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2005 Tri-Service Infrastructure Conference

St. Louis, Mo.   August 4, 2005

Design of Concrete Lined Tunnels in Rock

CUP McCook Reservoir – Distribution Tunnels Contract

David Force, S.E.

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Outline of Presentation

- General Project overview – McCook Reservoir Project
- Overview of Distribution Tunnels Contract
- Design of Circular Tunnel Lining on Distribution Tunnels Contract
- Design of Concrete Bifurcations on Distribution Tunnels Contract
- Overview of Steel Liner Design on Distribution Tunnels Contract

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McCook Reservoir Project

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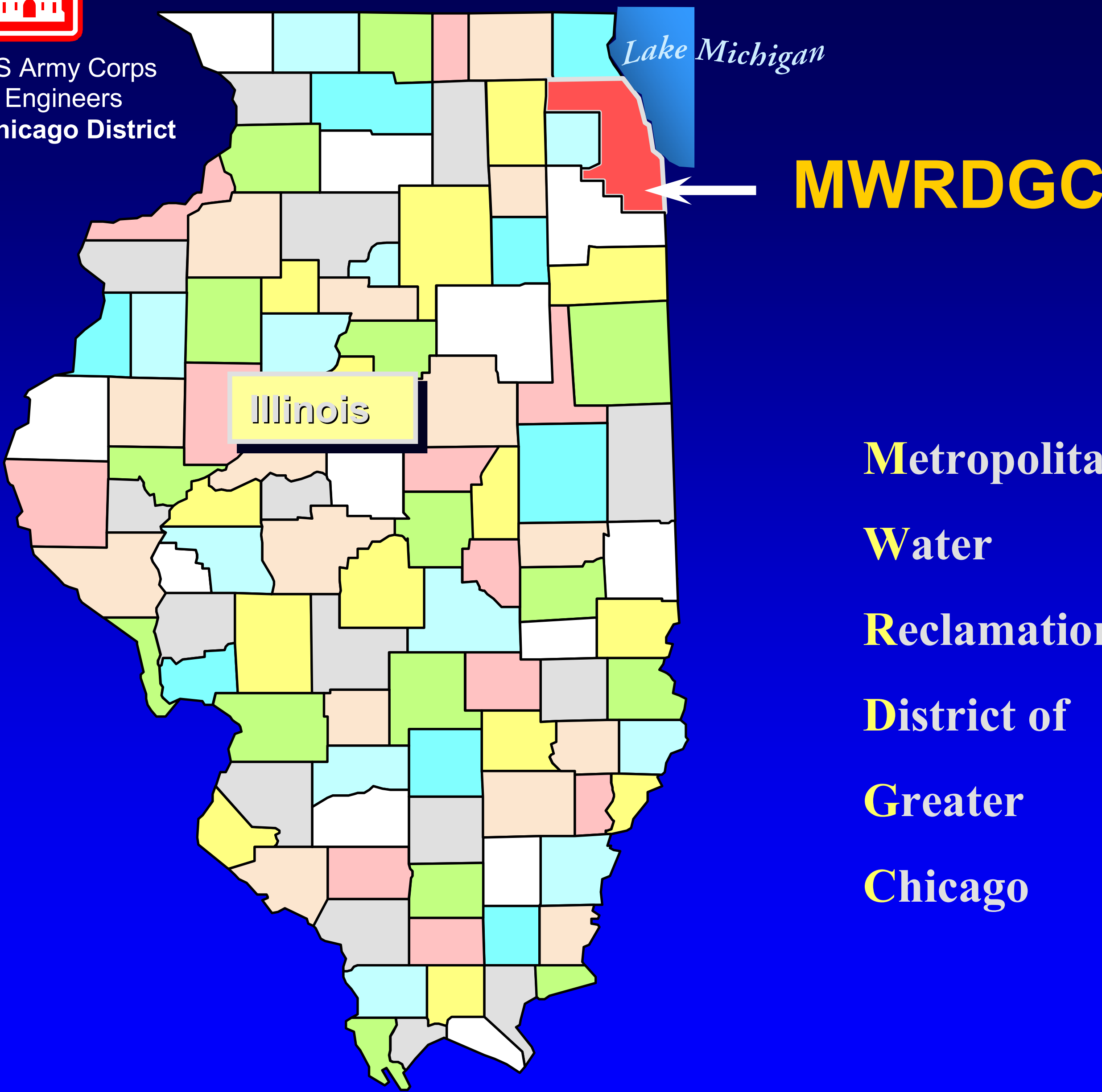

Metropolitan

Water

Reclamation

District of

Greater

Chicago

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Overall Goal – Control Flooding and Keep CSO Out of Lakes and Rivers !

