GPU Nuclear

TMI-1
OTSG Status Review

April 7, 1982

TMI-1 OTSG STATUS REVIEW

I.	INTRODUCTION	- R. F. WILSON
II.	FAILURE ANALYSIS	- DR. R. L. LONG
III.	STEAM GENERATOR REPAIR	- J. PEARSON
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V.	CONCLUSIONS/SUMMARY	- R. F. WILSON

BETHESDA, MARYLAND

APRIL 7, 1982

ORGANIZATIONS ACTIVELY WORKING

WITH GPUN ON

STEAM GENERATOR PROGRAM

- B&W, LYNCHBURG AND ALLIANCE RESEARCH LABS
- EPRI AND CONSULTANTS
- BATTELLE LABORATORIES
- MIT
- ORNL

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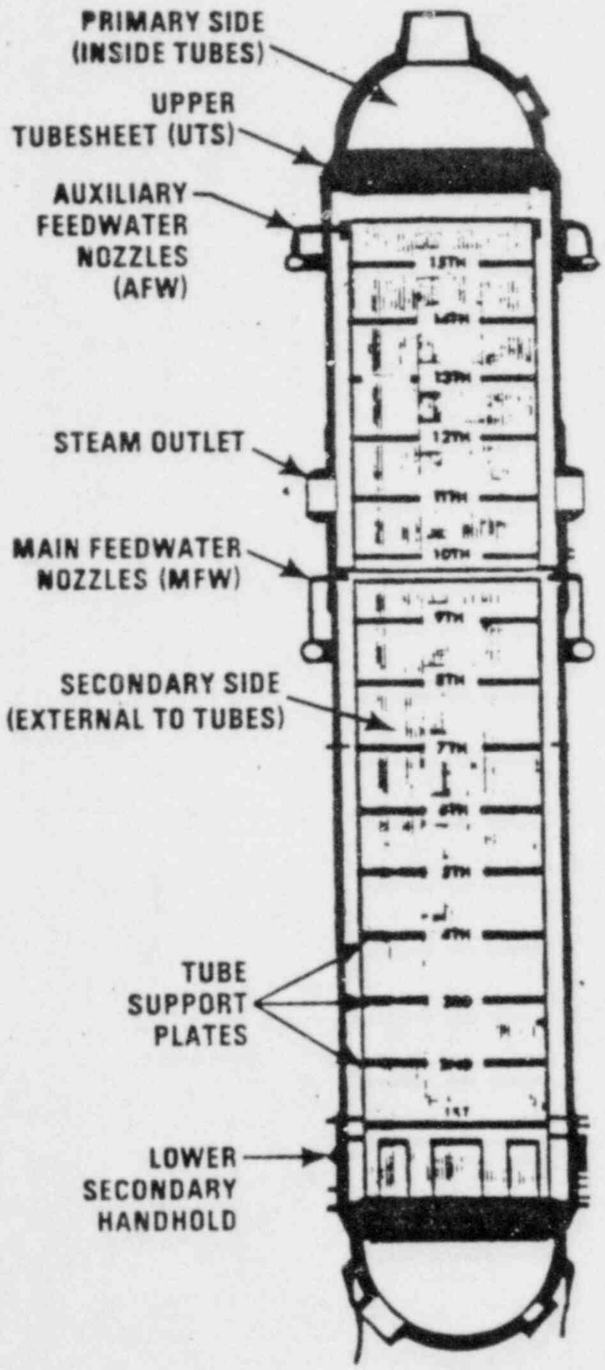
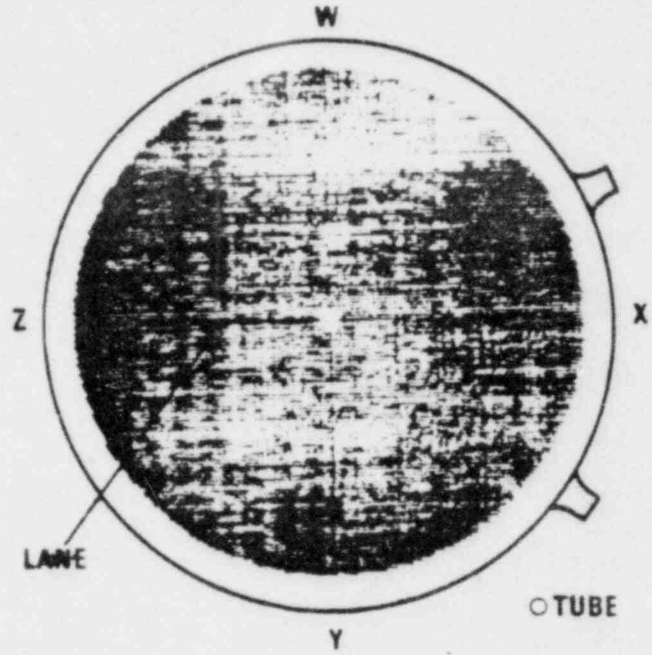
TMI-1 Steam Generator

ELEVATION

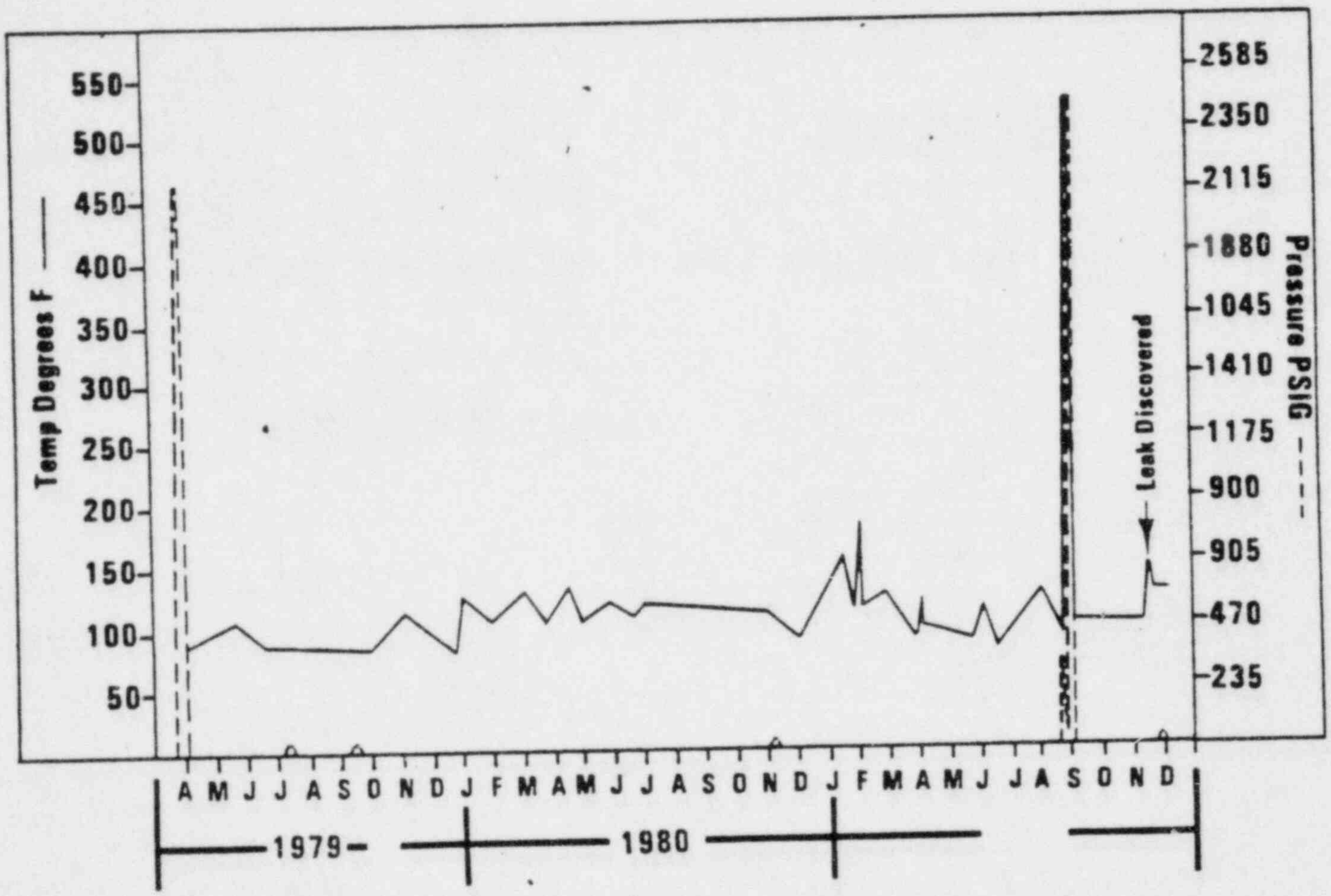


CROSS SECTION



Weight, operating	637 tons
Height	73 feet
Primary flow	69×10^6 #/hr.
Steam flow	6.1×10^6 #/hr.
Number tubes	15531
Tube size, material	0.625" od, .034 wall inconel 600
Manufacture date	5/69 to 11/70

Reactor Coolant System



TMI-1 STEAM GENERATORS

EXTENT OF ATTACK

- STEAM GENERATOR
  - NUMBER OF LEAKING TUBES — 200 TO 500
  - NUMBER OF TUBES WITH INDICATION OF SIGNIFICANT DEFECTS — 8000 TO 10,000
  - UNRESOLVED AREA AT SURFACE OF UPPER TUBESHEET — UNKNOWN

- ELSEWHERE
  - MATERIALS POTENTIALLY SUBJECT TO SIMILAR ATTACK USED ELSEWHERE IN REACTOR
    - EXAMINATION PROGRAM GETTING UNDERWAY
    - ATTACK, IF ANY, REQUIRES RIGHT COMBINATION OF MATERIAL CONDITION, STRESS, LOCAL ENVIRONMENT

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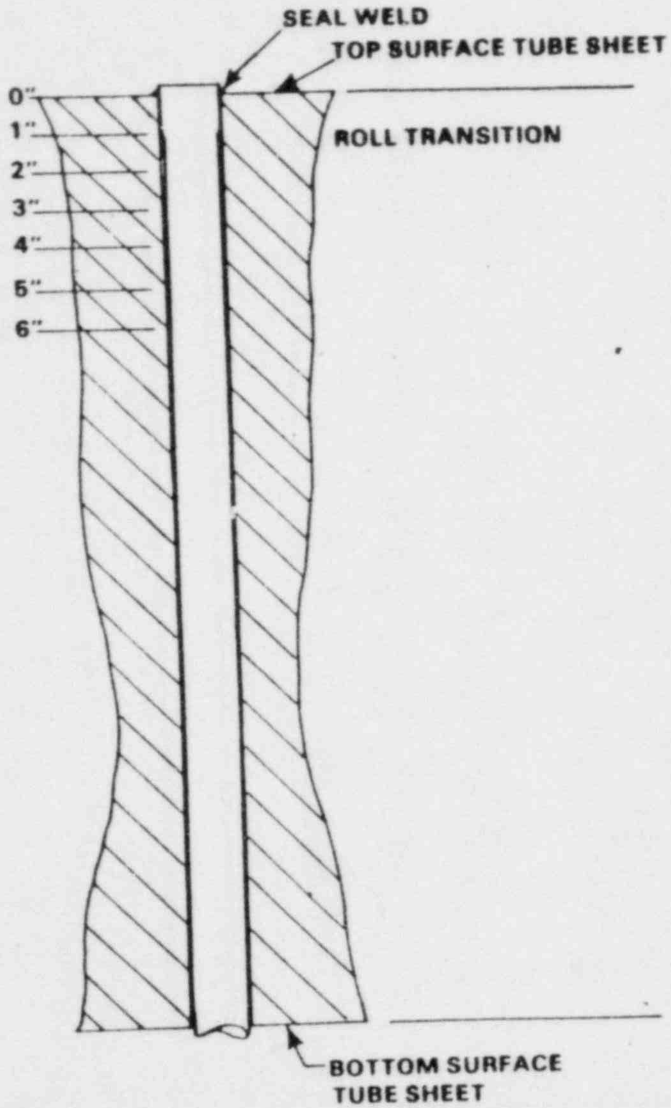
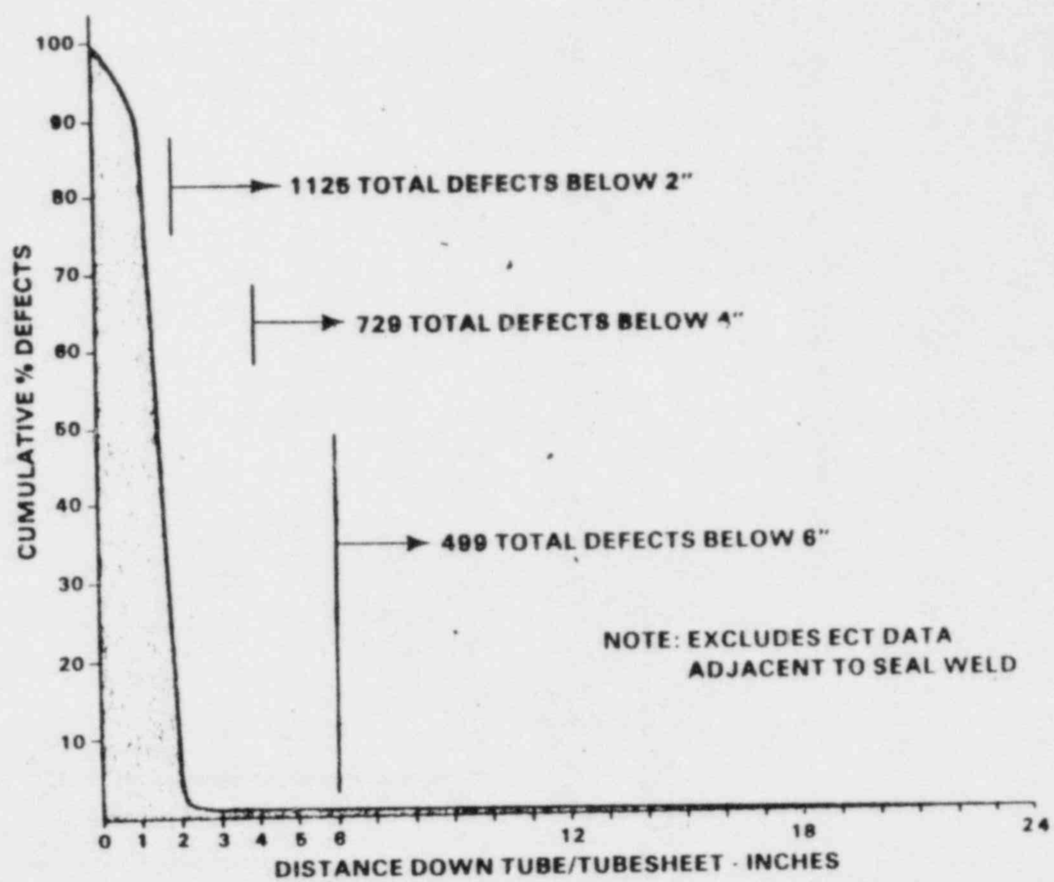
TMI-1 Steam Generator

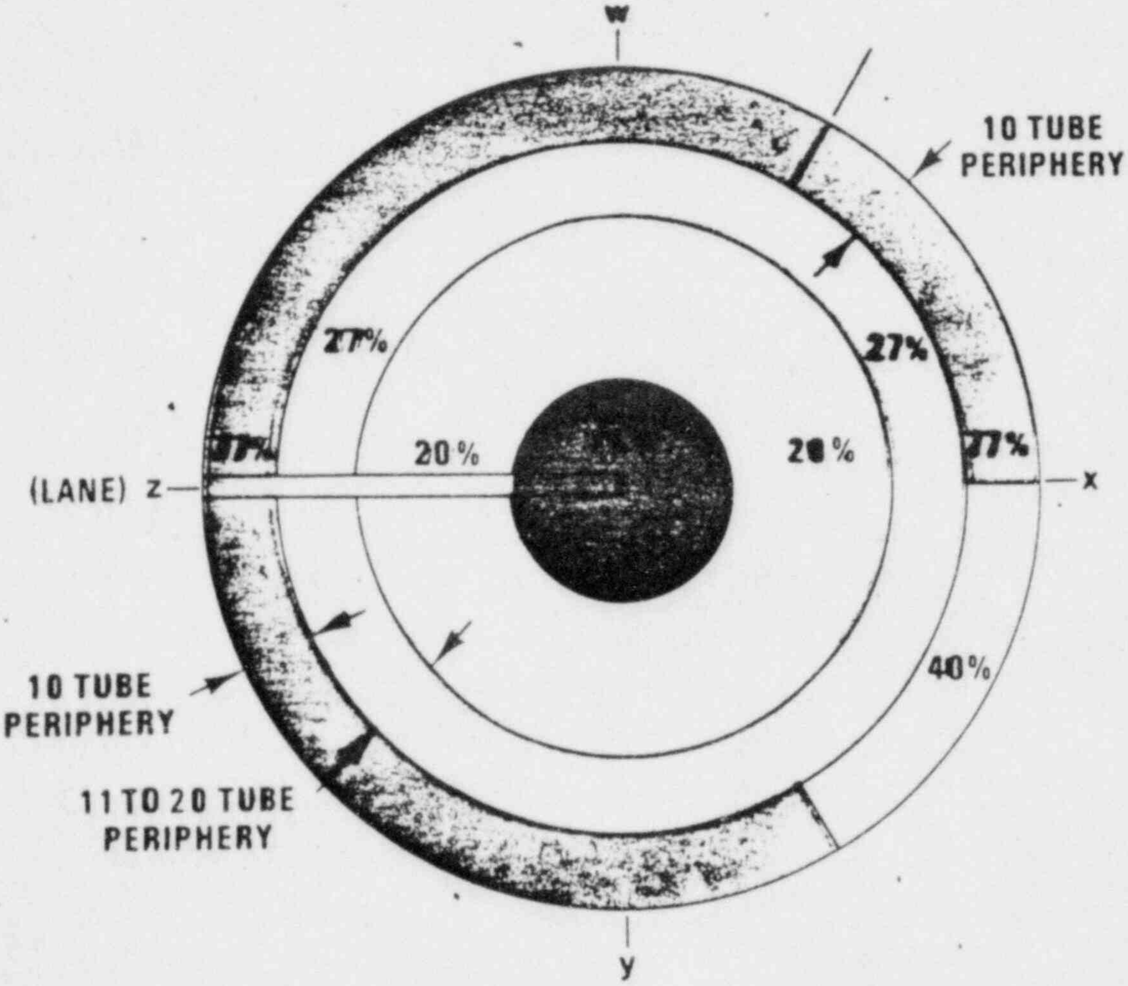
Tube Cracking





Potentially Defective Tubes
(Projection of Eddy Current Data)

OTSG-A



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Potentially Defective Tubes
(Projection of Eddy Current Data)

