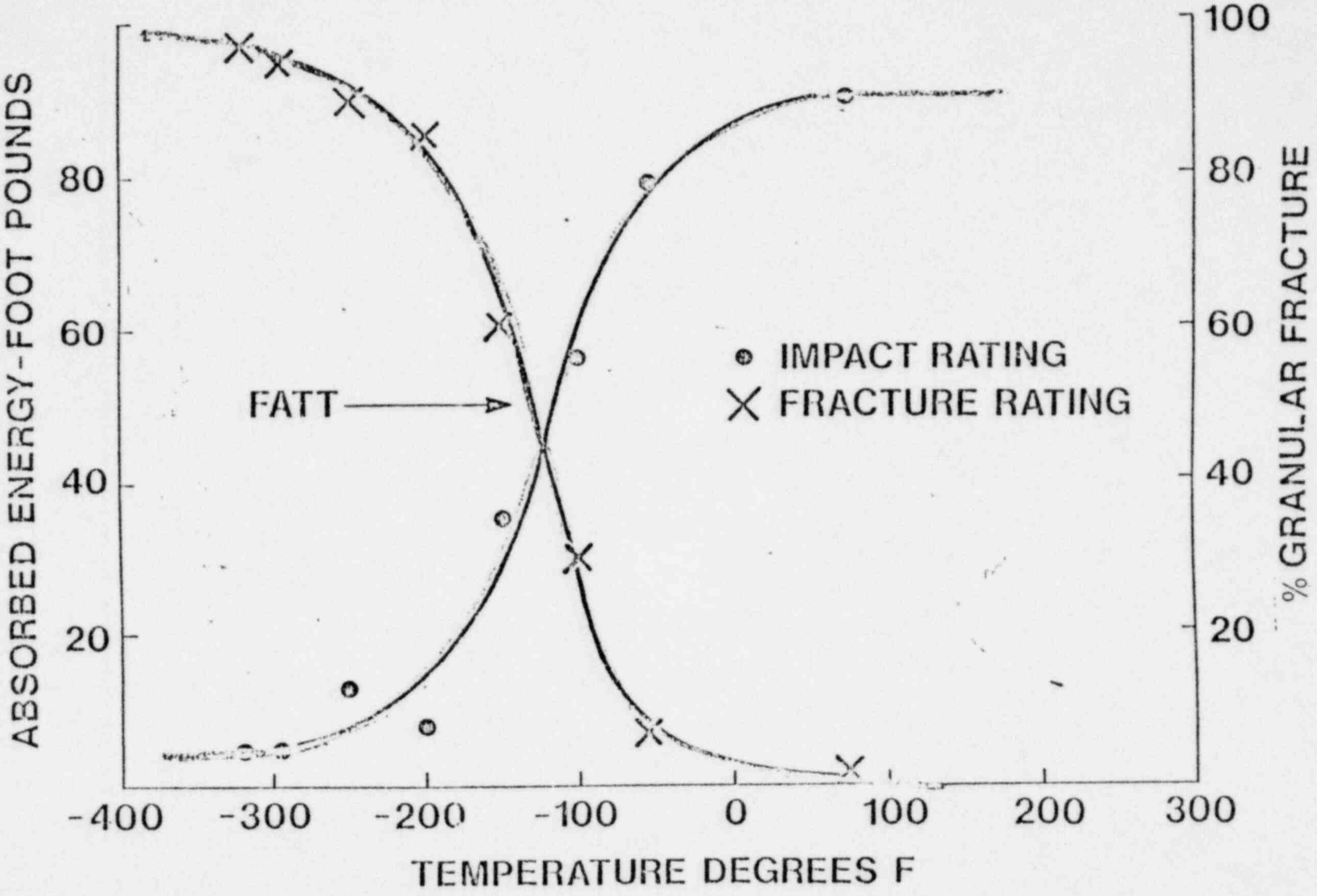
STEEL	RATE, MM/SEC X 10^8	
	90^oC	130^oC
CR-MO	2.3-4.3	2.5-42
3 NI CR MOV	0.6-2.5	3.5-10


○ ● PEARLITIC
△ ▲ BAINITIC
☐ ■ MARTENSITIC
SOLID POINTS – AVERAGE GROWTH RATE
OPEN POINTS – MAXIMUM GROWTH RATE
GROWTH RATE – mm/hour
10^{-3}
10^{-4}
10^{-5}
400
600
800
1000
1200
1400
TENSILE STRENGTH – MNm^{-2}
87
115
145
174
203 KSI