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McCook Reservoir

- Estimated cost $520 million
- Provides flood control between Des Plaines River and Chicago Sanitary and Ship Canal
- Excavation of reservoir will be by Drill and Blast (Quarrying)
- Captures CSO's from Chicago and 37 suburbs
- Provides > 10 billion gallons of storage
- Scheduled Project Completion - FY 2012

TARP / CUP SYSTEM

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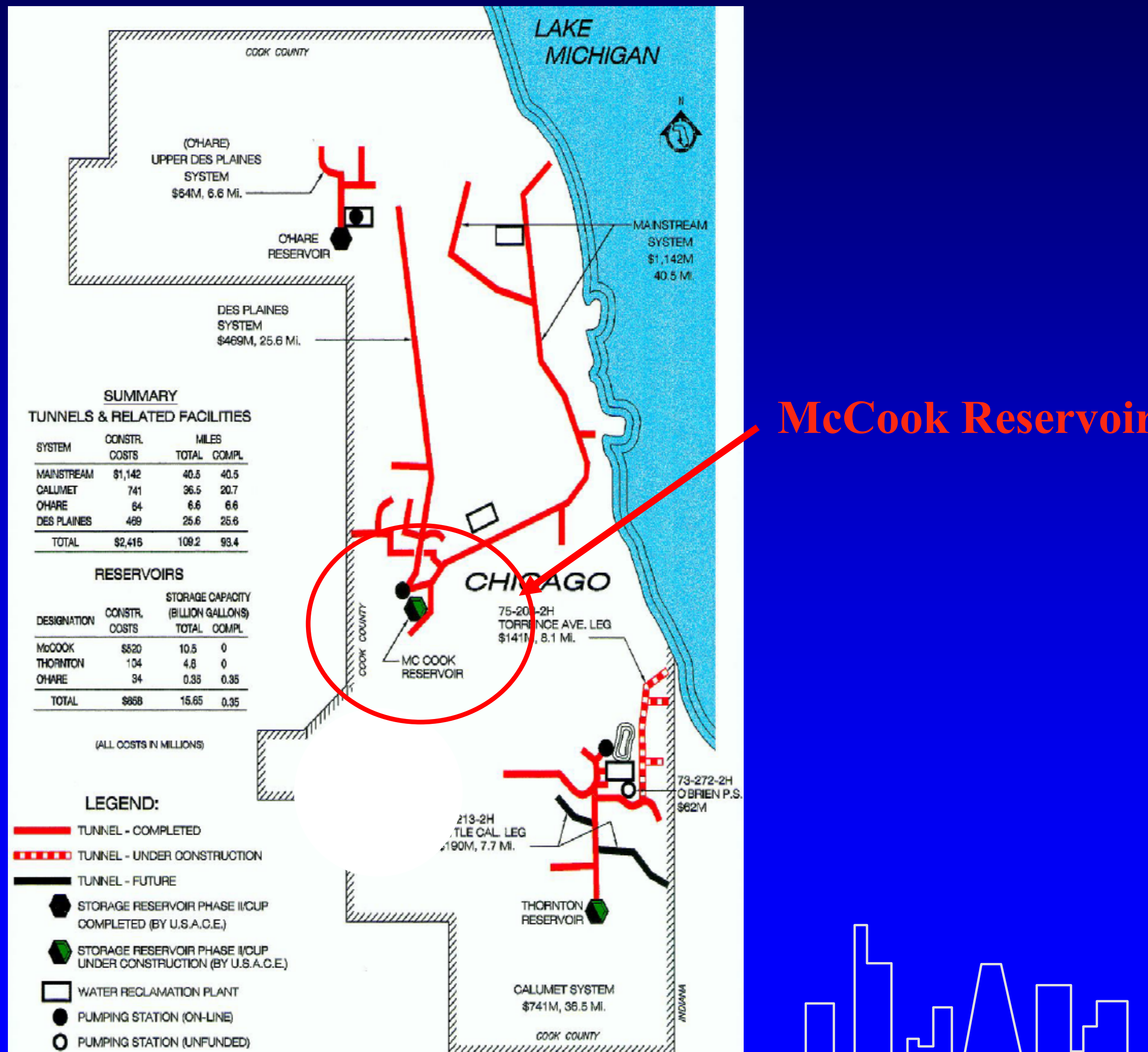