OTSG-B

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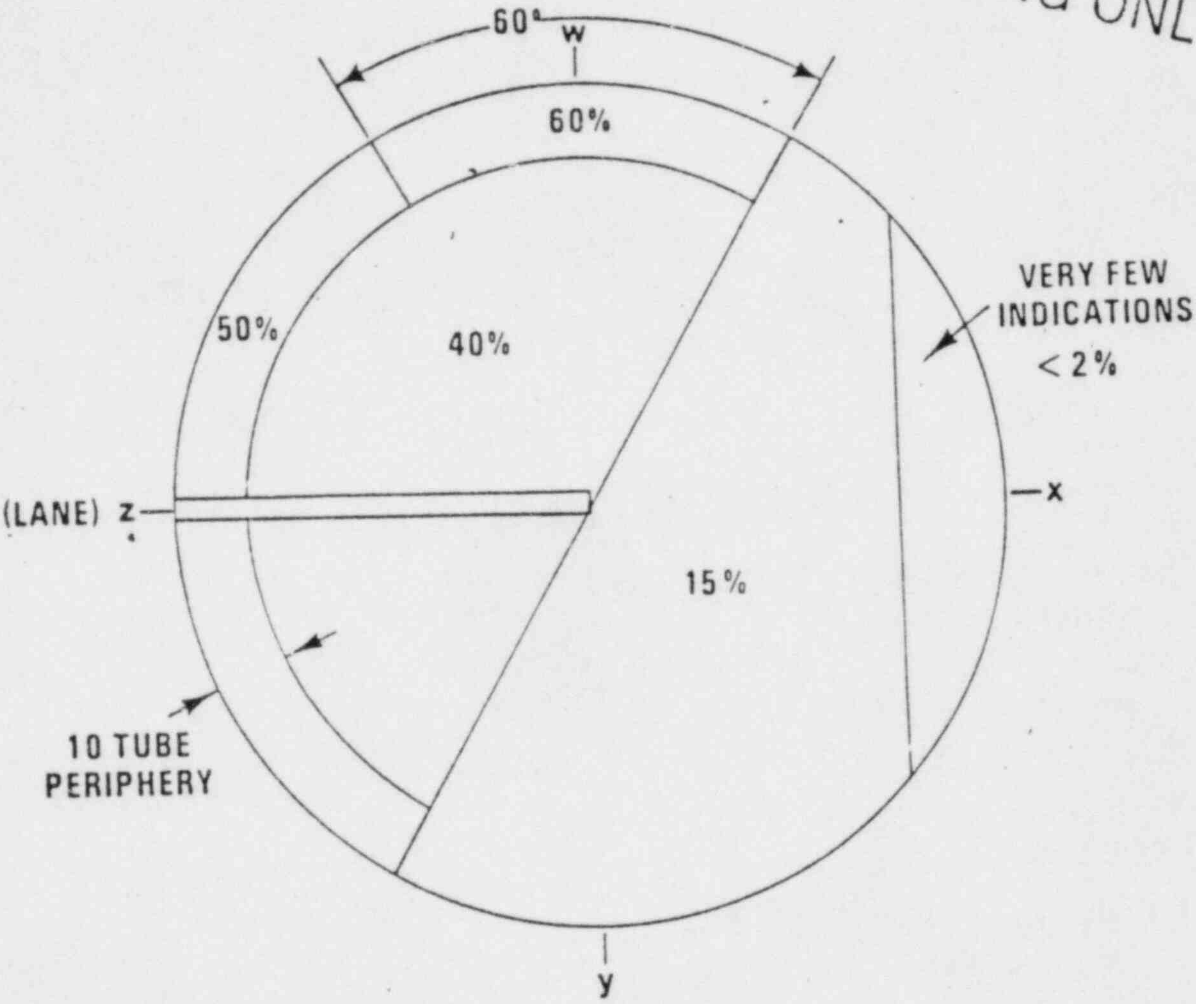

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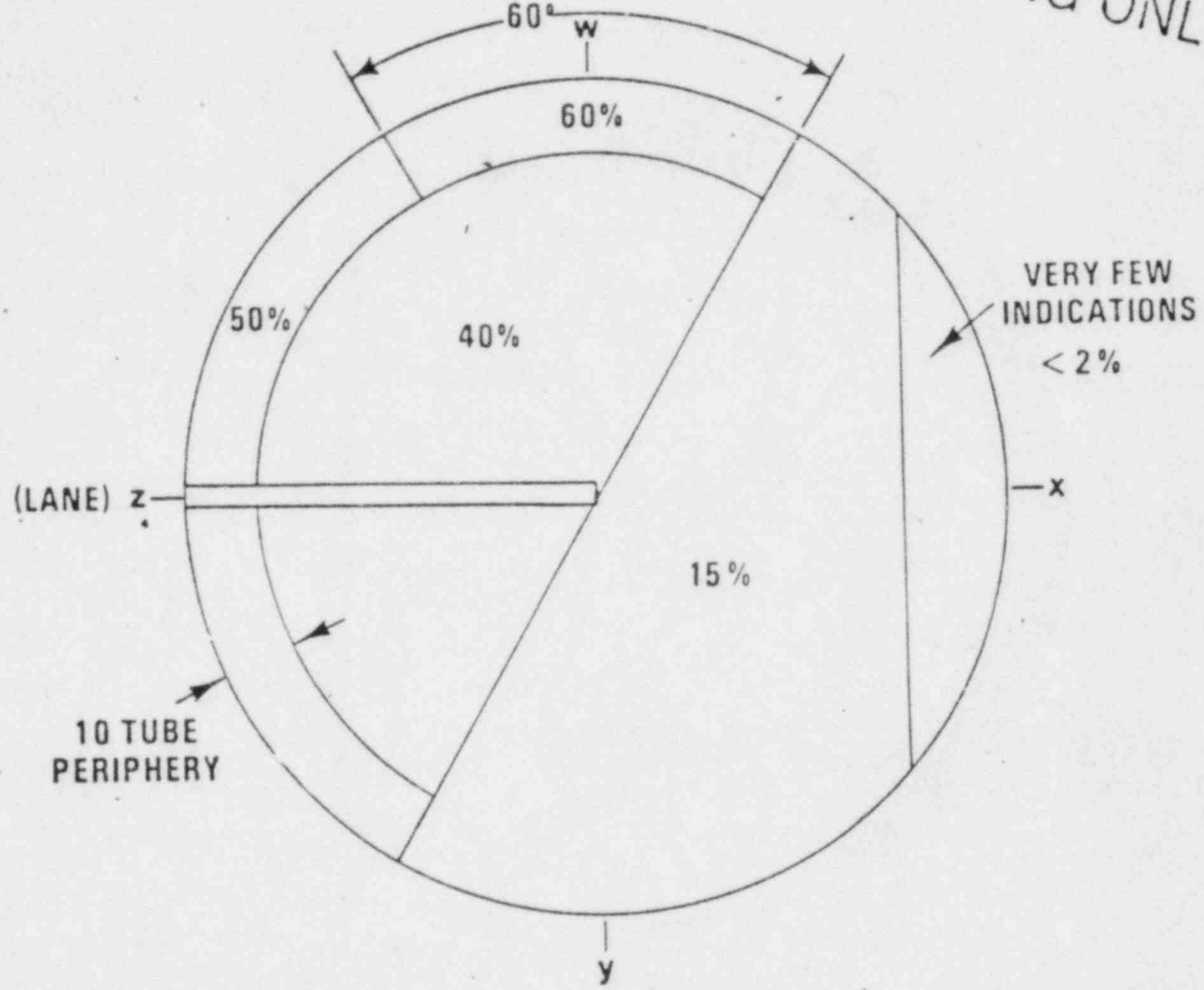
OK

Potentially Defective Tubes
(Projection of Eddy Current Data)

OTSG-B

FOR PROOFING ONLY



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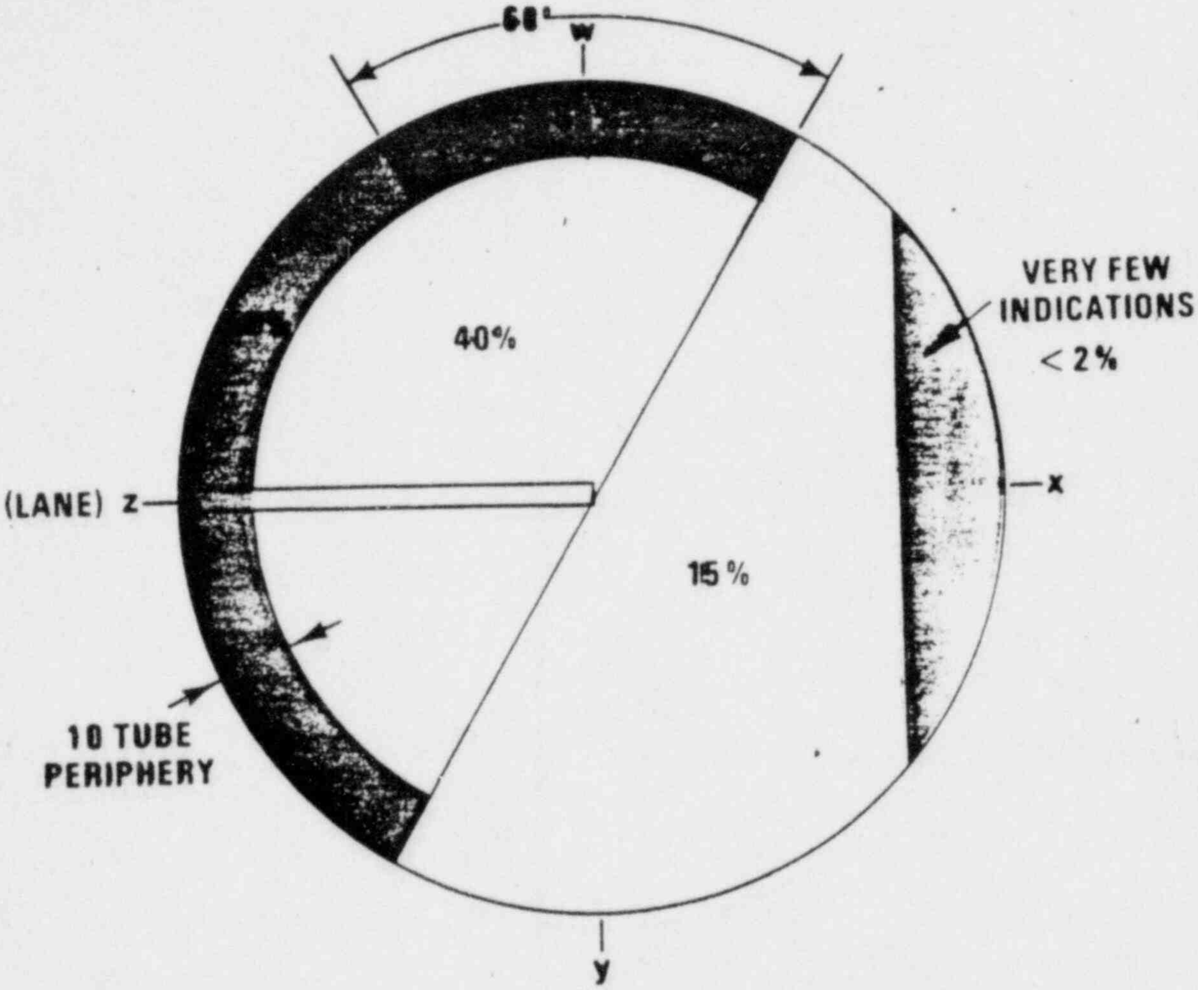
(10K)

Potentially Defective Tubes
(Prcjection of Eddy Current Data)
OTSG-B



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FUTURE WORK/DECISIONS REMAINING

- FINAL ECT AT ROLL TRANSITION AND UPPER END
- RCS INSPECTION
- FINAL RCS/SG CLEANUP METHODS/APPROACH
- REPAIR, DEVELOPMENT/QUAL. TESTING OF S.G. REPAIR
- FINAL TUBE SAMPLES/LABORATORY SIMULATION TESTS

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TMI-1 TECHNICAL BASIS FOR REPAIR LICENSING

- THE S.G. REPAIR APPROACH IS

  INITIAL - ROLL SEAL EXISTING TUBE TO TUBESHEET TO ISOLATE LEAKS/TUBE DEFECTS

  LONG RANGE - SLEEVE OVER DEFECTIVE TUBES (INCLUDING ROLL SEAL) TO ISOLATE LEAKS/TUBE DEFECTS/ INITIAL REPAIR, IF AND AS REQUIRED

- S.G. DAMAGE IS UNIQUE IN INDUSTRY IN TWO IMPORTANT WAYS

  - LOCATED WITHIN THE UTS
  - DAMAGE MECHANISM OPERATES COLD/REACTOR SHUT DOWN

- THE REPAIR APPROACH ISOLATES THE FAILURES AND RESTORES THE S.G. TUBE TO ITS ORIGINAL FUNCTIONAL/DESIGN BASIS CONDITION

- BELIEVE NO INCREASED PROBABILITY FOR LARGE PRIMARY/SECONDARY TUBE RUPTURE OR ACCELERATED DEGRADATION OF TUBES IN SERVICE

- THERE ARE INSPECTION/SURVEILLANCE/TESTS TO MONITOR CONTINUED SATISFACTORY PERFORMANCE OF THE S.G.

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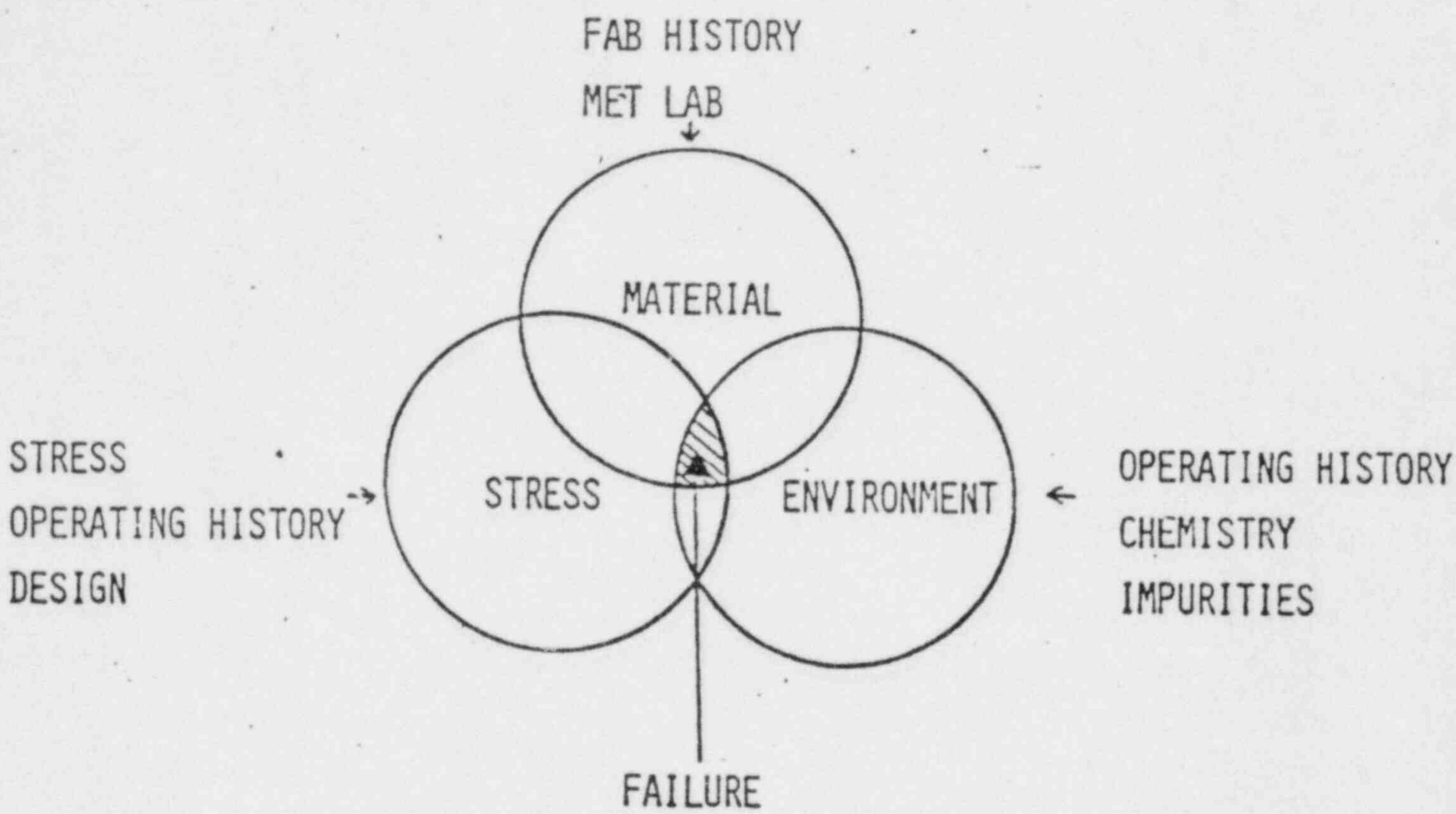
TMI-1 STEAM GENERATORS

GENERAL INTERGRANULAR STRESS CORROSION CRACKING



MUST EXPLAIN - TIMING OF CRACKING
- MATERIAL FAILURE MODE, I.E., INTERGRANULAR
- CONTAMINANT SOURCE FORM
- AXIAL/RADIAL CRACK DISTRIBUTION

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TMI-1 OTSG TUBE MAKING PROCESS

- o ALL TUBES MANUFACTURED BY PATCO
  - NO FORMAL PATCO RECORDS AVAILABLE
  - GPUN/B&W REPS VISIT TO PATCO (1982)
  - MPR TRIP REPORT TO PATCO (1968)
- o BASE MATERIAL SUPPLIED BY B&W TUBULAR PRODUCTS
- o GENERAL PROCESS
  - BASE MATERIAL - ROUND HOLLOW BARS ~2" OD, ~0.088" WALL
  - ONE COLD DRAW THRU ROCKER TYPE REDUCER DIE TO ~1¼" OD, ~0.080" WALL
  - FOUR COLD DRAWS OVER FLOATING MANDRELS THRU A DIE TO ~0.625" OD, ~0.034" WALL
  - TUBES CLEANED, ANNEALED IN HYDROGEN ENVIRONMENT AT 1650°F ± 25°F
  - TUBES STRAIGHTENED AND CENTERLESS GROUND - MINIMUM WALL IS 0.034"
- o OTHER DATA
  - EXTREME CARE TO PREVENT CONTAMINANT CONTACT WITH TUBE
  - NDE TESTS INCLUDED UT, PT, EC, HYDRO, METAL COMPARATOR CHECK
  - INTERMEDIATE CLEANING, ANNEALING AFTER EACH DRAWING OPERATION

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OTSG POST WELD HEAT TREATMENT

- o BASIC CYCLE TO PERFORM ASME CODE HT
  - HEAT TO 1100-1150°F
  - HOLD FOR WELDS, 1 HR. PER 1 INCH OF THICKNESS
  - FURNACE COOL TO BELOW 600°F
  - MAX. HEATING/COOLING RATES ~100°F/HR
  - WELD THICKNESSES, 9½ IN. AND 7 IN.
- o ACTUAL RATES
  - HEATING $<20^{\circ}$F/HR FOR $T>600^{\circ}$F
  - COOLING $<15^{\circ}$F/HR FOR $T>600^{\circ}$F
- o FURNACE
  - 85' x 18' x 18'
  - ELECTRIC HEATING ELEMENTS - CAR FLOOR, ROOF, EACH WALL
  - ARGON GAS CIRCULATED

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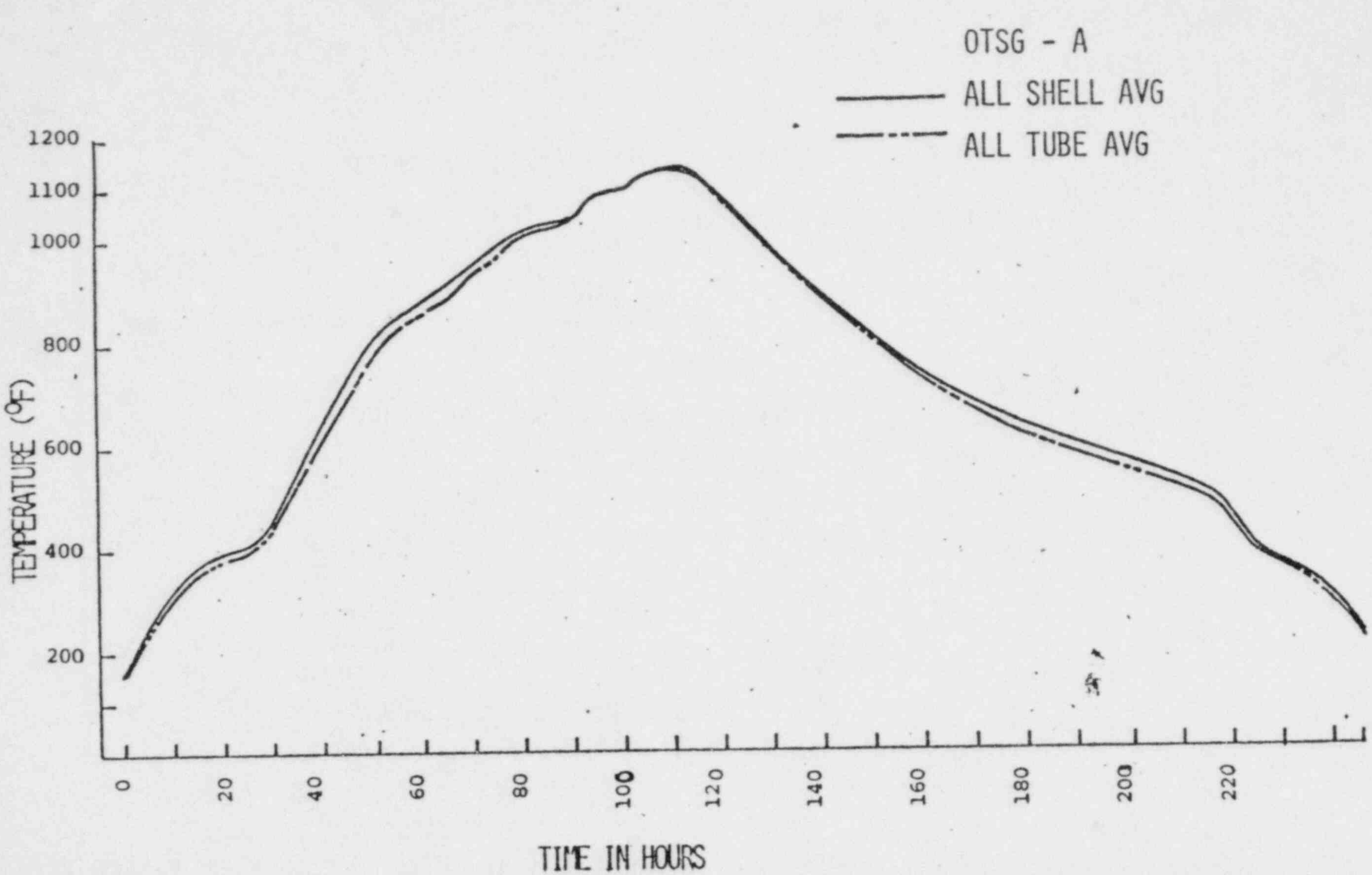
FINAL FULL VESSEL PWHT IN OTSG ELECTRIC FURNACE IN BARBERTON