IMPACT - K_{IC} CORRELATIONS

B. B. Seth

AS RECEIVED CHARPY 'V' NOTCH DATA ADJACENT TO THE CRACKED KEYWAY



AT UPPER SHELF:

$$K_{1C} = \left[5\sigma_{YS} \left(CVN - \frac{\sigma_{YS}}{20} \right) \right]^{\frac{1}{2}}$$

K_{1C} = FRACTURE TOUGHNESS AT UPPER SHELF

σ_{YS} = YIELD STRENGTH AT UPPER SHELF

C_{VN} = UPPER SHELF IMPACT ENERGY

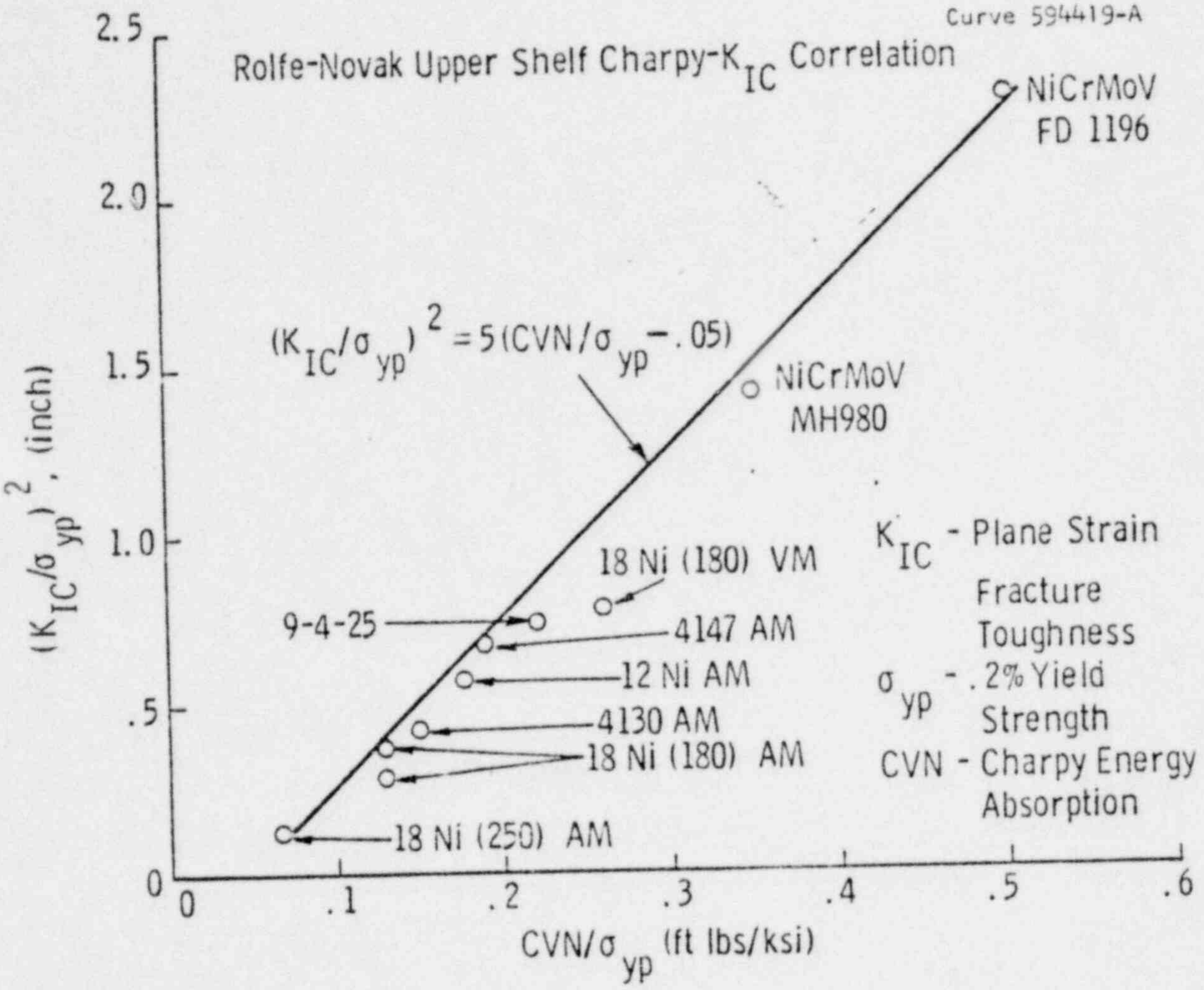


Fig. 1 —Rolfe-Novak upper shelf charpy energy-K_{IC} correlation

LOWER SHELF CORRELATION:

$K_{IC} = .45\,\sigma_{YS}$

K_{IC} = FRACTURE TOUGHNESS AT LOWER SHELF

YS = YIELD STRENGTH AT LOWER SHELF

FATT CORRELATION:

$$K_{IC} = \frac{\text{UPPER SHELF } K_{IC} + \text{LOWER SHELF } K_{IC}}{2}$$

K_{IC} = FRACTURE TOUGHNESS AT FATT

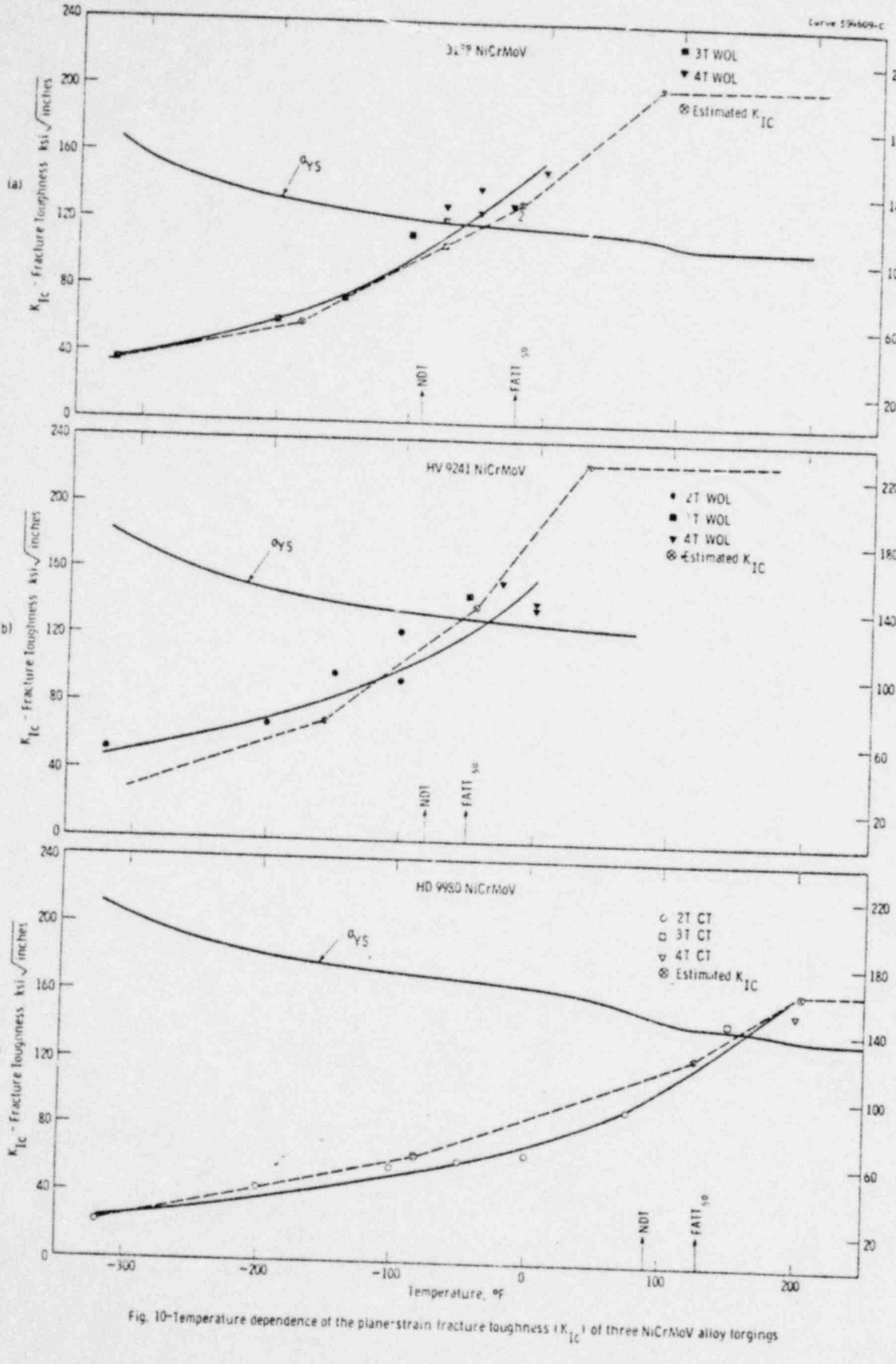
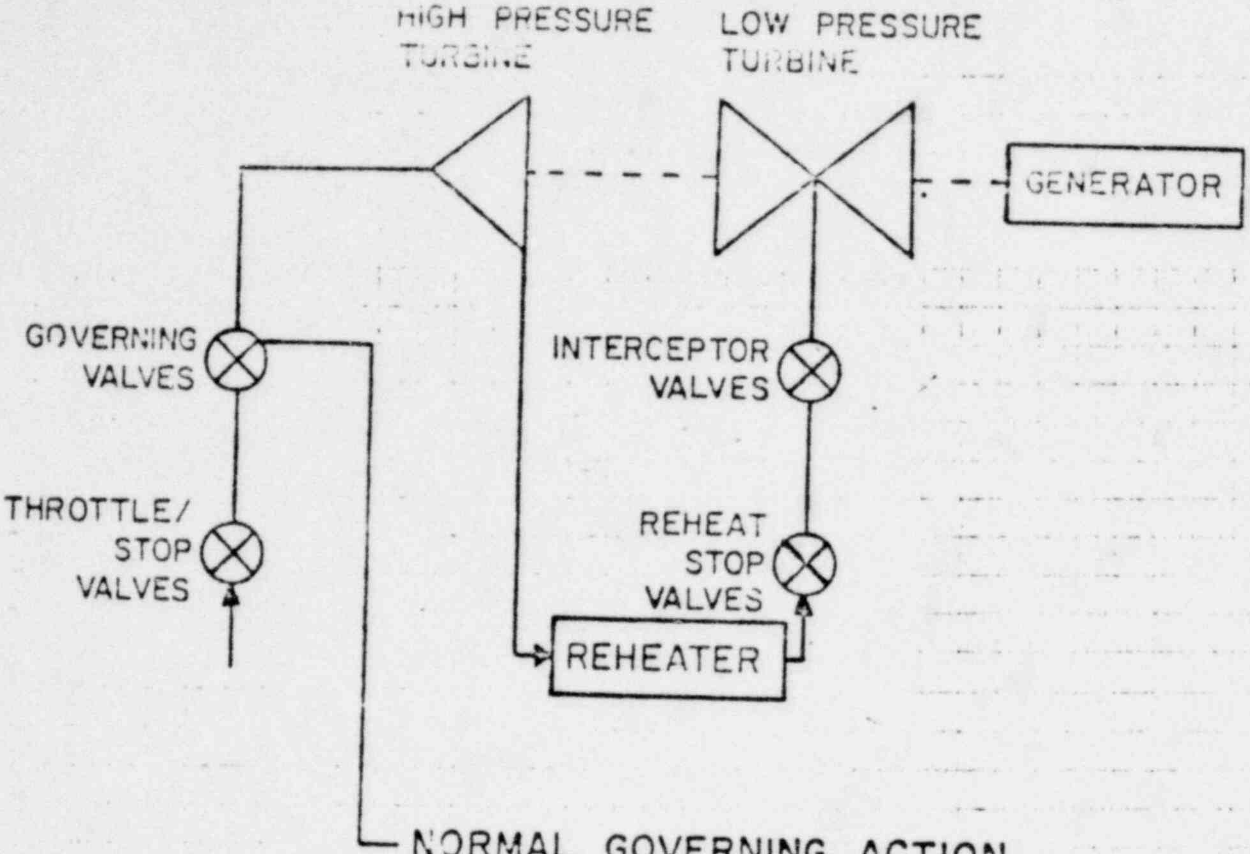


Fig. 10–Temperature dependence of the plane-strain fracture toughness (K_{IC}) of three NiCrMoV alloy forgings