SUMMARY

TUNNELS & RELATED FACILITIES

SYSTEM	CONSTR. COSTS	MILES TOTAL	MILES COMPL
MAINSTREAM	$1,142	40.5	40.5
CALUMET	741	36.5	20.7
O'HARE	64	6.6	6.6
DES PLAINES	469	25.6	25.6
TOTAL	$2,416	109.2	93.4

RESERVOIRS

DESIGNATION	CONSTR. COSTS	STORAGE CAPACITY (BILLION GALLONS) TOTAL	COMPL
McCOOK	$520	10.5	0
THORNTON	104	4.8	0
O'HARE	34	0.35	0.35
TOTAL	$658	15.65	0.35

(ALL COSTS IN MILLIONS)

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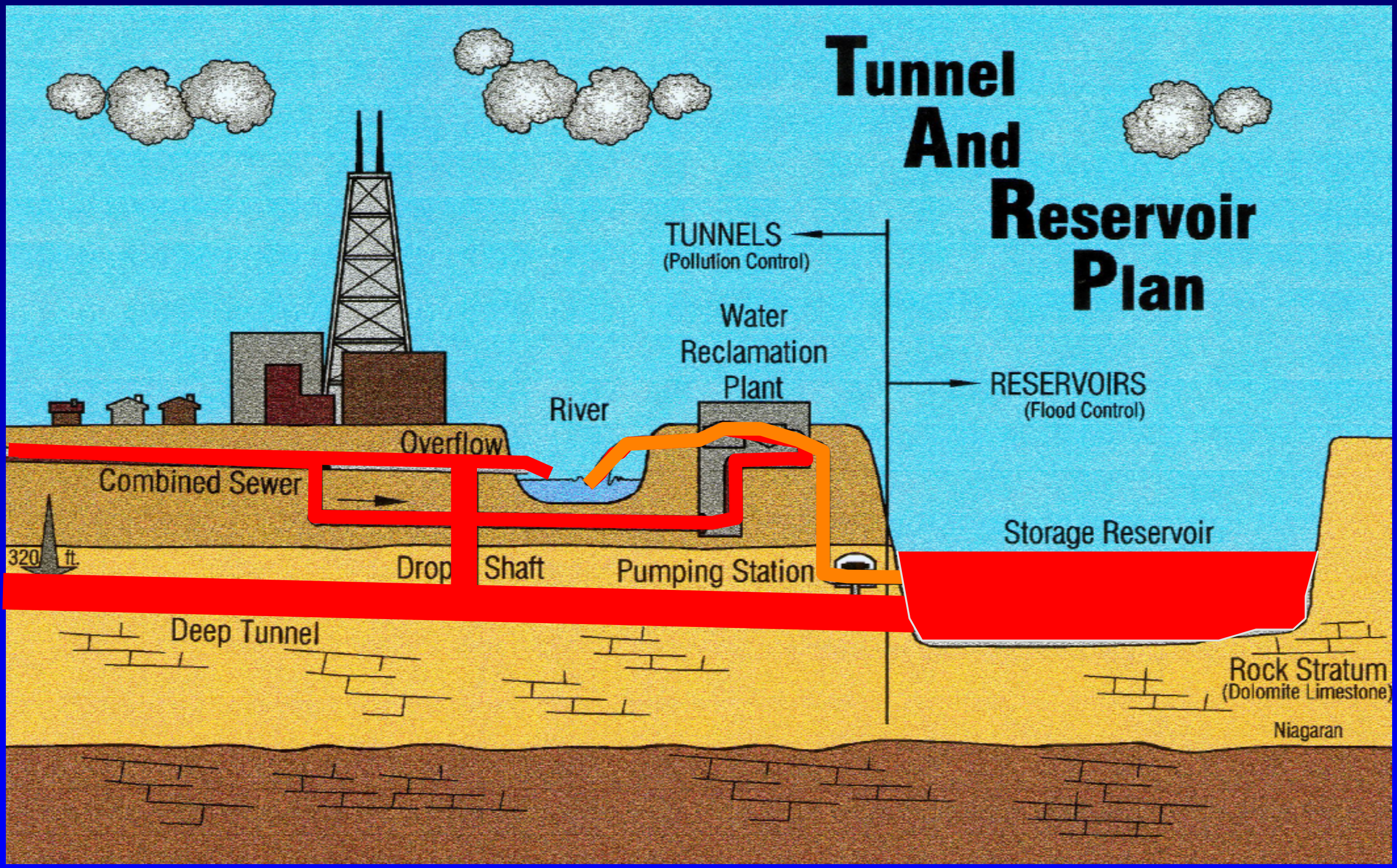