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OTSG POST WELD HEAT TREATMENT

OTSG	HEATUP TIME 200°F TO 1100°F	TIME AT G.T. 1100°F/850°F	COOLDOWN TIME 1100°F TO 200°F
A	~100 HRS	~18 HRS/~87 HRS	~128 HRS
B	~68 HRS	~13 HRS/~73 HRS	~129 HRS

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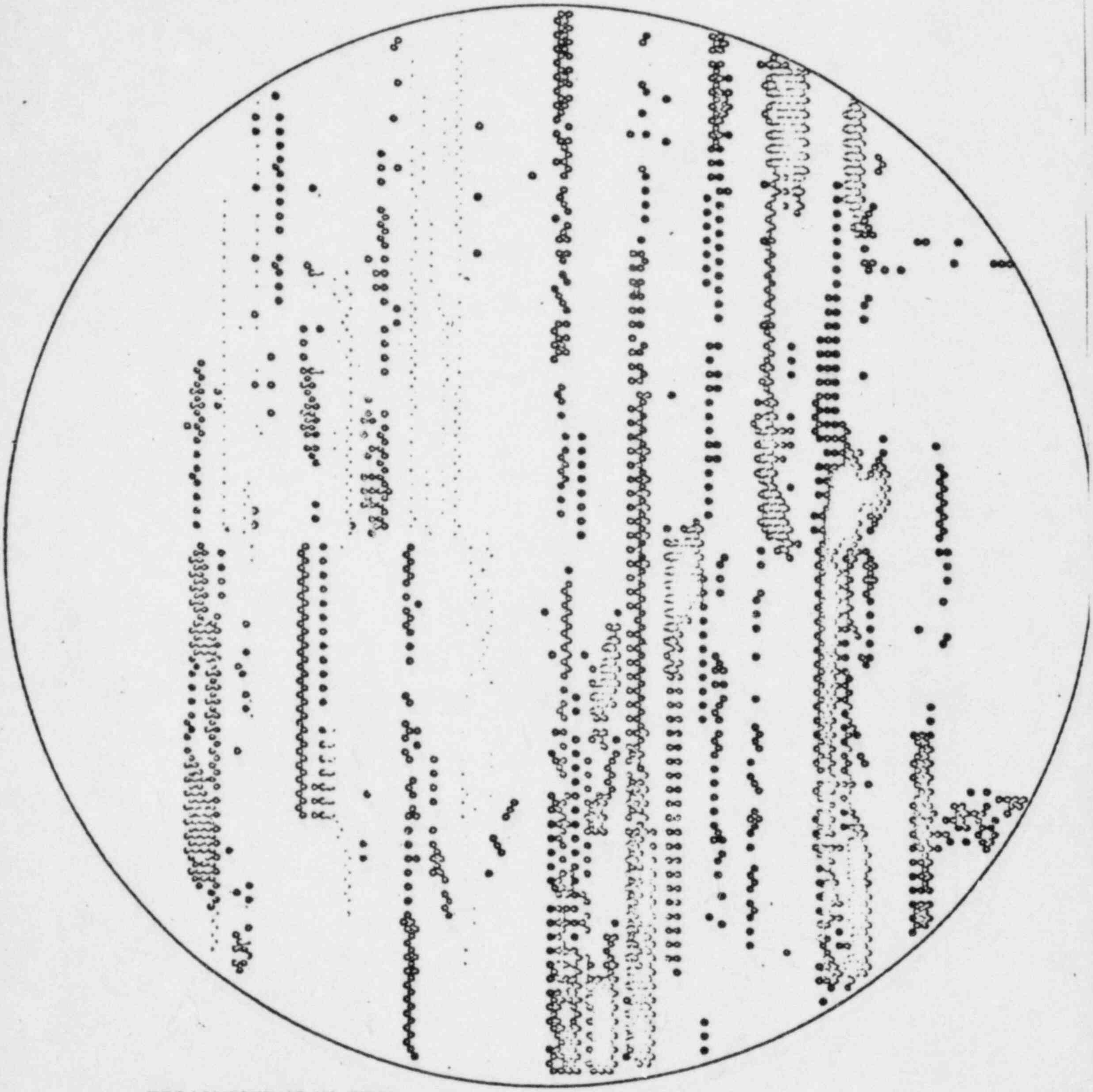
b

THREE MILE ISLAND NUCLEAR
GENERATING STATION
UNIT 1 STEAM GENERATOR A



TUBE LOCATIONS OF ALL TUBES
FOR TUBE HEAT NUMBERS
M2328
M2345

M2582

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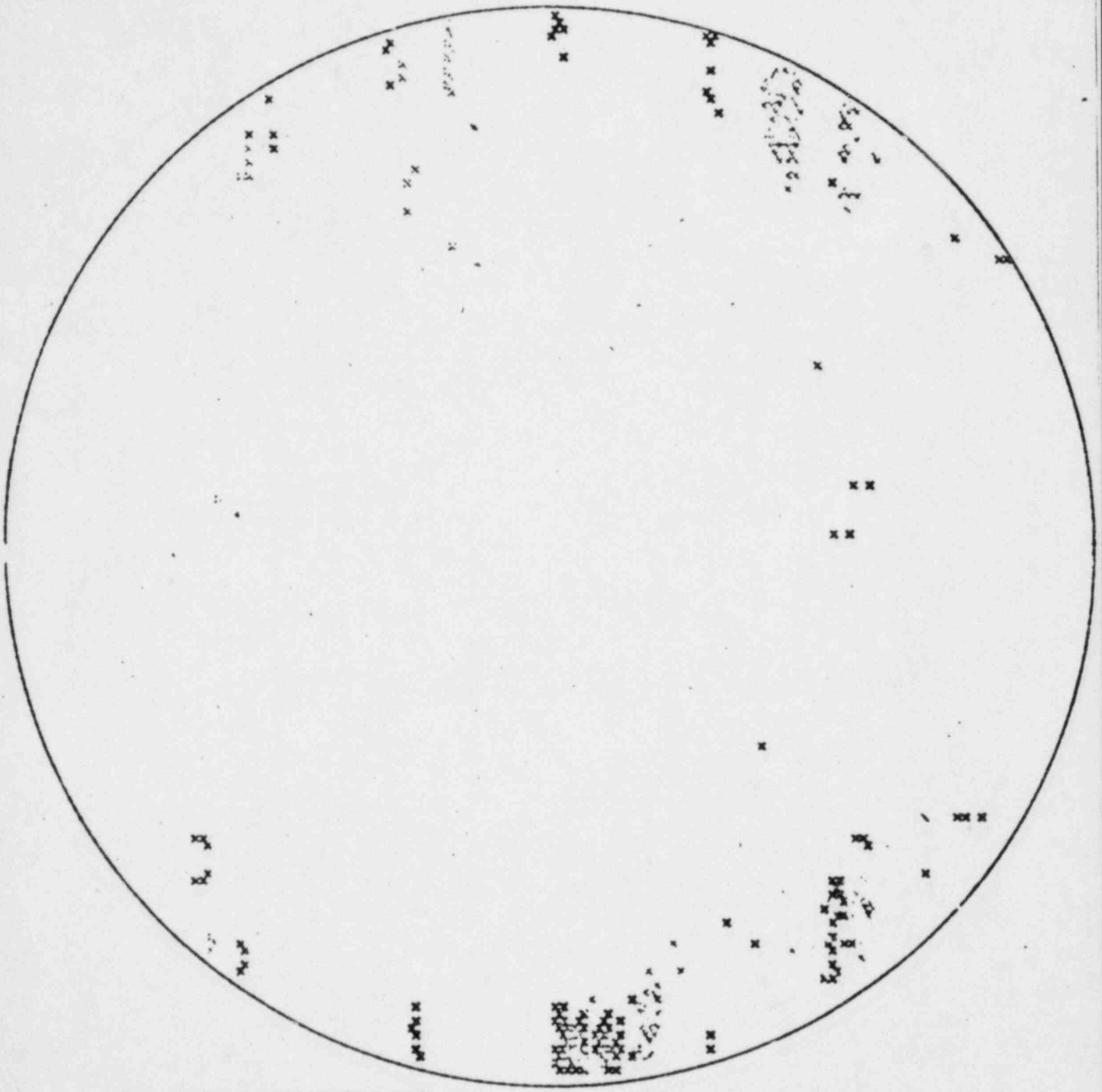
THREE MILE ISLAND NUCLEAR
GENERATING STATION
UNIT 1 STEAM GENERATOR A



TUBE LOCATIONS FOR DEFECTIVE TUBES
FOR TUBE HEAT NUMBERS
M2320

M2562

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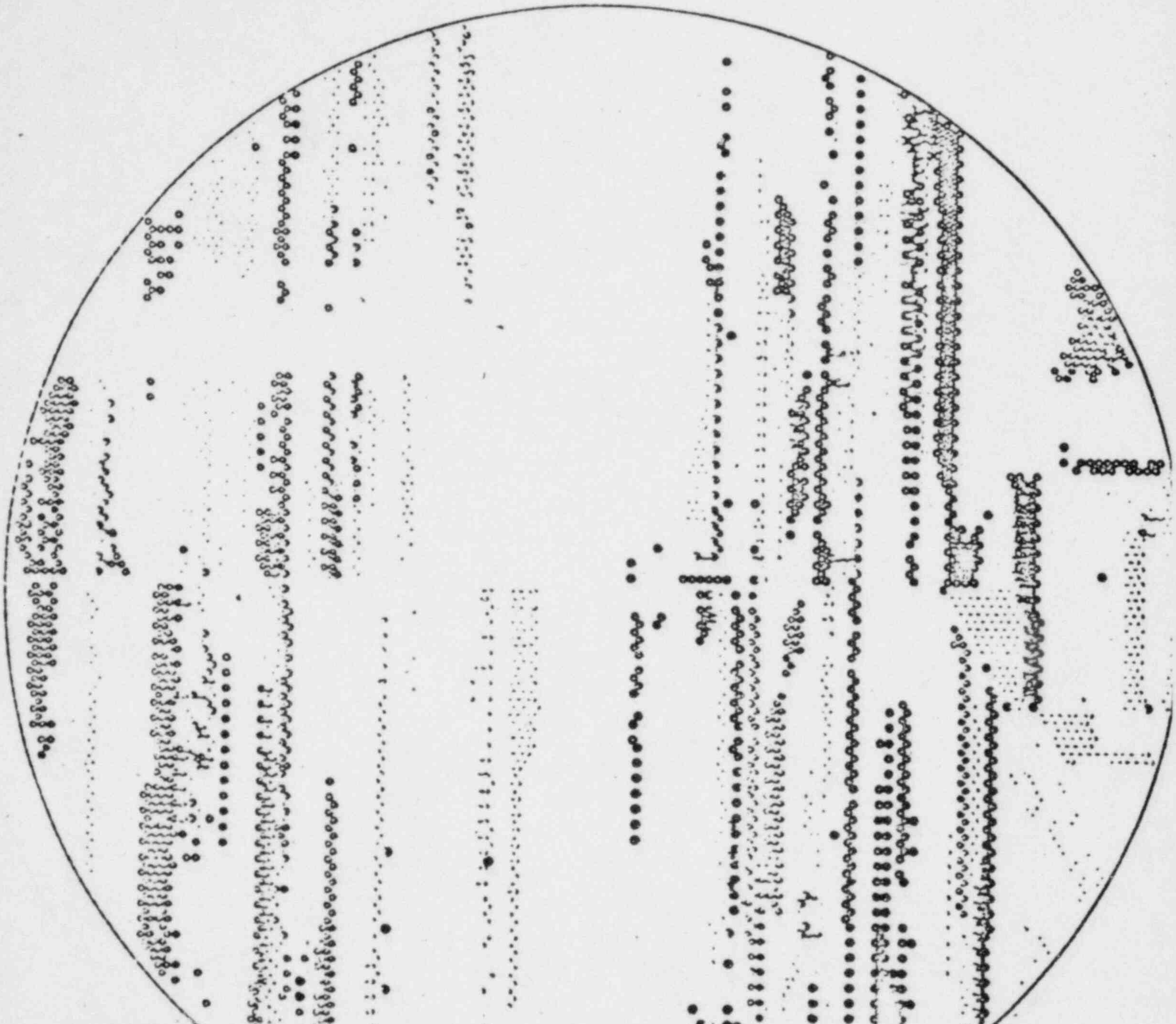
THREE MILE ISLAND NUCLEAR
GENERATING STATION
UNIT 1 STEAM GENERATOR B



TUBE LOCATIONS OF ALL TUBES
FOR TUBE HEAT NUMBERS
M2788

M2858

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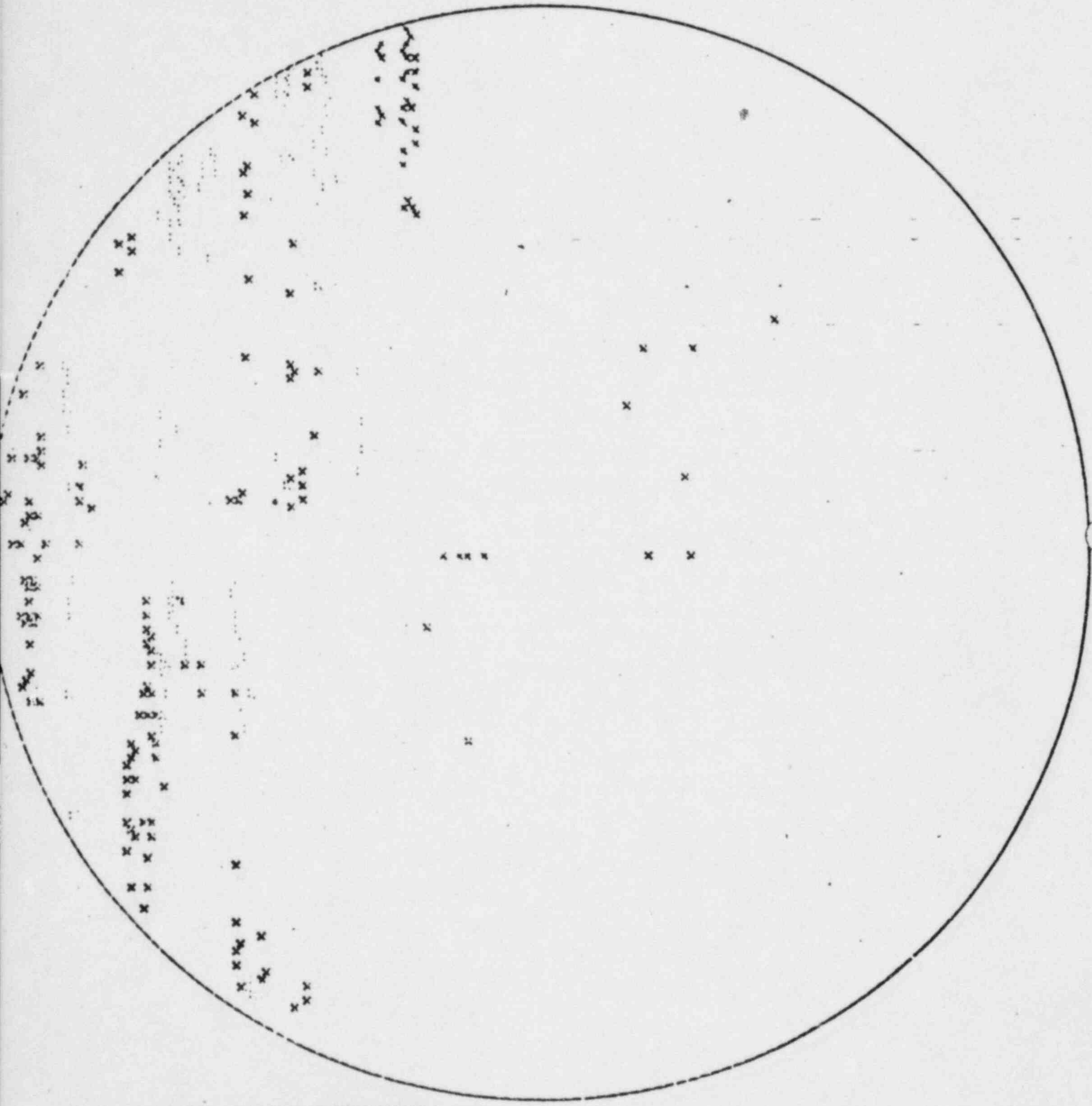
THREE MILE ISLAND NUCLEAR
GENERATING STATION
UNIT 1 STEAM GENERATOR B



TUBE LOCATIONS FOR DEFECTIVE TUBES
FOR TUBE HEAT NUMBERS
M2706
M2869

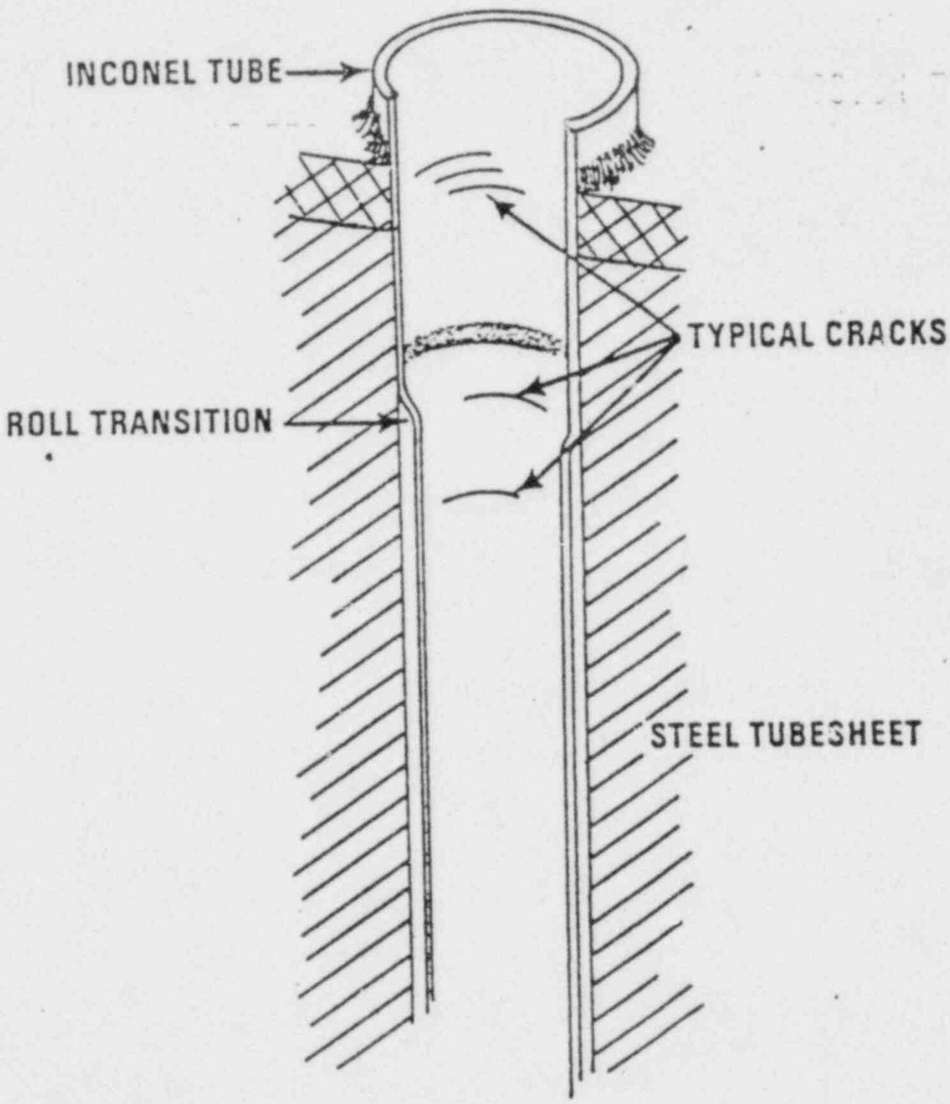
HEAT VS DEFECT CORRELATION
APRIL 2, 1982
SUMMARY

- TUBE FAILURES ARE ASSOCIATED WITH SPECIFIC LOCATIONS IN THE GENERATOR NOT HEAT RELATIONSHIPS.
- THE DEFECT PATTERNS IN THE TWO GENERATORS ARE DIFFERENT AND THIS WILL NEED TO BE EXPLAINED BY A PARAMETER OTHER THAN HEAT NUMBER.
- HEATS OF MATERIAL EXIST WHICH HAVE HIGH DEFECT FREQUENCIES IN BAD AREAS AND THE SAME HEATS WILL HAVE LOW DEFECT FREQUENCIES IN GOOD AREAS.