CONTROL SYSTEMS

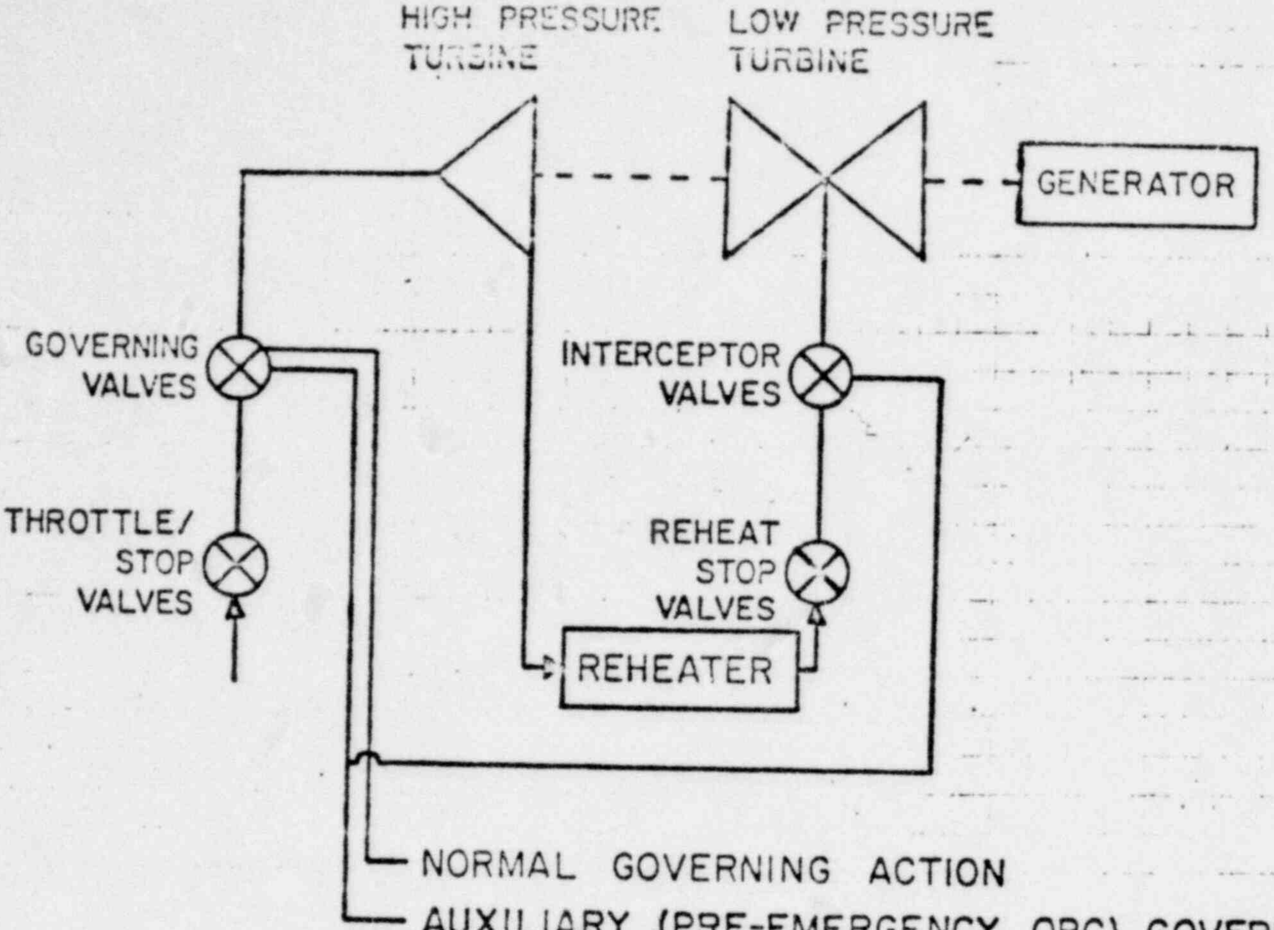
M. F. Smith



NORMAL GOVERNING ACTION

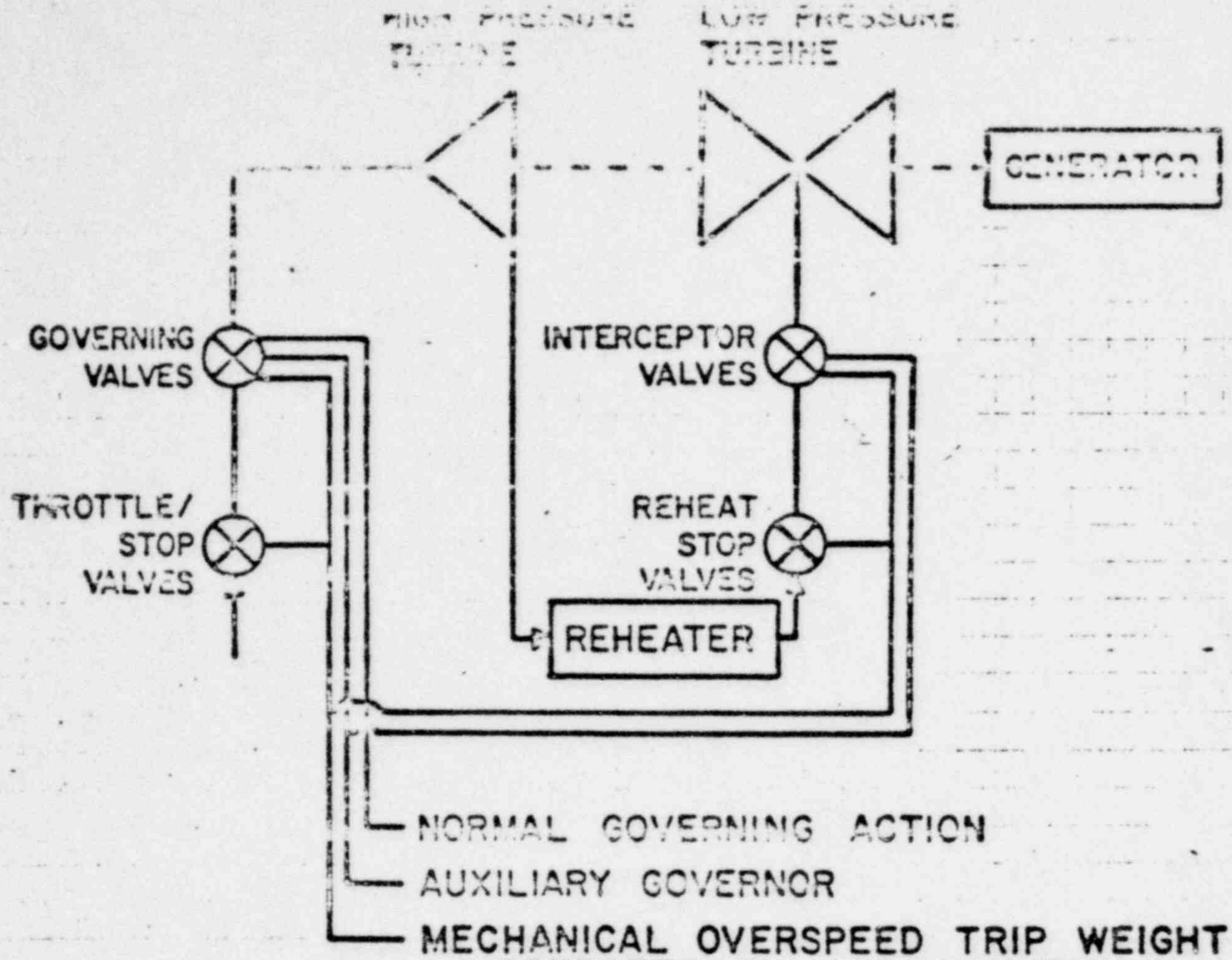
CONTROLS POSITION OF GOVERNOR VALVES

FULL STROKING TAKES SEVERAL SECONDS

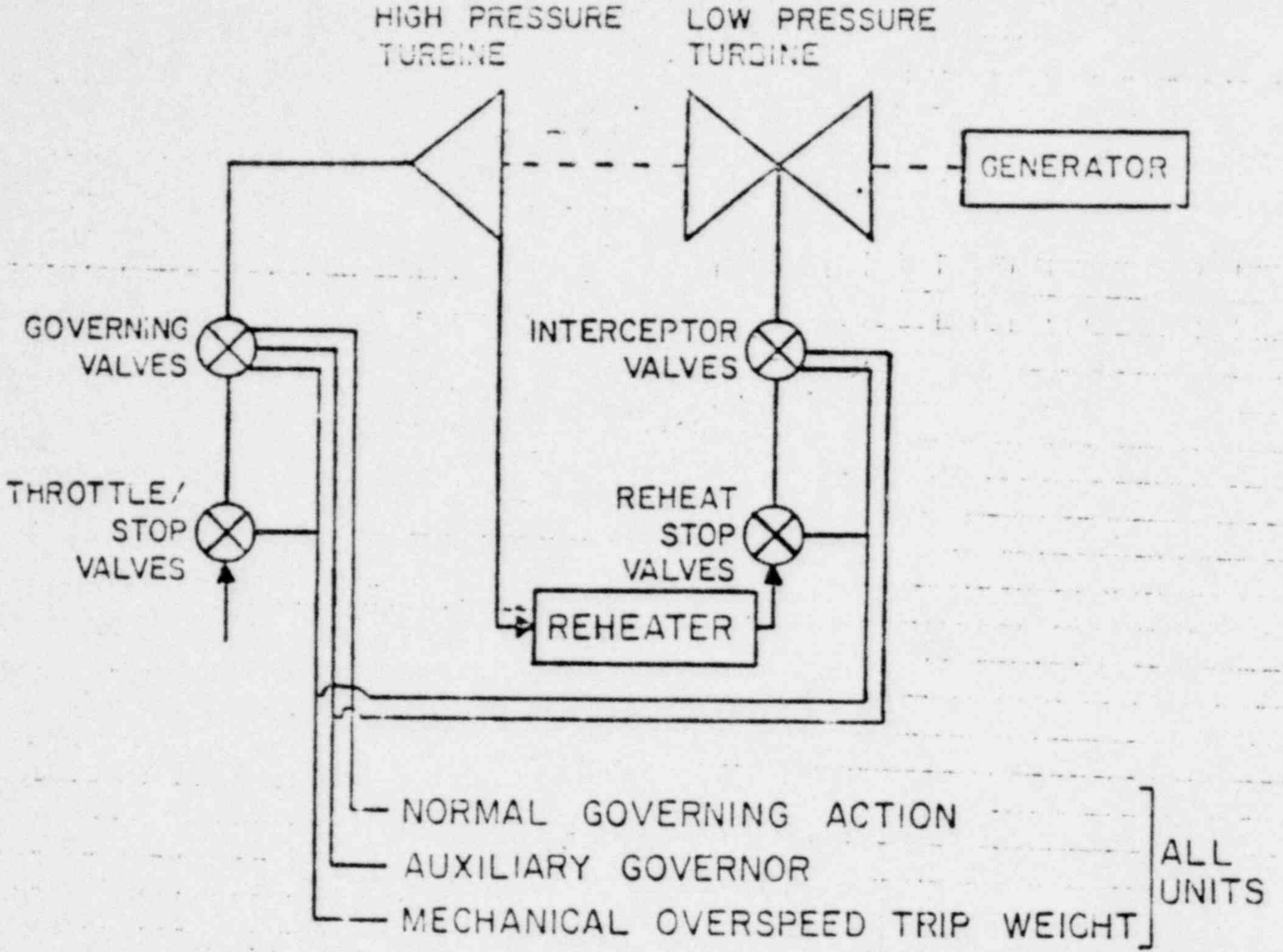


NORMAL GOVERNING ACTION

AUXILIARY (PRE-EMERGENCY, OPC) GOVERNOR
OPERATES ON GOVERNOR AND INTERCEPTOR VALVES
FUNCTIONS AT SMALL OVERSPEEDS (NOMINALLY 103 %)
CLOSES VALVES RAPIDLY - APPROX. 0.25 SEC.



OPERATES ON ALL VALVES
FUNCTIONS AT TRIP SETTING (APPROX. 110%)
CLOSES VALVES RAPIDLY
GOV. & INTERCEPT - APPROX. 0.25 SEC.
STOP VALVES - APPROX. 0.15 SEC.



NORMAL GOVERNING ACTION
AUXILIARY GOVERNOR
MECHANICAL OVERSPEED TRIP WEIGHT

ALL UNITS

PLUS

1. LOAD DROP ANTICIPATOR - <u>UNITS WITH ELECTRO-HYDRAULIC (EH) CONTROL SYSTEMS</u>
   RAPIDLY CLOSES GOVERNOR & INTERCEPT VALVES IF MAIN BREAKER OPENS AND UNIT WAS CARRYING MORE THAN 30 % LOAD.

PLUS

2. ELECTRICAL OVERSPEED TRIP SYSTEM - <u>UNITS SHIPPING SINCE 1977</u>
   RAPIDLY CLOSES ALL VALVES
   SYSTEM REDUNDANT TO MECHANICAL SYSTEM