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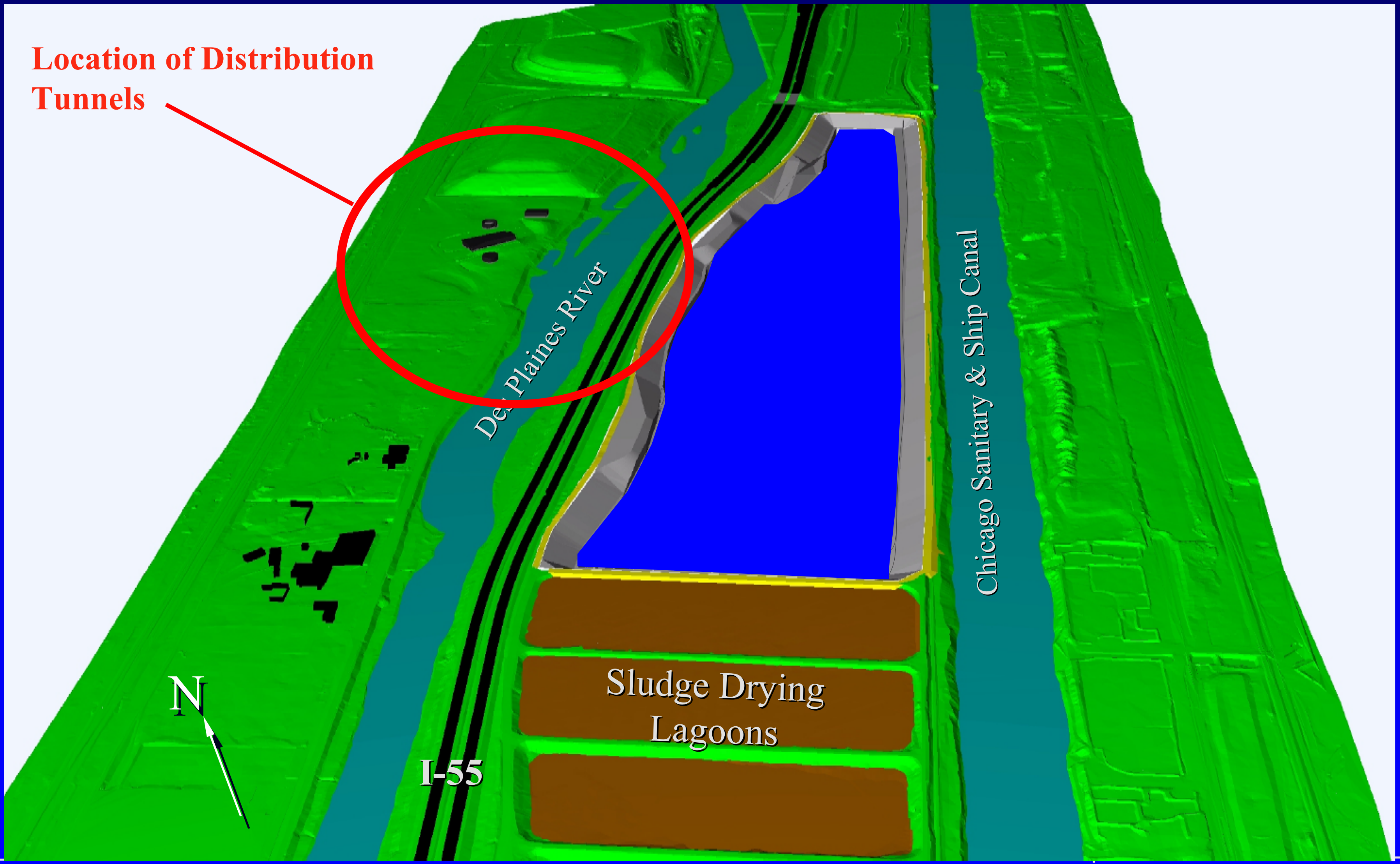
Reservoir Project



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Distribution Tunnels Contract

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Distribution Tunnels Contract