STRESS RELIEF DATA REVIEW, "B" OTSG UTS

- CENTER OF BUNDLE IN UTS IS 10 - 20^{o}F HIGHER IN TEMPERATURE DURING HEAT UP AND HOLD BUT IS 5 - 10^{o}F LOWER IN TEMPERATURE DURING COOLDOWN
- NO SIGNIFICANT TEMPERATURE VARIATIONS EXIST AROUND BUNDLE PERIPHERY
- NO SIGNIFICANT DIFFERENCES IN TIMES AT TEMPERATURE EXIST AROUND THE PERIPHERY
- MAXIMUM TUBE TEMPERATURE ACHIEVED DURING STRESS RELIEF WAS 1140^{o}F
- OVERALL THE TIMES AT TEMPERATURES INDICATE THE TUBES WERE HELD IN TEMPERATURE REGIONS WHERE SENSITIZATION WOULD BE EXPECTED TO BE SEVERE

TMI-1 Steam Generator
Typical Cracks



CRACK CHARACTERISTICS: CIRCUMFERENTIAL
NOT FULL ARC
GENERALLY VERY TIGHT
INSIDE INITIATED

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TUBE ANALYSIS SUMMARY

ANALYSIS	NO. OF TUBES	NO. OF SAMPLES
METALLOGRAPHIC	8	38
BEND TEST	15	19
SCANNING ELECTRON MICROSCOPY (SEM)	15	15
ENERGY DISPURSIVE X-RAY ANALYSIS (EDAX)	15	15
AUGER ELECTRON SPECTROSCOPY (AES)	5	7
ELECTRON SPECTROSCOPY FOR CHEMICAL ANLYSIS (ESCA)	5	6
SCANNING TRANSMISSION ELECTRON MICROSCOPY (STEM)	5	7
ELECTROCHEMICAL POTENTIOKENITIC REACTIVATION (EPR)	4	5
HUEY TEST	1	3
SECONDARY ION MASS SPECTROSCOPY (SIMS)	2	3
ELECTRON DIFFRACTION	1	1
TRANSMISSION ELECTRON MICROSCOPY (TEM)	2	2
TENSILE TEST	3	3
RESIDUAL STRESS	1	1
SODIUM AZIDE SPOT TEST	3	5

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GPUN FAILURE ANALYSIS
INVESTIGATION TEAM

BABCOCK & WILCOX LYNCHBURG RESEARCH CENTER	TUBE FAILURE ANALYSIS
BABCOCK & WILCOX ALLIANCE RESEARCH CENTER	CORROSION TESTING
BATTELLE COLUMBUS LABORATORIES	TUBE FAILURE ANALYSIS
OAK RIDGE NATIONAL LABORATORIES METALS & CERAMICS DIVISION	CORROSION TESTING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	TUBE ANALYSIS FOR SENSI- TIZATION
OHIO STATE UNIVERSITY	ANALYSIS OF SULFUR COR- ROSION MECHANISM CLEANING/PASSAVATION
ELECTRIC POWER RESEARCH INSTITUTE	FAILURE ANALYSIS REVIEW

<u>ADDITIONAL LABORATORIES</u>

WESTINGHOUSE ELECTRIC RESEARCH & DEVELOPMENT LABORATORIES	INDEPENDENT TUBE FAILURE ANALYSIS

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.JBE UTILIZATION SUMMARY
APRIL 2, 1982

TOTAL TUBING AVAILABLE:	37.8 FT.
TOTAL TUBING EXAMINED:	13.1 FT.
TUBING ALLOCATED FOR TESTING:	
o WESTINGHOUSE FAILURE ANALYSIS -	.35 FT.
o TENSILE TEST OF DEFECT TUBE -	.67 FT.
o CORROSION TESTING -	7.10 FT.
o ROLLING/SLEEVING TESTS -	7.10 FT.
TOTAL	15.22 FT.
UNALLOCATED TUBING	
o PIECES W/O DEFECTS	7.9 FT.
o PIECES WITH DEFECTS	1.6 FT.
TOTAL	9.5 FT.

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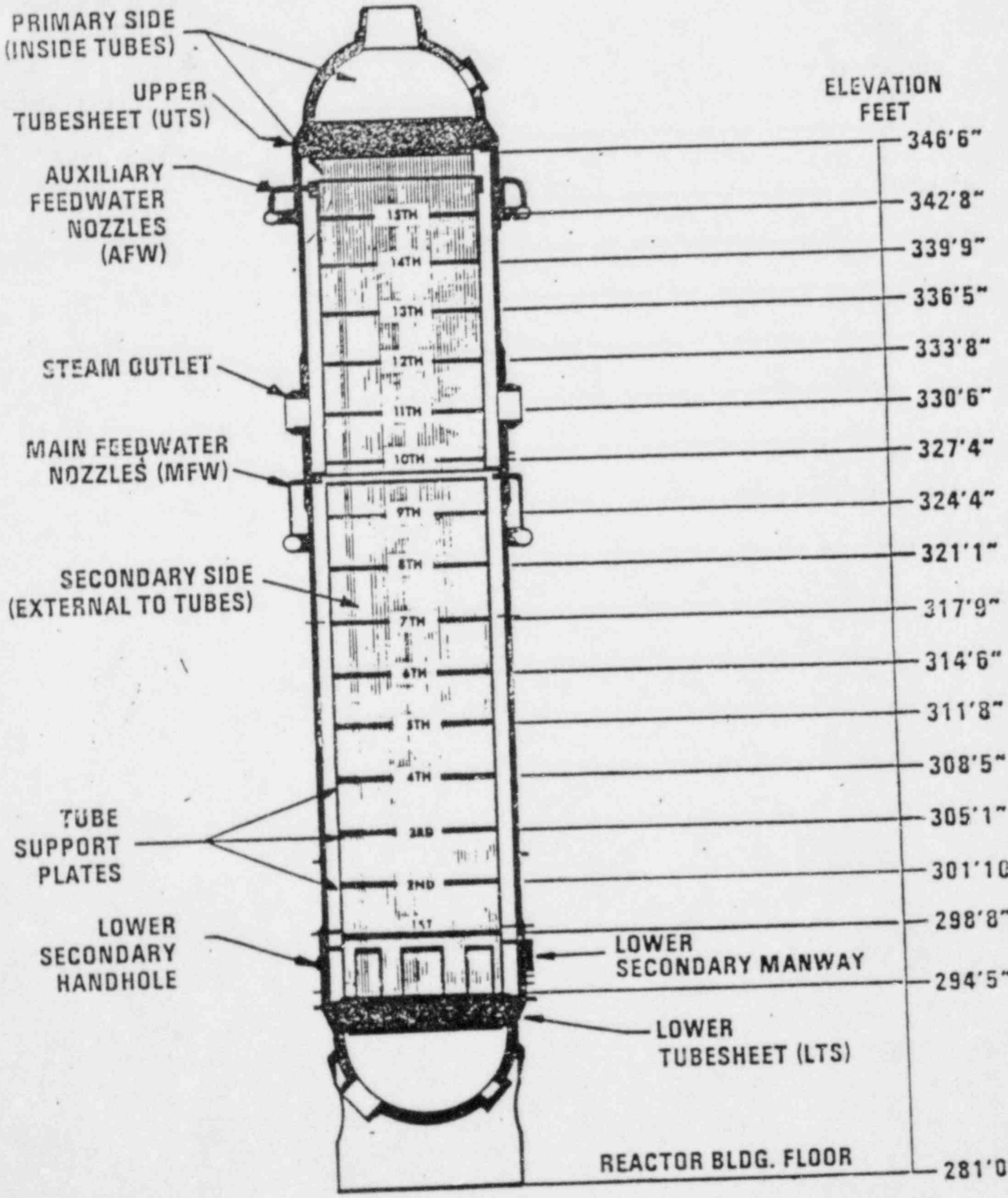
SUMMARY OF FAILURE ANALYSIS

APRIL 7, 1982

- ALL CRACKS ARE STRESS ASSISTED INTERGRANULAR CORROSION WITH INITIATION ON THE ID SURFACE
- EDDY CURRENT EXAMINATION HAS BEEN A RELIABLE INDICATOR OF CRACK LOCATION
- INCIPIENT CRACKS HAVE NOT BEEN DETECTED IN CLEAN SECTIONS (NO E.C. INDICATIONS) OF TUBING BY VISUAL AND DESTRUCTIVE EXAMINATION
- CARBON IN THE FORM OF A HYDROCARBON APPEARS AS THE MAJOR CONTAMINANT ON FRACTURE SURFACES. SULFUR AND CHLORINE ARE PRESENT AS SECONDARY CONTAMINANTS
- RESIDUAL STRESS MEASUREMENTS IN ROLL AND ROLL TRANSITION REGION SHOW NO STRESS PEAKS BUT RATHER A UNIFORM DISTRIBUTION
- CHROMIUM LEVELS IN THE GRAIN BOUNDARIES VARY FROM 8 WT. % TO 20 WT. %
- THE INCONEL MICROSTRUCTURE APPEARS TYPICAL FOR STEAM GENERATOR TUBING WITH DISCRETE CHROMIUM CARBIDE PARTICLES IN THE GRAIN BOUNDARIES
- SMALL AREAS OF INTERGRANULAR CORROSION SEVERAL GRAINS DEEP HAVE BEEN OBSERVED ON THE ID AND OD SURFACES AT RANDOM LOCATIONS
- NO RELATIONSHIP HAS BEEN ESTABLISHED BETWEEN MATERIAL HEATS AND DEFECTIVE TUBING
- MECHANICAL TESTING OF UNCRACKED TUBES SHOW THAT THE MATERIAL EXCEEDS MINIMUM SPECIFICATION REQUIREMENTS

FIGURE II - 4

OTSG Longitudinal Section Elevations (Typ.)



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TMI-1 STEAM GENERATORS - STRESSES

- STRESS MAXIMUM IN ROLL TRANSITION AREA, ~34 KSI±
- STRESS MAXIMUM ON OUTER EDGE OF GENERATORS
- STRESS EXPECTED TO BE QUITE VARIABLE IN ROLL TRANSITION AREA
- MAXIMUM STRESSES ARE AXIAL
- STRESSES SAME IN UPPER AND LOWER TUBESHEET
- STRESSES MAXIMUM DURING COOLDOWN, COLD
- AT OPERATING TEMPERATURE - HOOP STRESS > AXIAL STRESS

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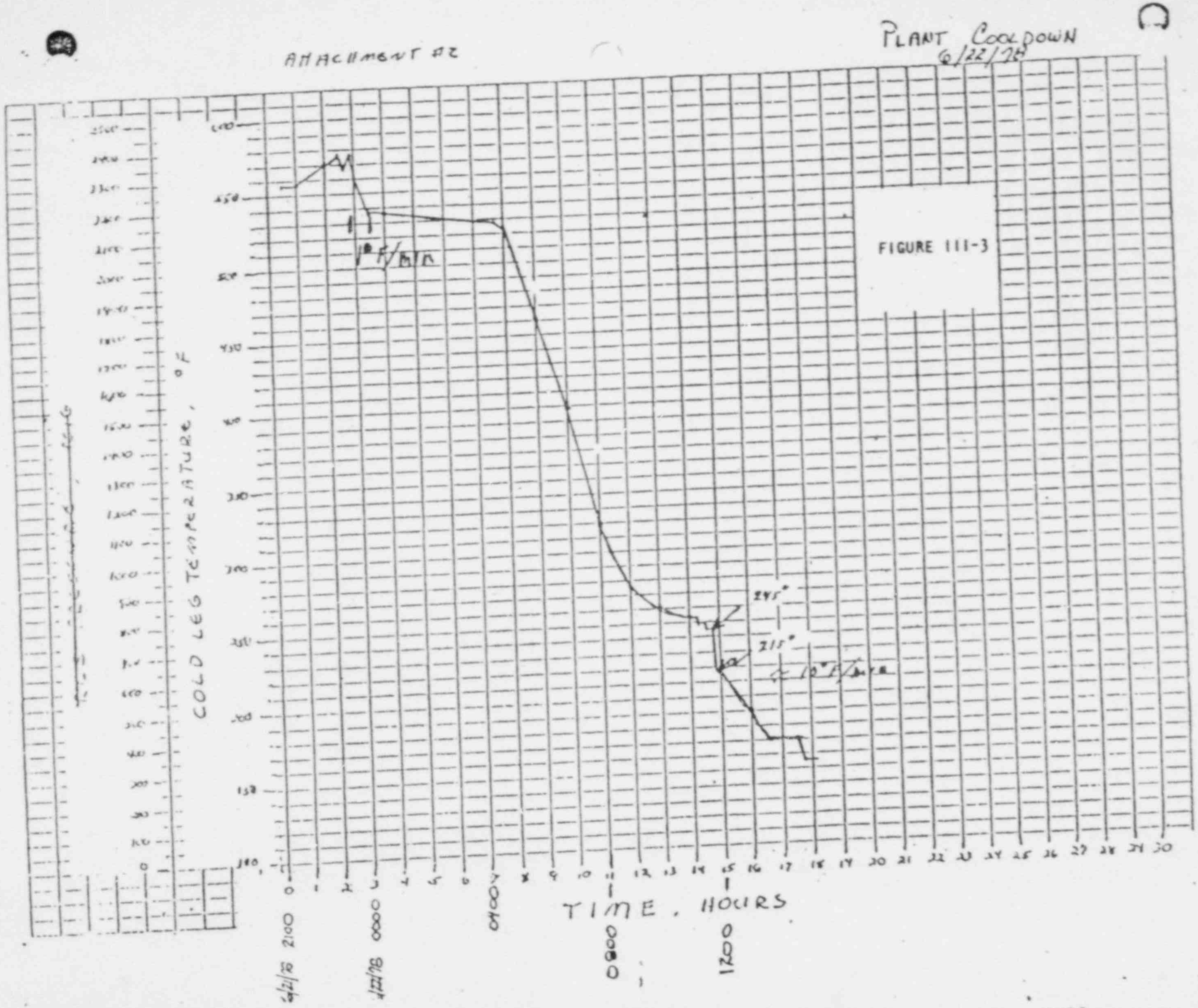

ATTACHMENT #2
PLANT COOLDOWN
6/22/78
FIGURE III-3
COLD LEG TEMPERATURE, °F
TIME, HOURS
1°F/MIN
245°
215°
≈ 10°F/MIN
6/21/78 2100
6/22/78 0000
0400
0800
1200

OPERATING HISTORY OBSERVATIONS-1

- LOWER END GENERATOR ALWAYS SUBMERGED (WETTED), UPPER END ALTERNATE WET AND DRY WITH AIR (OXYGEN) INTERFACE

- WATER LEVEL IN THE PRIMARY SIDE OF OTSG WAS IN UTS FOR BETWEEN 31 AND 243 DAYS

- SOME DIFFERENCES IN AMOUNT OF FLOW SINCE FEB '79
  - TOTAL PUMP HOURS OTSG - A = 681 HRS
  - TOTAL PUMP HOURS OTSG - B = 393 HRS
  - BACK FLOW IN OTSG - B FOR 10 HRS

  DURING SEPTEMBER '81 COOLDOWN

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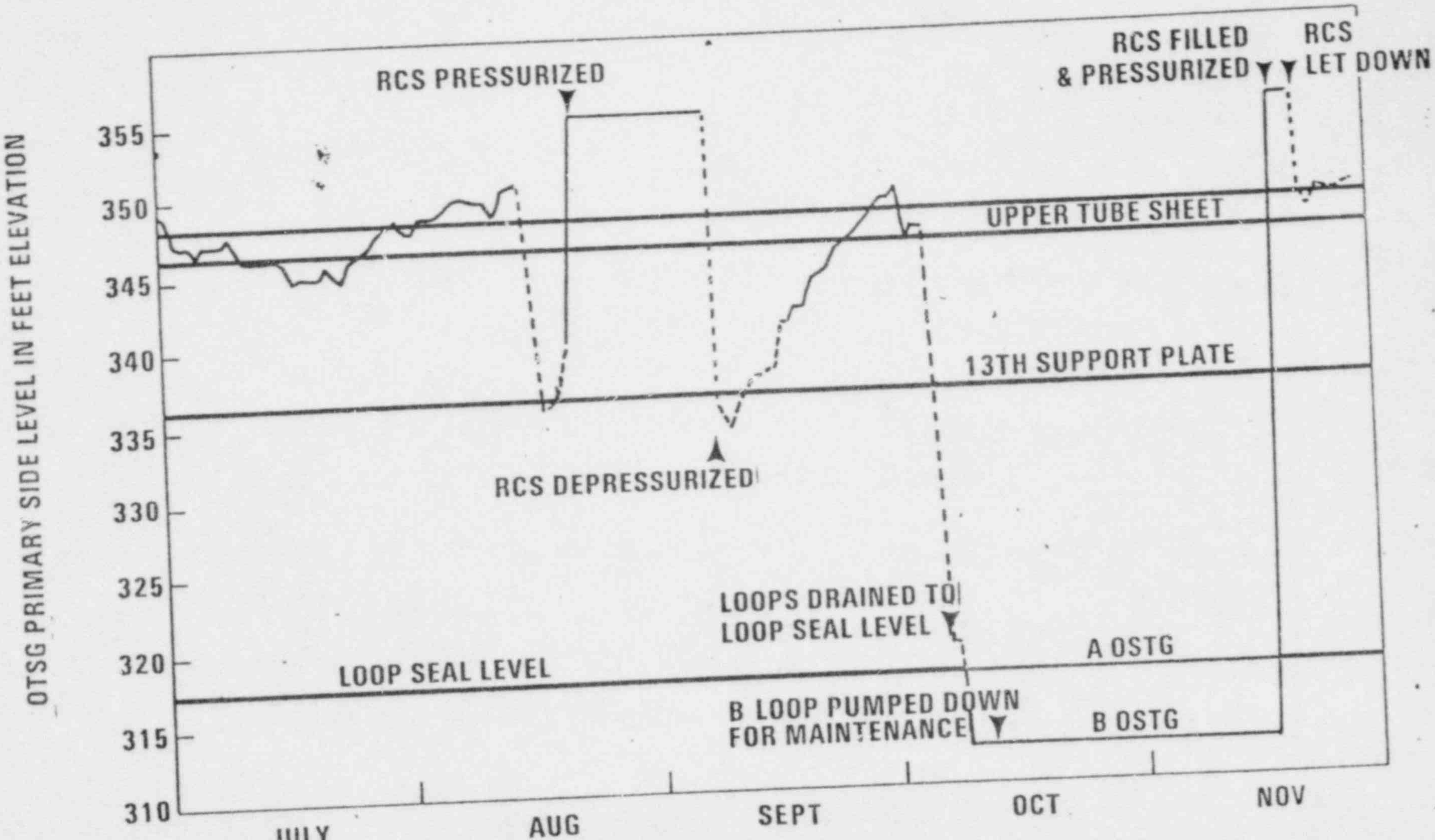
OTSG Level
July 1981 — November 1981



DOTTED LINE MEANS ESTIMATED LEVEL
VENTING ARRANGEMENT CAUSES UP TO 27" ERROR

OPERATING HISTORY OBSERVATIONS - 2

- o POTENTIAL SULFUR SOURCES PRESENT
  - SOME OIL INTRODUCED INTO RCS IN MAR '79
  - SULFURIC ACID ADDED TO RCS IN OCT '79
  - SODIUM THIOSULFATE ADDED TO RCS AT VARIOUS TIMES OVER LIFE OF PLANT
- o SODIUM THIOSULFATE THOUGHT TO BE PRIMARY CONTRIBUTOR
  - ACCUMULATED IN BUILDING SPRAY PIPING - 1979-81 - AS A RESULT OF VALVE LEAKAGE
  - JUN, AUG, SEP '81 OPERATION OF SPRAY PUMPS ADDED SOLUTION TO BWST
  - INJECTION INTO RCS OCCURRED DURING SEP '81 COOLDOWN

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TMI-1 STEAM GENERATORS - SULFUR SAMPLES

SYSTEM	DATE	SULFATE (PPB)	TOTAL SULFUR (PPB AS SO_4)
REACTOR COOLANT DECAY HEAT	7/31/79	-	1,500
	8/02/79	-	<600
	11/01/79	-	<660
	12/04/81	-	730
	1/18/82	-	400
	2/04/82	-	100
BORATED WATER STORAGE TANK	1/20/82	-	<100
REACTOR BUILDING SPRAY PUMP OUTLET	1/20/82	-	15,000
	3/17/82	2,876	-
	3/20/82	764	-
INTERCONNECT BETWEEN BUILDING SPRAY AND DECAY HEAT	1/20/82	-	176,000
	3/17/82	2,465	-
	3/20/82	752	-
SPENT FUEL POOL	1/18/82	-	400
	3/17/82	246	-
	3/20/82	149	-

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CORROSION TESTING
SUMMARY

- o TEST WITH ACTUAL DECAY HEAT COOLANT ON SENSITIZED INCONEL AND STAINLESS STEEL BENT STRIPS. RESULTS - NO CRACKING IN TWO WEEKS

- o TEST WITH ACTUAL DECAY HEAT COOLANT ON AN ACTUAL TUBE SAMPLE REMOVED WITH AN INCIPIENT DEFECT. RESULT - NO CRACK GROWTH

- o 34 ELECTROCHEMICAL CORROSION TESTS WITH VARIOUS CONTAMINATED PRIMARY COOLANT ENVIRONMENTS AND VARIOUS SPECIMENS

  - BORIC ACID (PPM) - 13,000, 5,000
  - THIOSULFATE (PPM) _ 100, 10, 1, 0
  - HYDRAZINE (PPM) - 200
  - MATERIALS - M5442, M2320 - ACTUAL
M2320 - ARCHIVE
  - TEMPERATURE - 550, 100°F
  - ATMOSPHERE - AIR, HYDROGEN

PRELIMINARY CORROSION TEST RESULTS

- CORROSION TESTS IN ACTUAL PRIMARY COOLANT INDICATE IT IS CURRENTLY INNOCUOUS
- REDUCED SULFUR SPECIES CAN REPRODUCE THE TYPE OF CRACKING OBSERVED IN STEAM GENERATOR TUBES
- THE DEGREE OF SENSITIZATION (I.E., PRIOR HEAT TREATMENT) IS A KEY PARAMETER IN DEFINING THE MATERIALS SUSCEPTABILITY TO IGSCC
- THE PROPENSITY FOR A SULFUR CONTAMINATED PRIMARY COOLANT ENVIRONMENT TO INITIATE CRACKING VARIES INVERSELY WITH THE BORIC ACID AND LITHIUM HYDROXIDE CONCENTRATIONS
- CRACK INITIATION APPEARS TO BE THE RATE CONTROLLING PAR-AMATER
- CRACK GROWTH RATE IS VERY RAPID ON THE ORDER OF 1MM/DAY
- CRACKING APPEARS TO BE A LOW TEMPERATURE OCCURRENCE
- CRACKING TENDENCY IS REDUCED BY RAISING THE pH

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KEY ELEMENTS IN EXP REVIEW

- IGSCC OF I-600 OBSERVED AT 575^{o}F IN SULPHATE CONTAINING WATER; UNLIKELY TO OCCUR UNDER PWR PRIMARY SYSTEN REDUCING ENIVRONMENT
  - NOT ASSOCIATED WITH DEGREE OF SENSITIZATION
- IGSCC OF I-600 OBSERVED AT 75- 225^{o}F IN SULPHUR OXYANION (E.G. THIOSULPHATES) CONTAINING WATER; MORE LIKELY TO OCCUR IN PWR PRIMARY SYSTEM
  - CRACKING IS RAPID
  - SUSCEPTIBILITY DEPENDS ON SENSITIZATION, pH, TEMPERATURE, AND ELECTROCHEMICAL POTENTIAL
- PLANT AND MODEL BOILER EXPERIENCE IS ENTIRELY RELATED TO SECONDARY SIDE PROBLEMS
- NONE OF PRIMARY SIDE INDUSTRY EXPERIENCE IGSCC OF I-600 ATTRIBUTED TO ATTACK BY BULPHUR SPECIES

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HIGHLIGHTS OF STRESS ANALYSIS

- TUBING AXIAL TENSILE STRESSES LARGEST DURING COOLDOWN; MAY APPROACH YIELD STRESS
- SIGNIFICANT AXIAL TENSILE STRESSES ALSO EXIST DURING COLD SHUTDOWN
- LOCALLY HI AXIAL TENSILE STRESSES POSSIBLE IN SEAL WELD HAZ AND NEAR ROLL TRANSITION
- AXIAL STRESSES GENERALLY LARGER AT PERIPHERY THAN IN CENTER OF TUBE BUNDLE

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SUSCEPTIBLE MATERIAL MICROSTRUCTURE

- o FAB HISTORY SHOWS TUBING TO BE MILL ANNEALED PLUS STRESS RELIEVED
  - °°° HIGHLY SENSITIZED
- o MET EXAMS CONFIRM EXPECTED MICROSTRUCTURE
- o CORROSION TESTS SHOW PULLED TUBES SUSCEPTIBLE TO CRACKING IN THIOSULFATE/BORIC ACID SOLUTIONS

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AGGRESSIVE ENVIRONMENT

- SO_4^{--} AND $S_2O_3^{--}$ CONTAMINATION PROBABLY PRESENT

- CHANGES IN S-SPECIES EXPECTED DURING HOT FUNCTIONAL -- DIFFICULT TO PREDICT SPECIES PRESENT AFTERWARDS

AQUEOUS SULFUR SPECIES

Formula	Structure	Sulfur Oxidation Number*	Name
H_2S or $S^{=}$		-2	sulfide
H_2S_2, $S_2^{=}$	$[S-S]^{=}$	-1	
H_2S_3, $S_3^{=}$	$[S-S-S]^{=}$	-2/3	polysulfides
H_2S_x,	$[S-S--]^{=}$	-2/x	
S S_8 rings		0	sulfur
$S_2O_3^{=}$	$\left[O-\overset{O}{\underset{O}{S}}-S\right]^{=}$	+2	thiosulfate
$S_4O_6^{=}$	$\left[O-\overset{O}{\underset{O}{S}}-S-S-\overset{O}{\underset{O}{S}}-O\right]^{=}$	+2.5	tetrathionate
$SO_3^{=}$	$\left[O-\overset{O}{S}-O\right]^{=}$	+4	sulfite (sulfurous acid)
SO_2		+4	sulfur dioxide
$S_2O_6^{=}$	$\left[O-\overset{O}{\underset{O}{S}}-\overset{O}{\underset{O}{S}}-O\right]^{=}$	+5	dithionate
$SO_4^{=}$	$\left[O-\overset{O}{\underset{O}{S}}-O\right]^{=}$	+6	sulfate

* Oxidation number is the formal electrical charge assigned to the sulfur on the assumption that H is +1 and O is -2 in these compounds.

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PROPOSED FAILURE SCENARIO

1. SO_4^{--} AND $S_2O_3^{--}$ (POSSIBLY OTHERS) ADDED DURING LAYUP
2. REDUCED S-SPECIES FORMED DURING HOT FÛNCTIONAL
3. WATER LEVEL DROPPED. HIGH CONCENTRATION OF AGGRESSIVE S-SPECIES FORMED IN DRY-OUT REGION
4. CRACKING OCCURS IN DRY-OUT ZONE
5. CRACKING TERMINATES DUE TO REDUCTION OF CONCENTRATION
6. CRACKING IS DISCOVERED WHEN OTSGs ARE PRESSURIZED

4/7/82

FEATURES COVERED BY SCENARIO

- TIME OF CRACKING
- MODE OF CRACKING
- AXIAL DISTRIBUTION OF CRACKING
- RADIAL DISTRIBUTION OF CRACKING (OTSG-A)
- CORROSION TEST RESULTS

4/7/82

IMPLICATIONS OF SCENARIO

. SULPHUR REDUCTION NECESSARY TO PREVENT RECURRENCE

-- OXIDATION TO SOLUBLE FORM
-- REMOVAL VIA DEMINERALIZER

. ATTACH OF OTHER PRIMARY SYSTEM COMPONENTS, IF ANY, MOST PROBABLE IN VICINITY OF WATER LINE LOCATION FOLLOWING HOT FUNCTIONAL

-- INCONEL X-750

-- SENSITIZED TYPE 304 STAINLESS STEEL

4/7/82

REACTOR COOLANT SYSTEM REVIEW

OBJECTIVES

- o REVIEW REACTOR COOLANT SYSTEM COMPONENTS FOR CONTINUED SAFE OPERATION
- o CLASSIFY ITEMS FOR MATERIAL CONDITION, ENVIRONMENT EXPOSURE AND APPLIED STRESS
- o SELECT CANDIDATES FOR INSPECTION AND TESTING THAT ARE REPRESENTATIVE OF WORST CONDITIONS
- o MINIMIZE EXPOSURES
- o EMPLOY STANDARD ACCEPTANCE TESTING BUT SELECT SUSCEPTIBLE MATERIALS FOR DESTRUCTIVE METALLURGICAL EXAMINATION

4/7/82

REACTOR COOLANT SYSTEM REVIEW

PROGRAM PLAN

- O CLASSIFY ALL MATERIAL TYPES USING FABRICATION HISTORY AND LOCATION IN RCS
- O IDENTIFY ASSOCIATED STRESS LEVELS AND SAFETY CONSIDERATIONS FOR APPLICATION
- O EVALUATE RCS MATERIAL CORROSION SUSCEPTIBILITY
- O IDENTIFY POTENTIAL PROBLEM AREAS FOR RECERTIFICATION INSPECTION AND TEST
- O DEVELOP INSPECTION PLAN
- O PERFORM INSPECTIONS AND EVALUATE RESULTS PROVIDING AS NECESSARY ANY CONTINGENCY TESTING
- O DOCUMENT ACCEPTABILITY OF PRIMARY SYSTEM FOR SAFE RESTART

4/7/82

REACTOR COOLANT SYSTEM REVIEW

INSPECTION PLAN

O DESTRUCTIVE METALLURGICAL ANALYSIS	- INCONEL 600 - INCONEL X-750 - SS 304 - INCONEL 718
O EDDY CURRENT	- I-600 NOZZLE TO SS FLANGE - I-600 (NOT AXIALLY LOADED)
O ULTRASONIC TESTING	- SS 304 - BOLTS - INCONEL X-750 - SS 304 TUBING - I-600 SAFE ENDS - SS 304 WELDMENTS
O RADIOGRAPH TESTING	- I-600 SAFE ENDS - SS 304 WELDMENTS
O PENETRANT INSPECTION	- SS 304 CLAD - I-600 CLAD
O FUNCTIONAL TESTS	- IN-CORE DETECTORS - VENT VALVES

INSPECTION PLAN (CONT'D)

O VISUAL EXAMINATION	- CORE COMPONENTS - PLENUM - HOLD DOWN SPRINGS - END FITTINGS - FUEL RODS - SPACER ASSEMBLIES - CONTROL RODS - SHELLS AND BOLTING RINGS - BAFFLE PLATE REGION - LOWER BOLTING RINGS - LOWER VESSEL HEAD
O OVERALL	- INSPECT OR TEST APPROXIMATELY 1000 ITEMS

Repair Criteria

(1) The maximum allowable primary-to-secondary leakage rate for normal operation shall be as low as reasonably achievable and allow plant operation within the radioactive effluent limits of the technical specifications.

Repair Criteria

(2) Repaired tube shall sustain, with adequate margins, the design basis loads

Loads	Generic 177FA	TMI-1
LOCA	+ 2641 lb	+ 2641 lb
MSLB	+ 3140 lb	+ 3140 lb (being reanalyzed)
FWLB	- 620 lb	- 620 lb
Normal cooldown:	+ 1107 lb	+ 1107 lb

+ = tension
- = compression

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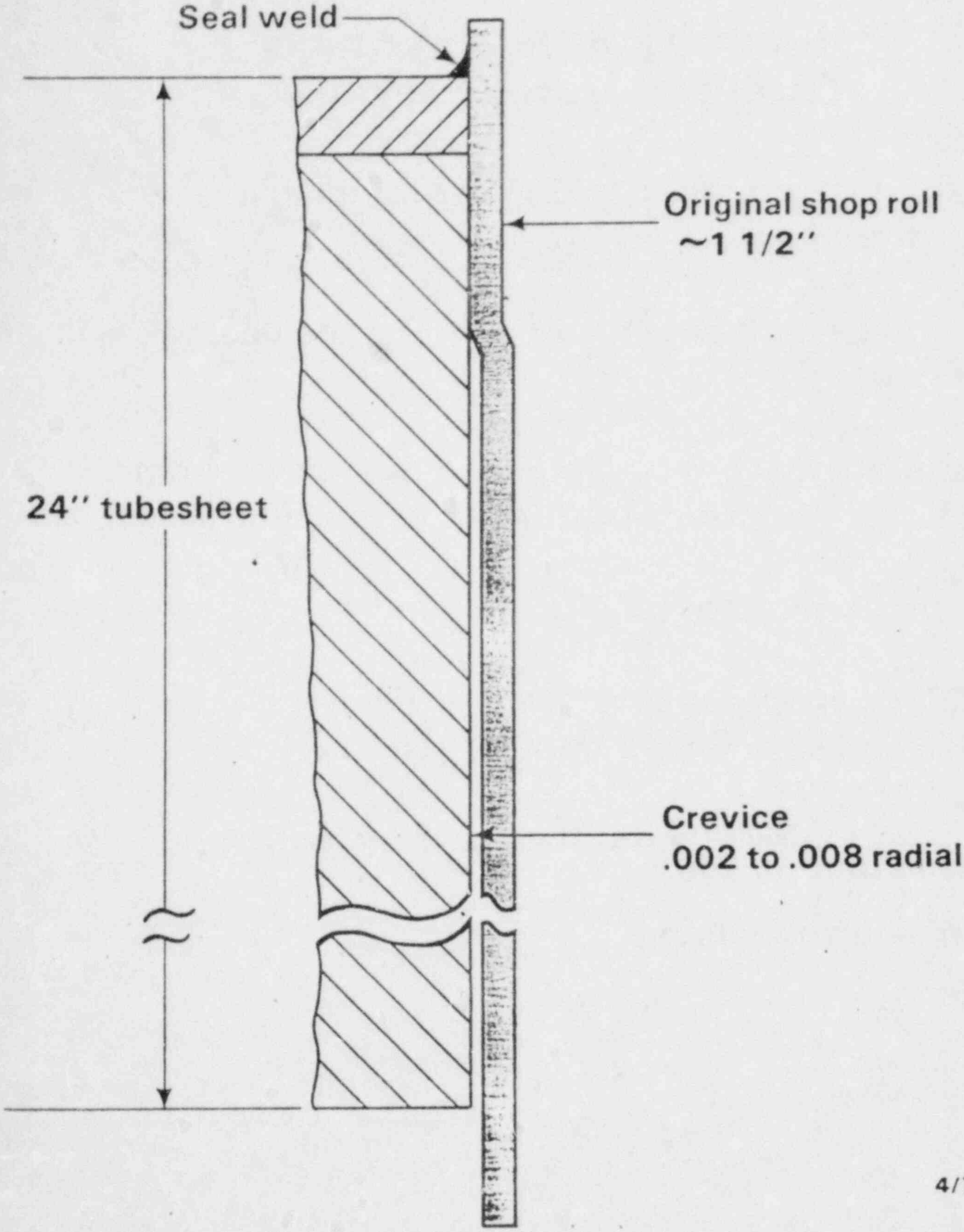
Repair Criteria

(3) The effects of both repaired and plugged tubes on the thermal and hydraulic performance of the plant and on the structural and vibrational adequacy of the steam generator shall be evaluated and shall be within the acceptance criteria for both normal operating and design basis accident conditions as specified in the licensing basis documents.

Preliminary Repair Process Qualification Criteria

- Result in a process capable of providing a leak-tight joint
- Produce a joint capable of carrying the design basis loads
- Maintain the tensile preload in the free standing portion of the tubes within allowable limits
- Result in minimal tensile stresses
- Produce an expansion capable of being non-destructively examined
- Be adaptable to remotely operated tooling
- Permit future sleeving

Original Configuration of OTSG Tubes



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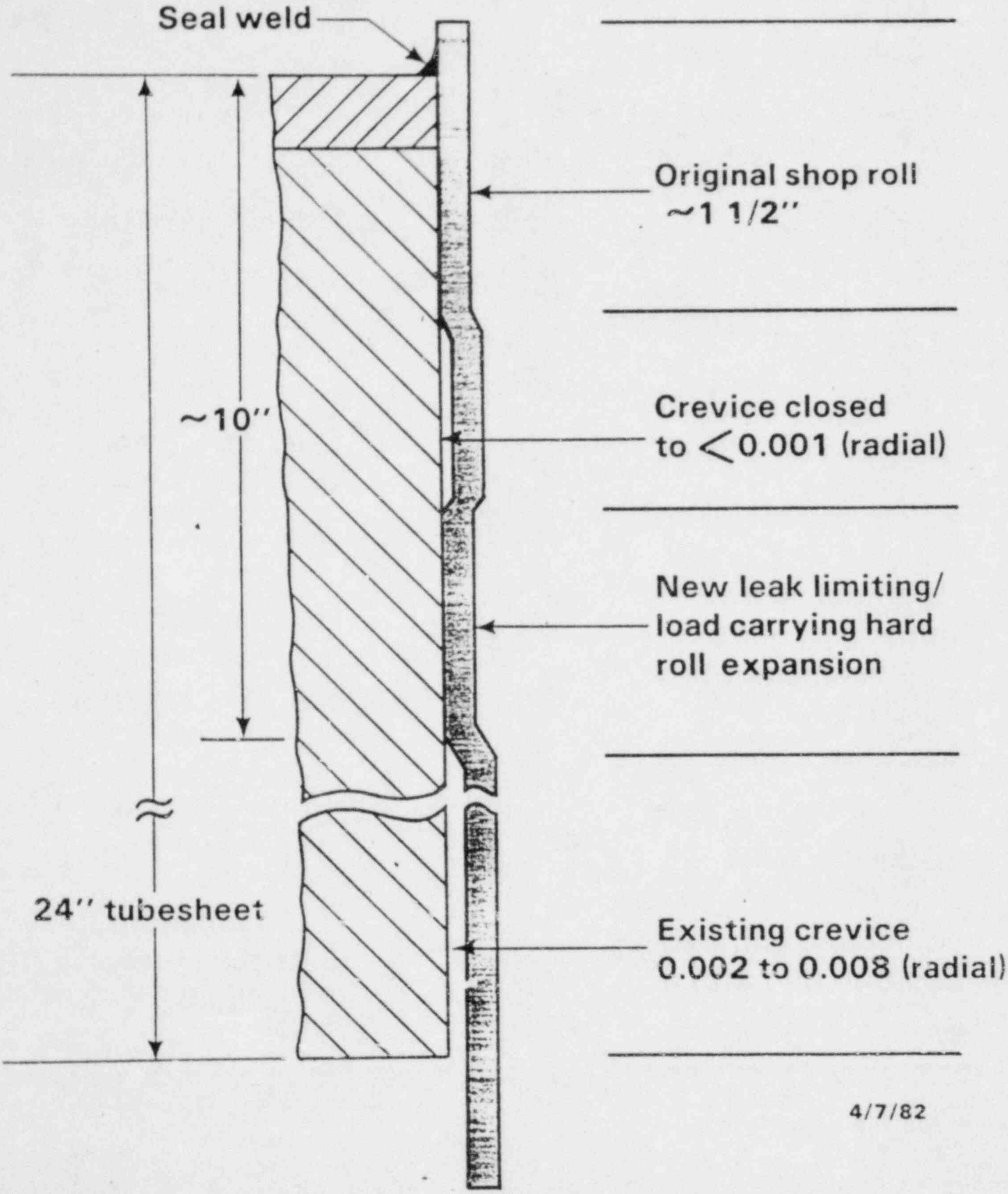
Repair Configuration of OTSG Tube



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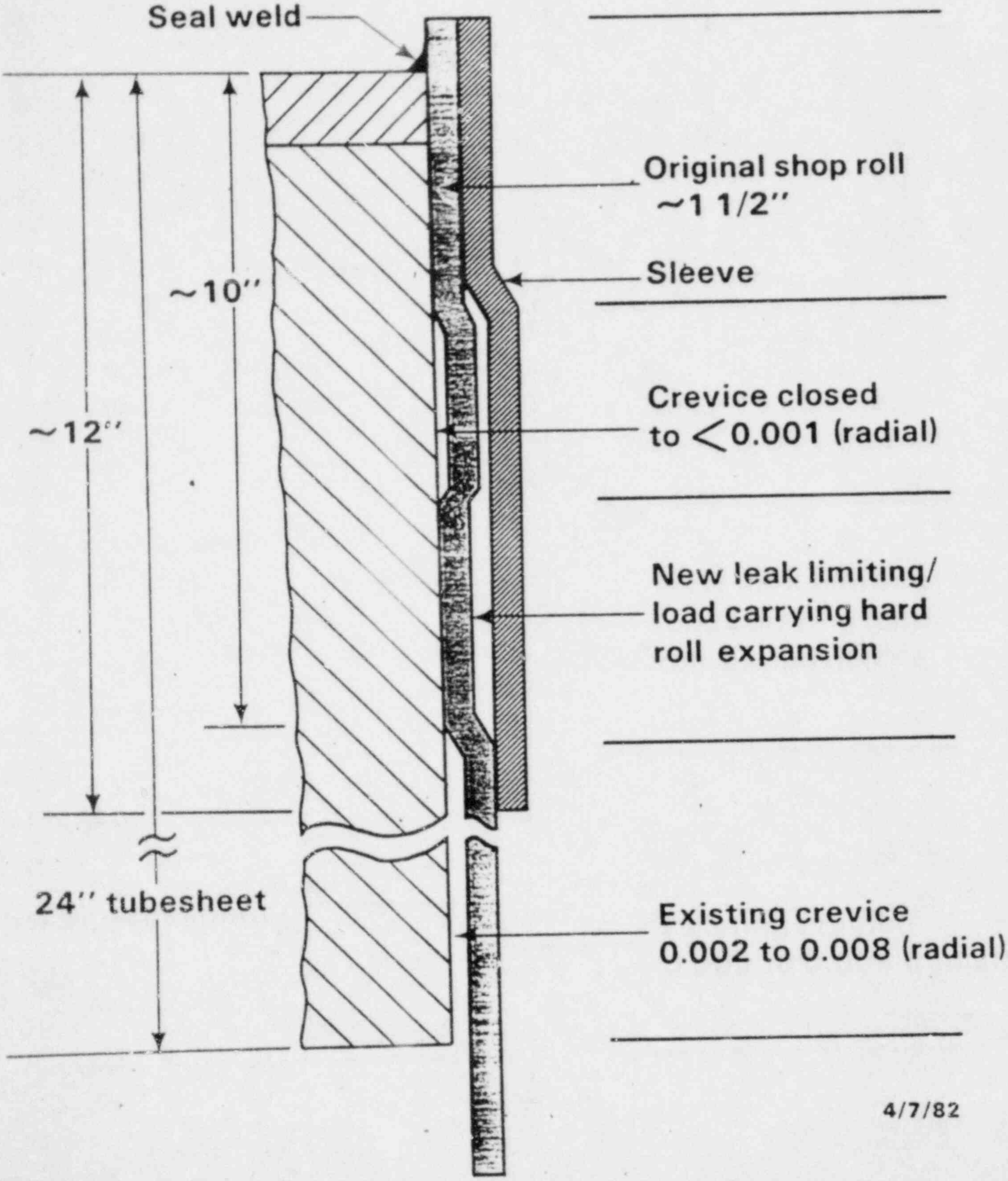
Sleeved Configuration of OTSG Tube



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Scope of Process Qualification Design Variables

- Hone ID surface in area to be expanded
  - —avoids inclusion of contaminants
- Depth of roll approximately 10″ max
  - —allows later sleeving
  - —leaves approximately 500 tubes or less to be plugged or otherwise repaired
- Crevice closure by low-torque roll, explosives, or hydraulics
  - —proven techniques
  - —minimizes residual stresses
  - —inspectable
- Mechanical roll with 4-10% wall thinning
  - —carries axial load
  - —retains preload
  - —leak tight
  - —proven technique
- Sound tube material below repair

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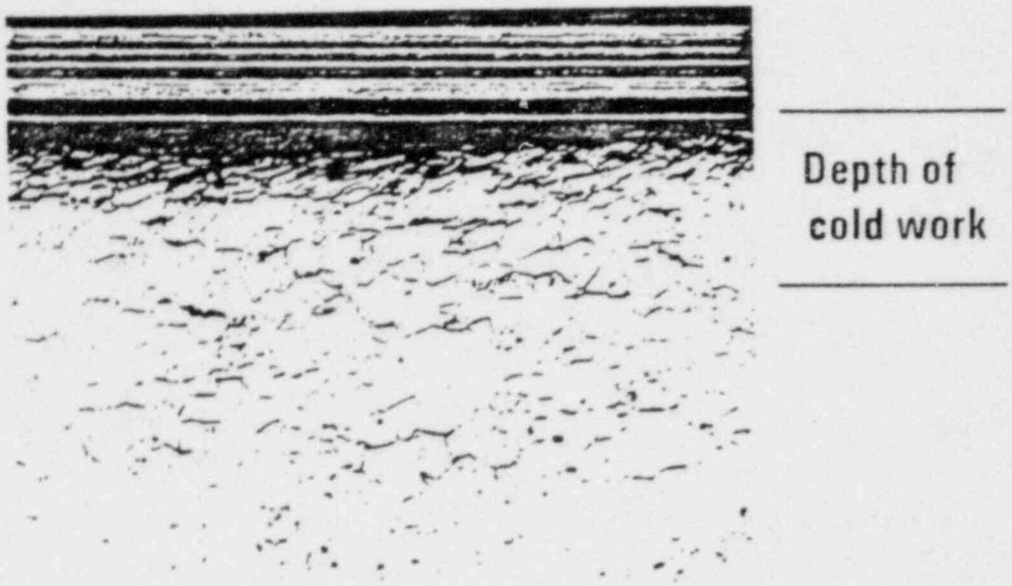
Facts on Mechanical (Roller) Expansion

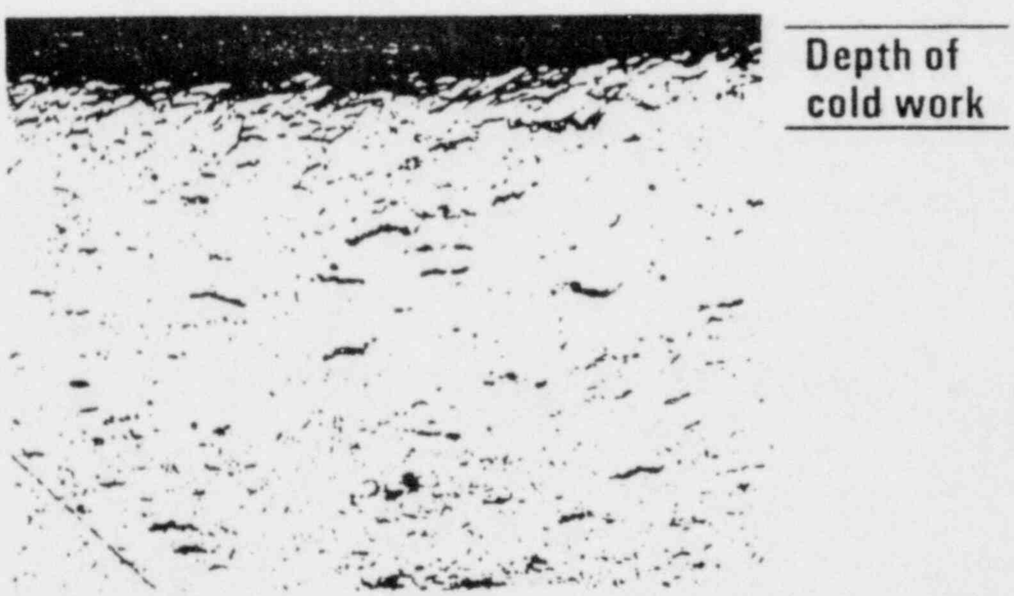
- Residual stresses in roll transition zones can be reduced by increasing the end radius on the rollers
- The optimum roller geometry has been determined to be:
  - —1 1/2" long rollers with largest standard available diameter
  - —1" effective length of roller with 2 1/2" end radii
- Axial residual stresses are greater than those produced by hydraulic or explosive expansions
- Residual hoop stresses are less than those produced by hydraulic or explosive expansions
- Roll expansions produce thinning of the tube wall in the expanded area; industry standards (based on allowable metal strain) are 4 to 10%
- Roll expansions produce a net elongation of the tube due to the extrusion of the tube walls



10% Chromic 100X

— Figure 8 —

Rolled portion of a tube showing the amount of cold work present in the overlap area using standard rolls.



10% Chromic 100X

— Figure 9 —

Depth of cold work produced by increasing the leading radius to 2-1/2 inches.

Experience with Mechanical Joints

- Industry SG experience with mechanical joints

- Doel-2	Tube/tubesheet rolls (repair)	About 100 rolled in 1980 & 1981
- Point Beach-1	Rolled sleeves (repair)	About 12 sleeves in 1982
- San Onofre-1	Rolled sleeves (repair)	About 7000 sleeves in 1981
- Obrigheim	Tube/tubesheet rolls (original)	12 years service
- Palisades	Hydraulically expanded sleeves (repair)	Installed commencing 1976

- Other industry experience with repair hard roll

- Big Rock Point	RTR vessel/CRD housing	4" tube in 1979. No leakage
- Oyster Creek	RTR vessel/in core flux monitor tube	2" tube in 1975. No leakage
- Gargliano	- Ditto -	2" tube in 1966. No leakage

- Standard heat exchanger manufacturing process

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Preliminary Tube Expansion Process Comparison

	Mechanical Roll	Hydraulic Expansion	Explosive Expansion
Residual stresses			
ID	Greater	Base	Equal
OD	Less	Base	Equal
Effect on tube	Decrease	Increase	Little change
Load carrying capability	Greater than	Base	Greater than
Leak tightness	Greater than	Base	Greater than

Supporting data based on:

- B&W Canada and B&W USA R&D and production work accomplished on both once-through and u-tube steam generators

Points to Be Addressed by Qualification Program

Adequacy of repair process

- Leak tightness following thermal cycling
- Load carrying capability following thermal cycling
- Tubesheet hole ovality
- Water or moisture in crevice
- Statistical leak tightness margin determination
- Roll torque/length vs leak tightness
- Roll torque/length vs load carrying capability
- Inspectability

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Points to Be Addressed by Qualification Program

Effect of repair on total OTSG performance

- Primary water in crevice and tubesheet corrosion
- Change of tube preload
- Residual stresses in tube
- Effect of trapped contaminants
- OTSG performance with specific tubes plugged
- Confirm adequacy of existing operating and accident analyses

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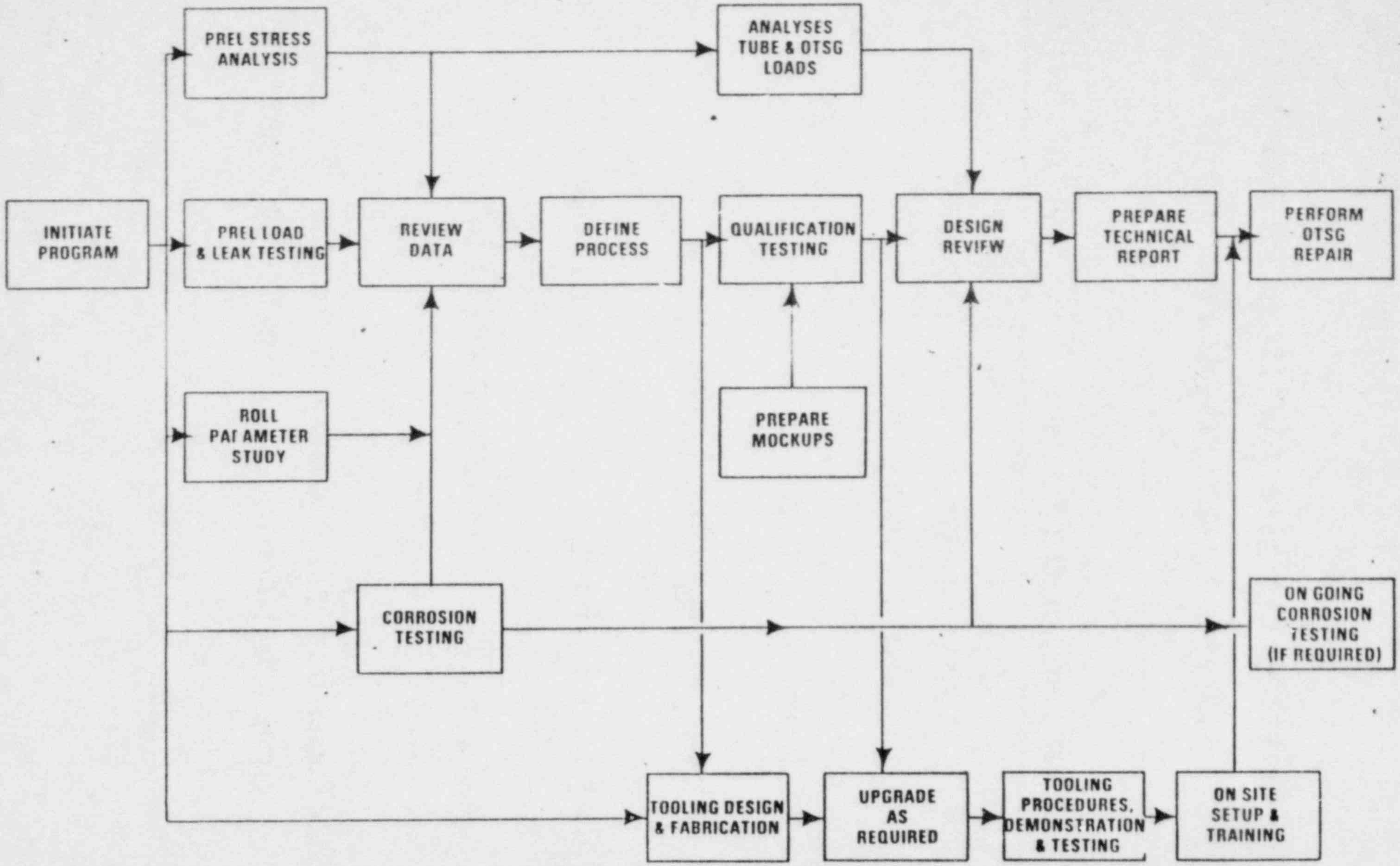
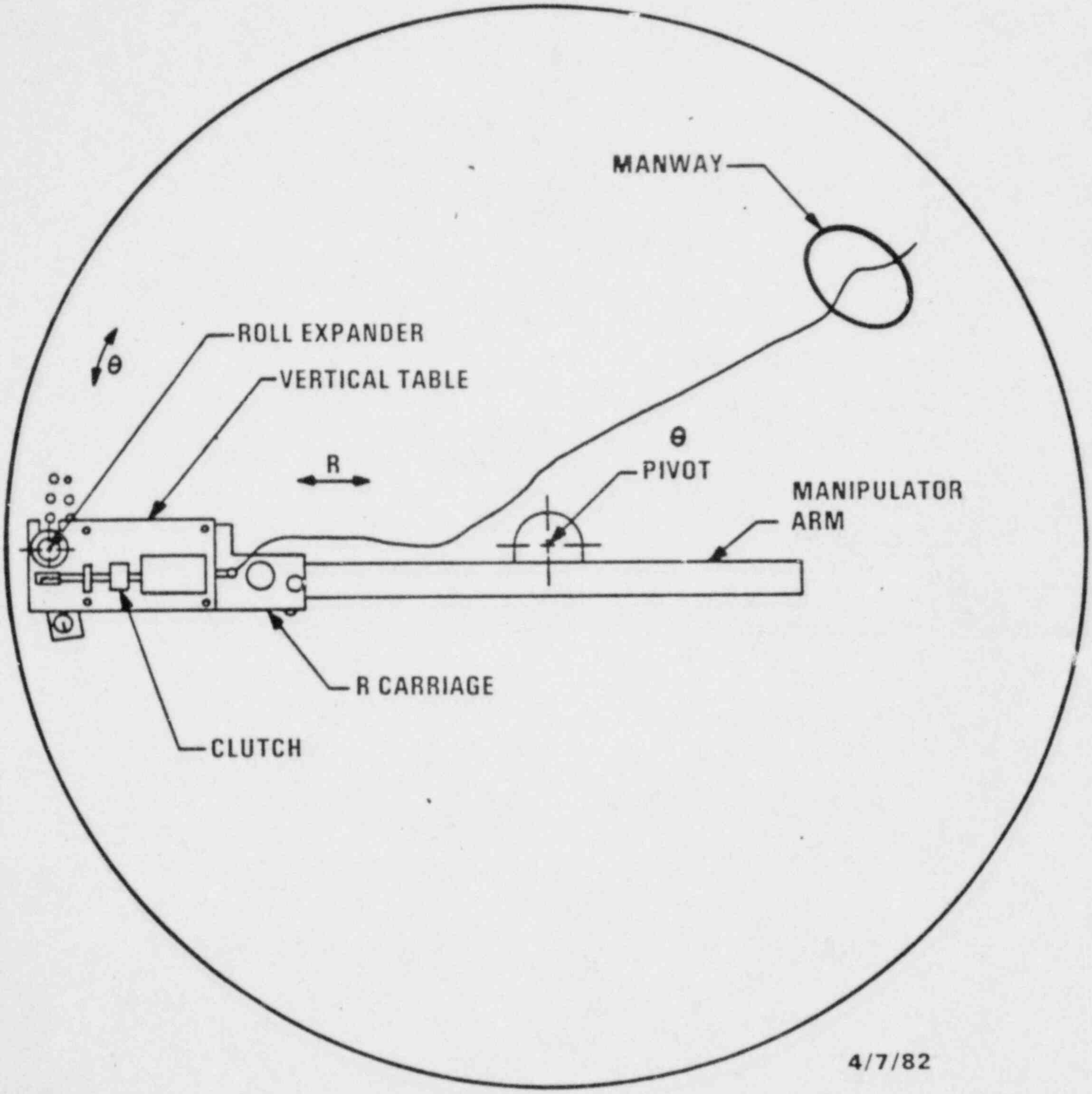
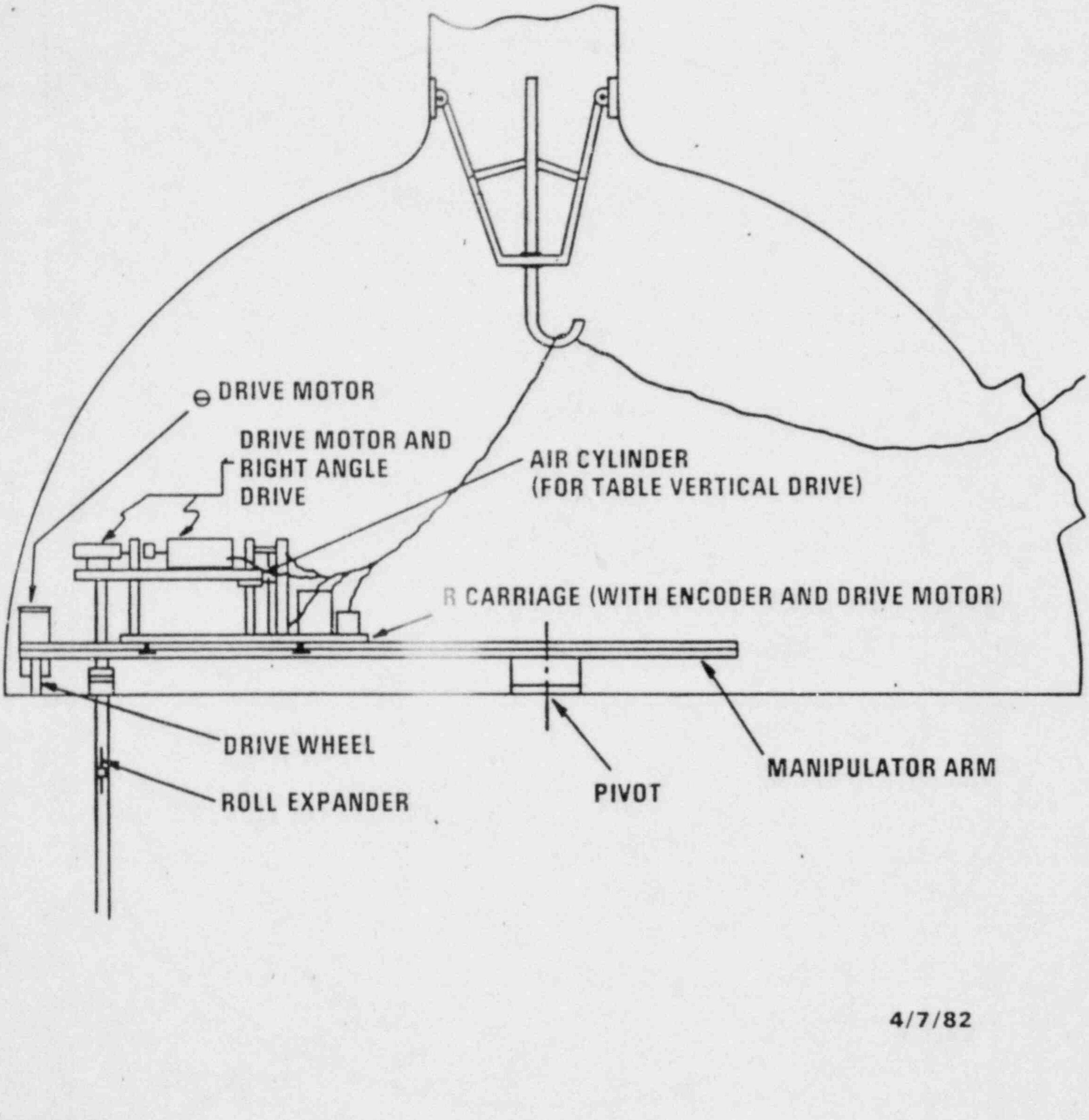
TMI-1
Tube Expansion Qualification Program



OTSG Tube Rolling
Top View-Manipulator



OTSG Tube Rolling — Elevation



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Currently Planned
Process Monitoring and Inspection

Tube identification	• E/C manipulator record • Video record
Depth of rolls	• Automated insertion tool • Tool location feedback • Video
Torque	• Transducer feedback • Air pressure alarm • Periodic calibration • Frequent equipment inspections and cleaning

4/7/82

OTSG Repair Program Overview

I. Tube expansion/testing complete Oct. '82

II. Projected total repair exposure
$<$ 500 man rem

III. 100% ECT examination in affected area

IV. Plug or repair all tubes with inside diameter ECT indications in the roll, roll transition or tubesheet crevice

V. Plug/stabilize all tubes with inside diameter ECT indications that are not within the tubesheet

VI. RCS cleanup to reduce the amount of sulfur on surfaces

VII. Sensitive leak tests following repair

VIII. Sensitive and continuous leak rate monitoring during operation

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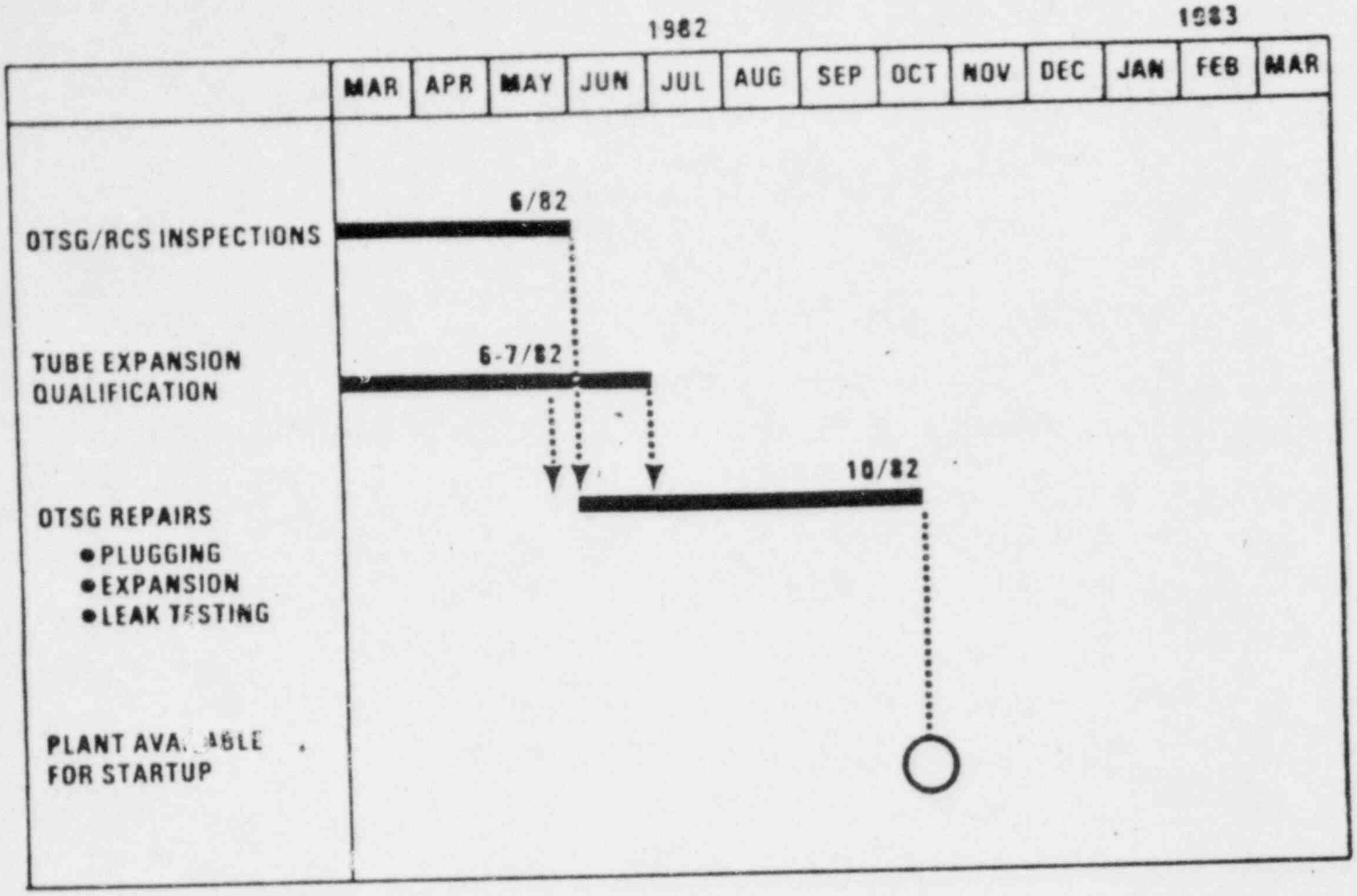
OTSG Repair Program Plan/Schedule



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Preliminary Cumulative Man Rem Exposure

I. Actual OTSG exposure to date ~70 man rem

II. Estimated additional exposure ~230 man rem

A. RCS inspection	~	60R
B. Eddy current testing	~	10R
C. Tube samples	~	10R
D. Tube plugging	~	100R
E. Tube expansion	~	50R

III. Projected total OTSG repair exposure with 200 man rem contingency < 500 man rem

4/7/82

OTSG Tubing Eddy Current Inspection Program

I. Objective

- Identify scope and extent of tubing damage and soundness of tubing areas accepted for service
- Repetitive inspections to detect new defects and/or defect growth

II. Scope

- 100% of affected areas
- Statistical sample below affected areas

III. Techniques

- Standard differential probe (multi-frequency system — increased gain settings) tubing areas between lower and upper tubesheet roll transitions
- Absolute probe upper tubesheet roll transitions and rolled areas (4 coils — 2 orientations — 360 degrees coverage)

4/7/[illegible]

Standard Differential Eddy Current Technique Qualification

I. Metallurgical Analysis	• 100% correlation on 29 E/C defects located at or below the roll transition
II. Other destruct Testing	• Laboratory testing of ~13 feet of tubing verifies soundness of portions of removed tubes accepted by eddy current examination
III. Correlations among E/C designs/ techniques	• Circumferential coils vs pancake coils • Standard differential vs absolute techniques
IV. Production E/C data interpretation	• Evaluation of all intelligible signals irrespective of amplitude to account for crack orientation and geometry

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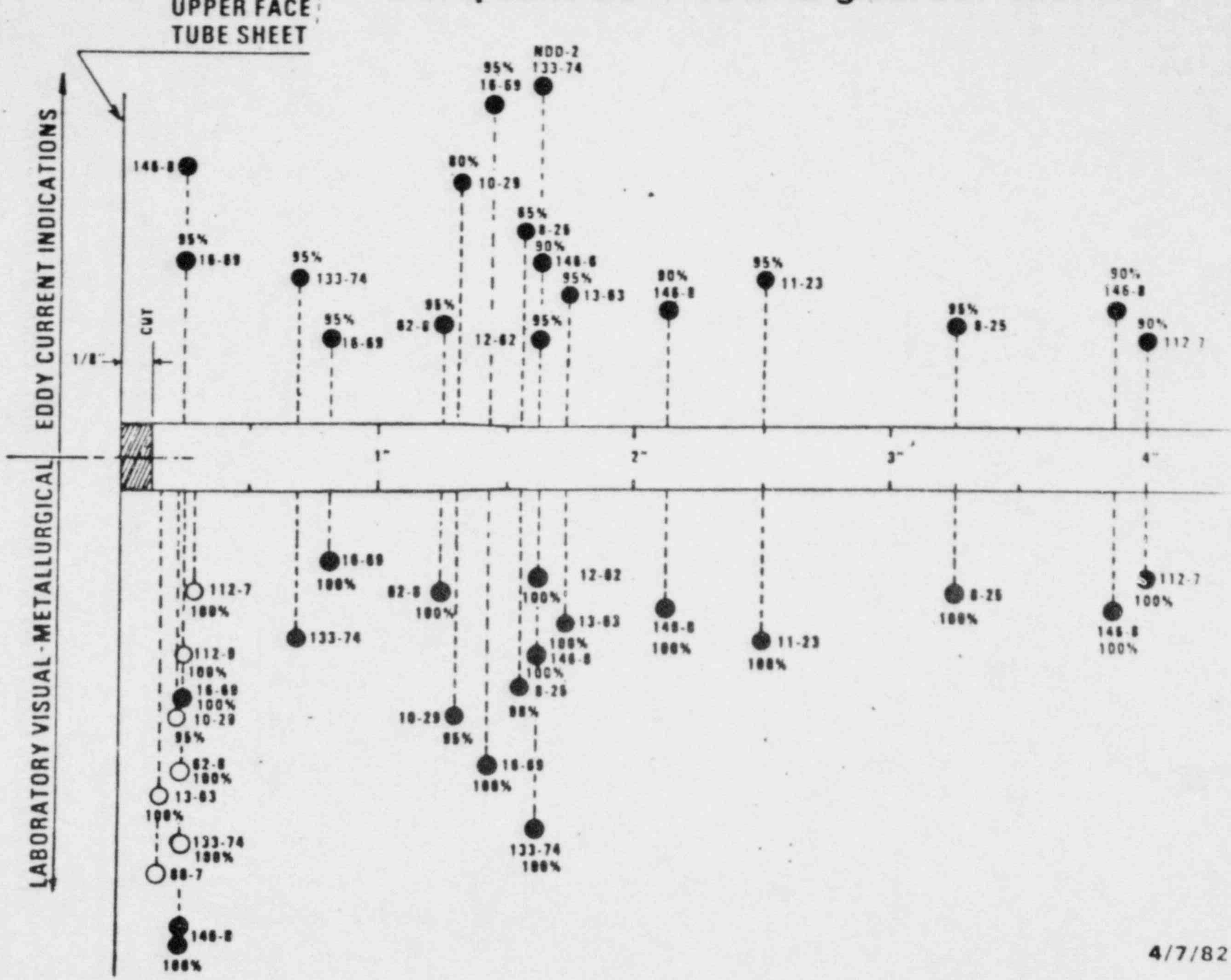
Composite ECT/Metallurgical Correllations



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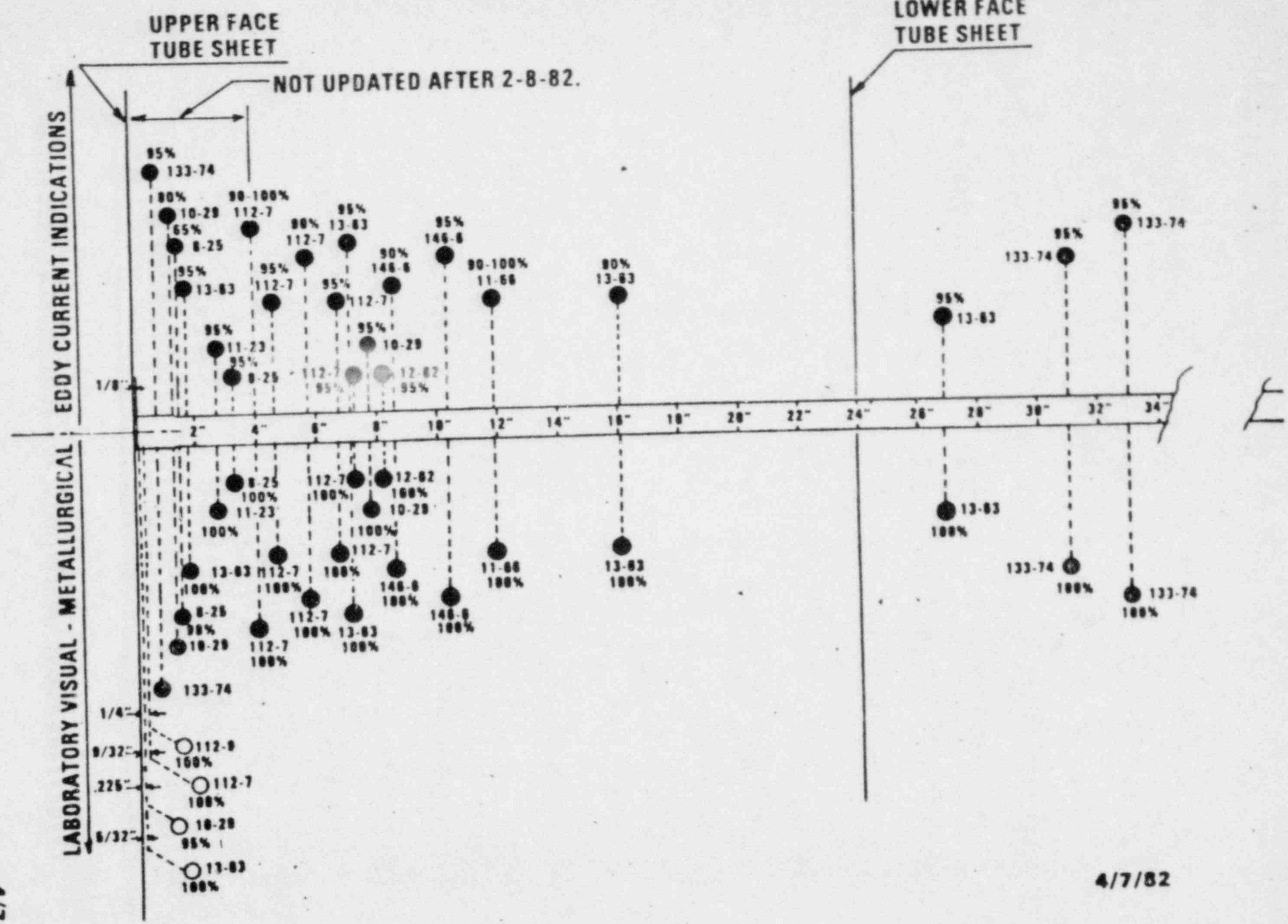
Composite ECT/Metallurgical Correllations



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Correlations Among Coil Designs

I. Scope

- Standard differential vs 4X absolute

  ~435 tubes full length
  ~4500 tubes partial length

- Standard differential vs 3X pancake differential

  ~100 tubes full length

II. Conclusions

- In all cases there was good correlation

- Inconsistencies can be explained by:

  — low level signals (< 1 volt) drop in and out by both techniques

  — resolution of multiple defects that are close together

4/7/82

TMI-1 OTSG
Absolute Eddy Current Technique Qualification

I. Metallographic analysis — 100% correlation on 30 E/C defects (top 0.25 inch excluded due to alignment problems which we are correcting)

II. Tube/tubesheet mockup testing — demonstrates detection of simulated cracks located at the primary tube seal weld and below

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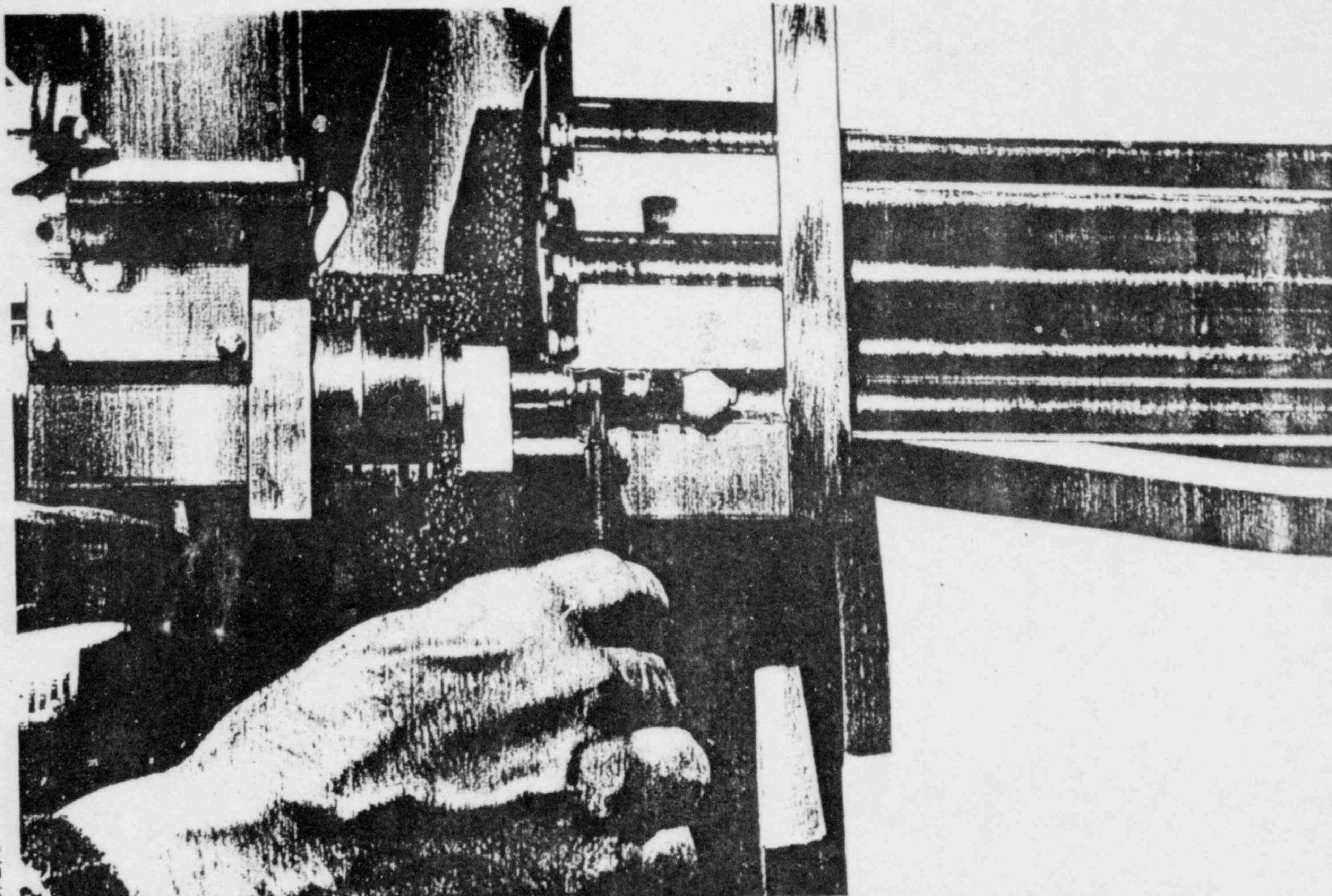

Absolute ECT Probe and Mockup

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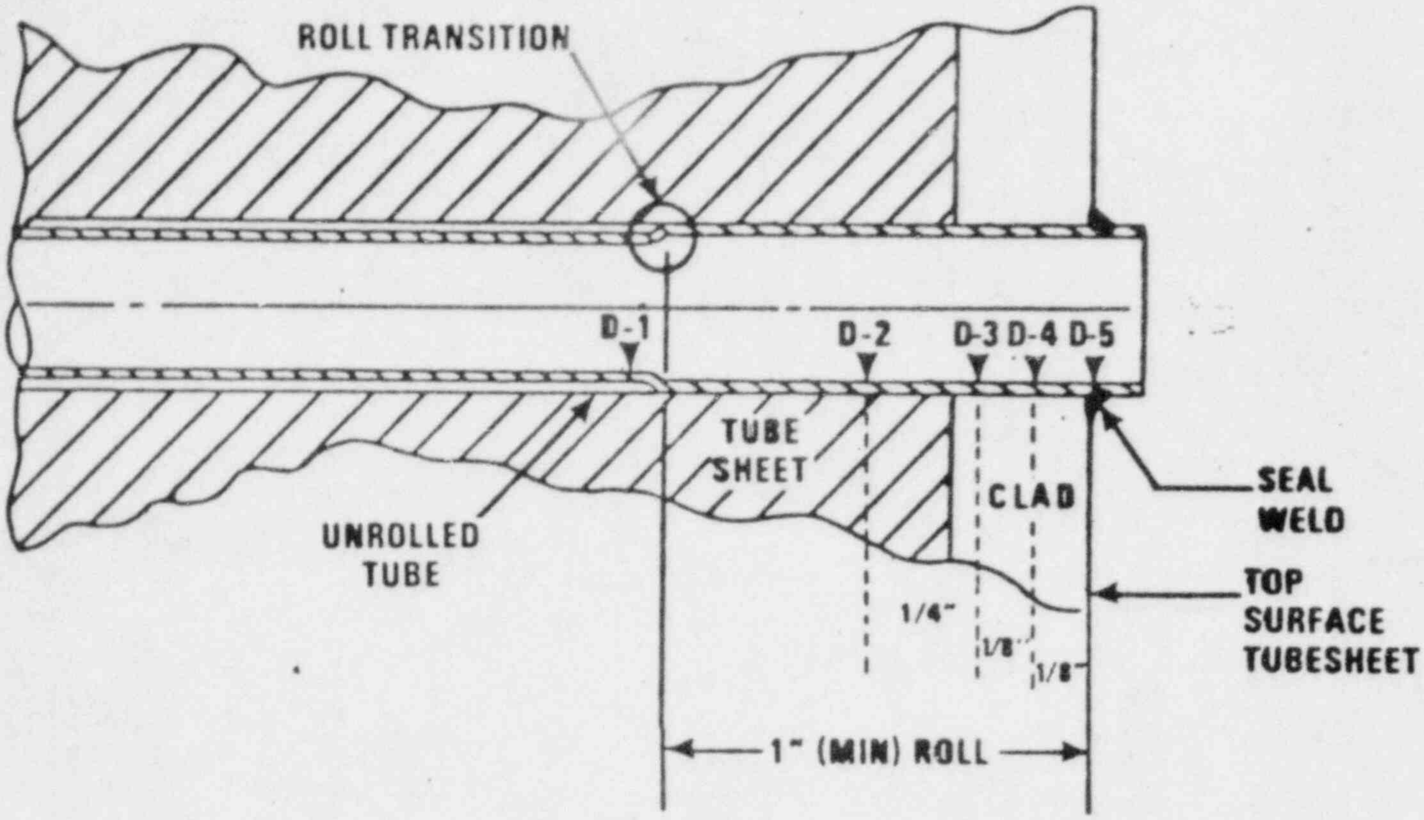
TMI-1
Eddy Current Defect Mockup
Absolute Technique Qualification



- Defects #1 thru 5 (D1 — D5) are ID defects located as shown
- Extent of defects varied from 20% thru 100% of tubing wall thickness — defects are 3/16 inch long (EDM notches)
- 40% and greater defect depths were detected

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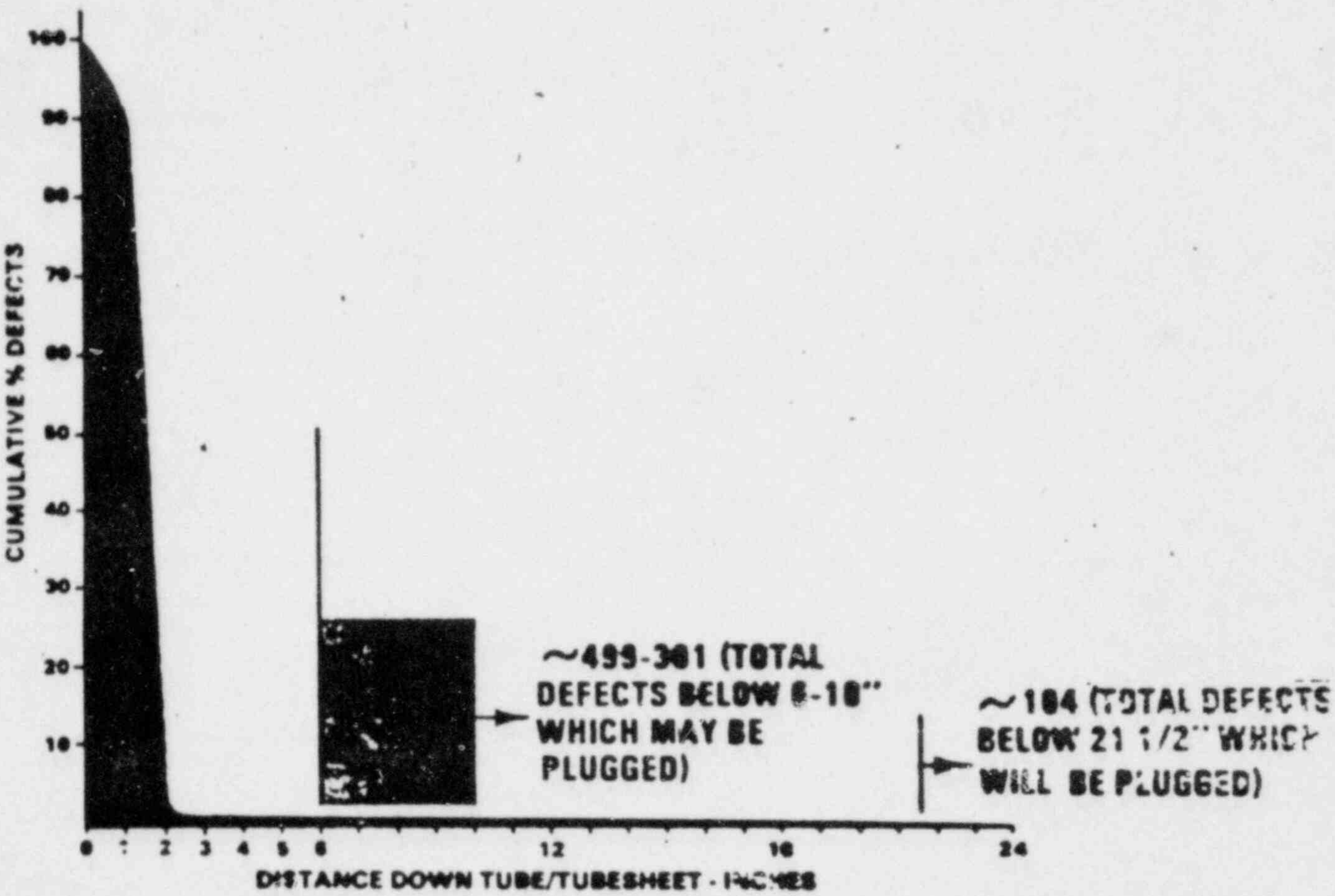
OTSG Tube Plugging Plans



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Analysis of Tube Plugging Affects on OTSG Performance

- Reactor coolant system flow rate
- Safety analysis for LOCA
- OTSG exit steam quality

RC Flow Results

• Calc RC flow w/o plugging:	109.86%
• Error in calc:	1.50%
• Resulting flow:	108.36%
• Tubes plugged:	500/OTSG
• RC flow reduction:	0.25%
• Resulting flow:	108.11%
• Tech spec limit:	−106.50%
• Margin:	1.61%

Conclusion

The reduction in RCS flow is acceptable

4/7/82

LOCA Results

Considerations

- Boiler — condenser mode heat transfer
- Initial RCS liquid inventory
- EFW spray cooling
- RC flow rate
- Core cooling

Conclusion

No effect on licensed power level of 2568 MW_T for up to 500 plugged tubes per SG

OTSG Exit Steam Superheat (100% Power Results)

- Normal superheat = 54°F
- 300 tubes plugged in one SG (uniform Dist'n)
  - average exit superheat = 49°F
- 300 tubes plugged (25% of tubes plugged in a peripheral region)
  - central region superheat = 54°F
  - peripheral region superheat = 11°F
  - average exit superheat = 49° F

Conclusion

The reduction in OTSG exit steam superheat is acceptable

Removable Plug Development

I. Objective
- Install removeable plugs in tubes which may be returned to service by sleeving

II. Type
- Roll plugs similar to those used at San Onofre

III. Qualification
- 100 thermal cycles (120°F to 650°F)
- Leak tests at $\Delta P = 2250$ psig
- Rapid cooldown from 650°F
- Simulated circumferential crack in roll
- Ejection/pull-out tests

IV. Results
- Leak rate.03 drops/minute (avg. all tests)
- 6200-12,000 psi plug ejection pressure
- 3510 lb average pull-out load

V. Conclusion
- Roll plug qualified for intended use at TMI-1

4/7/82

Primary System Cleanup

I. Sulfur in RCS water has been reduced from 750ppb to 100ppb

II. If analysis shows it is required, we plan to reduce the amount of sulfur on the surfaces of primary system components and OTSG tubes

III. Cleanup method identification will consider:

- H_2O_2 concentrations of 0, 10, 100, and 1000ppm
- pH of 7.0, 8.0, and 9.0 with LiOH or NH_4OH additive
- Normal RCS chemistry

Preliminary OTSG
Pre-Service Testing Plans

• ECT	— Statistical baseline examination of the new expansion and transition
• Drip test	— 150 psi on OTSG secondary side (H_2O)
• Bubble test	— 150 psi on OTSG secondary side (N_2) — Sensitivity $\sim$.1 gpd/tube
• Leak test	— 2155 psi on primary side $\Delta P \geq$ 125% of normal ($\geq$ 1500 psi) — Sensitivity $\sim$ 10 gpd (after 5 hours, current RCS activity level)
• Power escalation testing	— Natural circulation cooldown Main feed pump trip (40% power) Turbine trip (100% power)

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OTSG In-Service Monitoring

- Continuous leak rate monitoring using activity, mass balance and/or chemical concentrations
  - —sensitivity ~10 gpd
    - •after 5 hours of leakage
    - •.03% failed fuel
    - •condenser vacuum pump discharge activity

- Basis for corrective action
  - —total leak rate
  - —rate of change of leak rate

4/7/82

OTSG Repair Program Overview

We expect that the overall OTSG repair program, including inspections, repair process qualification, primary system cleanup, leak testing and differential pressure testing, will provide assurance that the probability of abnormal primary to secondary leakage during operation is very low.

SUMMARY

- THE REPAIR METHOD IS EXPECTED TO SHOW CONFORMANCE TO EXISTING LICENSE AND REGULATORY REQUIREMENTS

- TECH SPECS FOR APPENDIX I MAINTAIN NORMAL OPERATIONAL CONDITIONS WELL WITHIN ACCIDENT ASSUMPTIONS

- THE REPAIRED STEAM GENERATOR IS EXPECTED TO PRESENT NO SIGNIFICANT HAZARD TO STATION OR PUBLIC

4/7/82

REMAINING WORK

- DEVELOP, TEST, QUALIFY THE TUBE - TUBESHEET REPAIR METHOD AND PROCESS DETAILS

- RESTORE ADEQUATE STATE OF CLEANLINESS

- INSPECT OTHER PRIMARY SYSTEM INTERNALS

- COMPLETE DETAILS OF FAILURE ANALYSIS AND TECHNICAL AND SAFETY ANALYSIS OF REPAIRED STEAM GENERATORS

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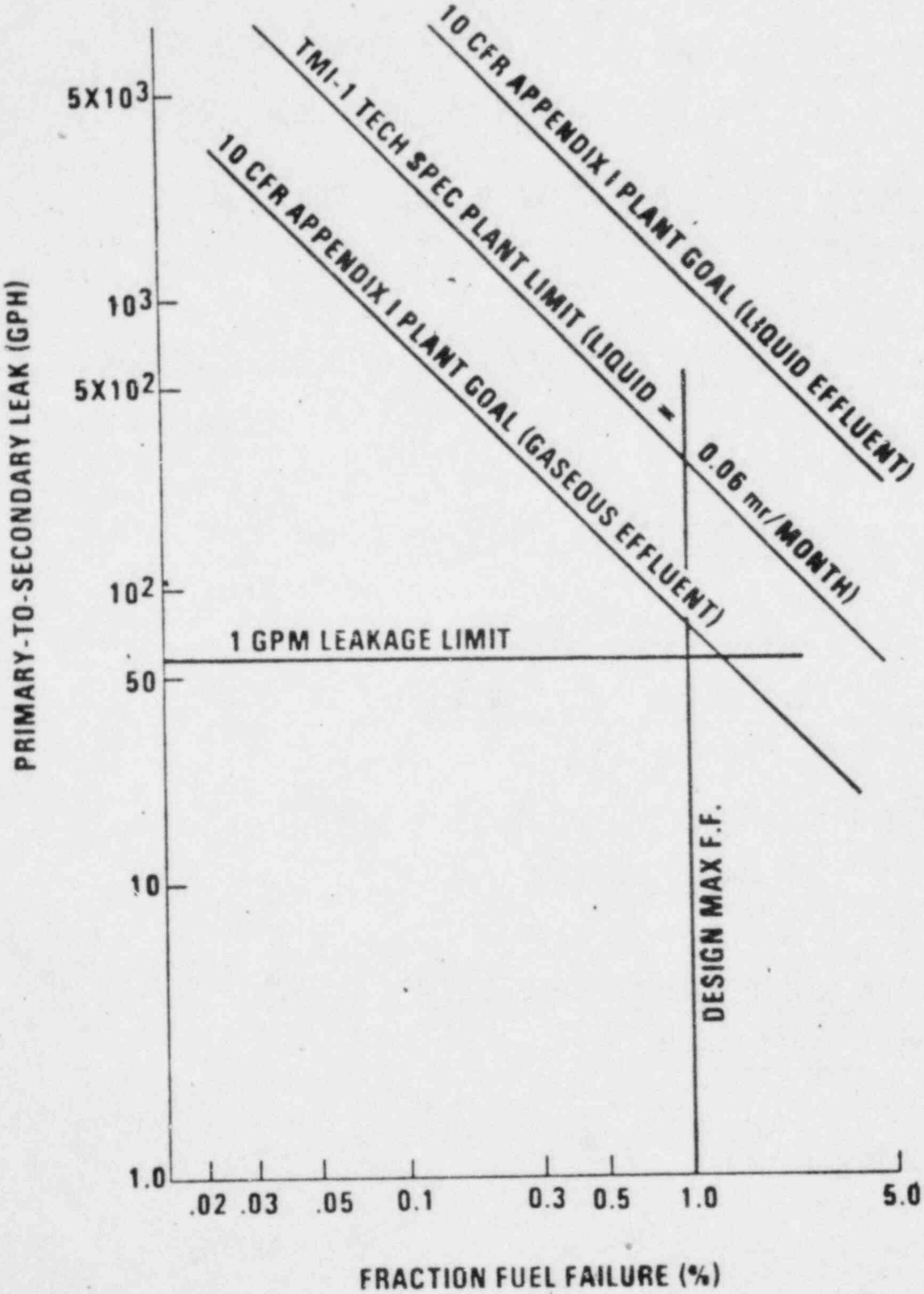
Current TMI-1 Operating and Effluent Limits



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SAFETY EVALUATION PARAMETERS - STEAM GENERATOR REPAIR

- TUBE PLUGGING - AFFECTS PRIMARY SYSTEM FLOW
  - AFFECTS LOCA ANALYSIS (HEAT TRANSFER)

  ≤ 1000 ± TUBES MAY BE PLUGGED WITHIN BOUNDS OF EXISTING SAFETY ANALYSIS/TECH SPEC'S

- TECHNICAL SPECIFICATION LEAKAGE - UNIDENTIFIED 1 GPM
  - STEAM GENERATORS 1 GPM

- TECHNICAL SPECIFICATION RELEASE - ≤ 0.06 MR/MO WITHOUT TREATMENT

- DESIGN BASIS STEAM GENERATOR RUPTURE - 435 GPM

- APPENDIX I - LIQUIDS ≤ 3 MR/YR
  - GAS ≤ 5 MR/YR

- ALARA CONSIDERATIONS FOR SECONDARY SYSTEMS ACTIVITY, IF ANY ACTIVITY PRESENT

4/7/82

SAFETY REVIEW

- WILL PERFORM A COMPLETE INTERNAL REVIEW UNDER THE PROVISIONS OF 50.59

- WILL HAVE THE INTERNAL SAFETY ASSESSMENT/REVIEW FURTHER EXAMINED BY
  - THE GPUN GENERAL OFFICE REVIEW BOARD (GORB)
  - AN EXTERNAL (TO GPUN) FURTHER INDEPENDENT REVIEW GROUP

- THE REVIEW WILL BE BASED ON MEETING ESTABLISHED NRC REGULATORY REQUIREMENTS AND EXISTING TMI-1 TECH SPEC'S

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CONCLUSIONS - STEAM GENERATORS

- FAILURE MECHANISM THEORY IDENTIFIED
- BASIC STEAM GENERATOR TUBE MATERIAL REMAINS GOOD
- REPAIR WILL NOT DEGRADE THE ORIGINAL DESIGN MARGINS
- CAUSATIVE CHEMICAL SPECIES DEPLETED BEFORE RESTART
- EVEN WITH LARGE NUMBERS OF TUBE FAILURES IN UTS - DESIGN BASIS TUBE RUPTURE ACCIDENT IS NOT APPROACHED OR EXCEEDED
- OPERATIONAL EXPERIENCE SUGGESTS TIGHT/VERY SMALL LEAK PATHS CLOSE DURING OPERATION
- METHODS EXIST TO CONFIRM CONTINUED SERVICEABILITY OF THE STEAM GENERATORS AFTER REPAIRS ACCOMPLISHED
    - ECT
    - ABSOLUTE LEAKAGE AND LEAKAGE TREND MONITORING
    - SECONDARY SAMPLING/RADIATION MONITORING
    - LIMITED PLANT THERMAL CYCLE TESTING

4/7/82