- **LS:** *Metropolitan Water Reclamation District of Chicago (MWRD)*
- **Designer:** *Montgomery Watson Harza*
- **Construction Contractor:** *Kenny Construction*
- **Gate Designer:** *INCA (sub to Kenny)*
- **Steel Liner Fabricator:** *CBI (sub to Kenny)*

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Purpose of Distribution Tunnels

- Convey and Distribute CSO's between the new Reservoir and the existing TARP Pump Stations and Tunnels

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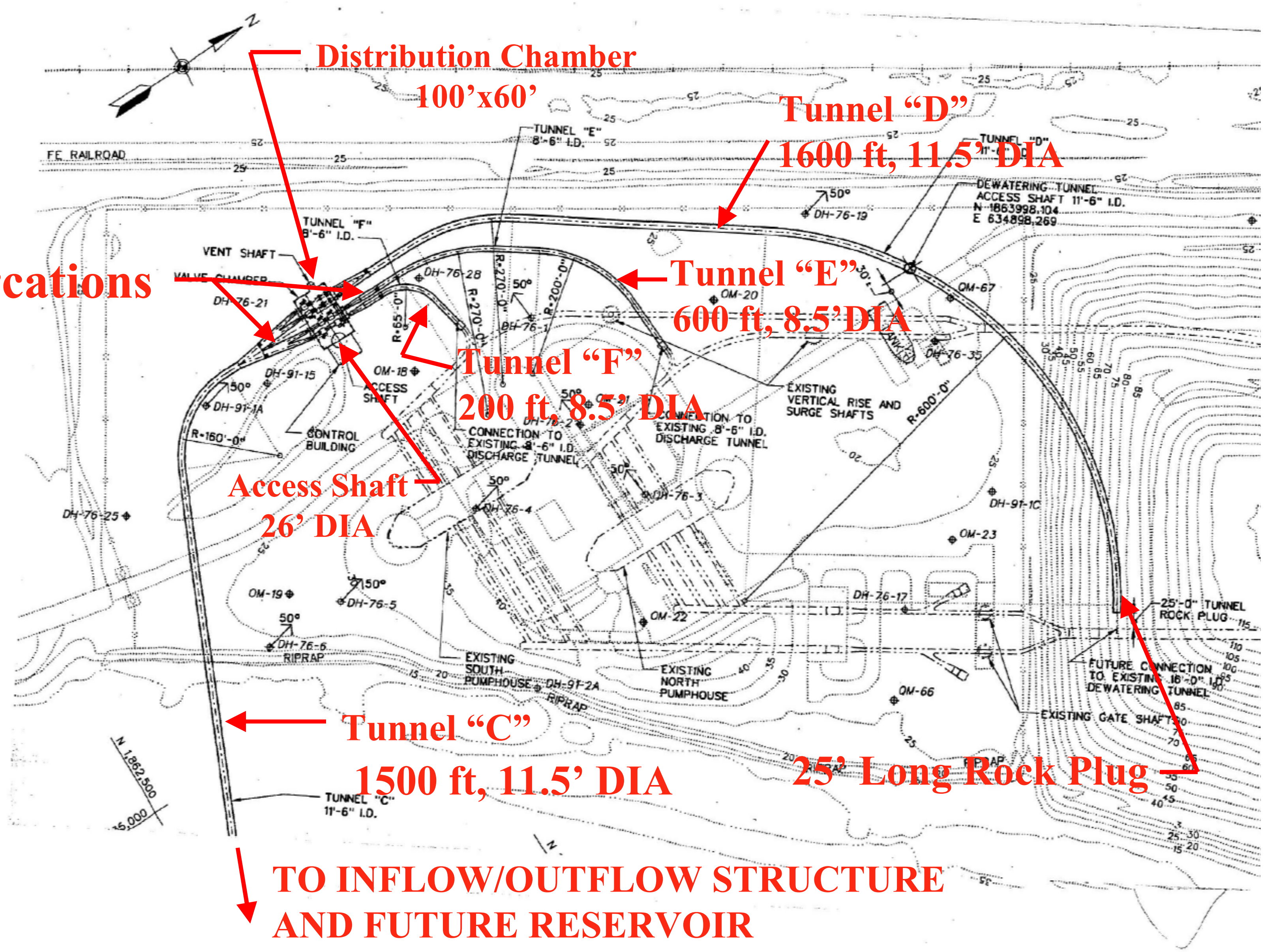

Plan – Distribution Tunnels

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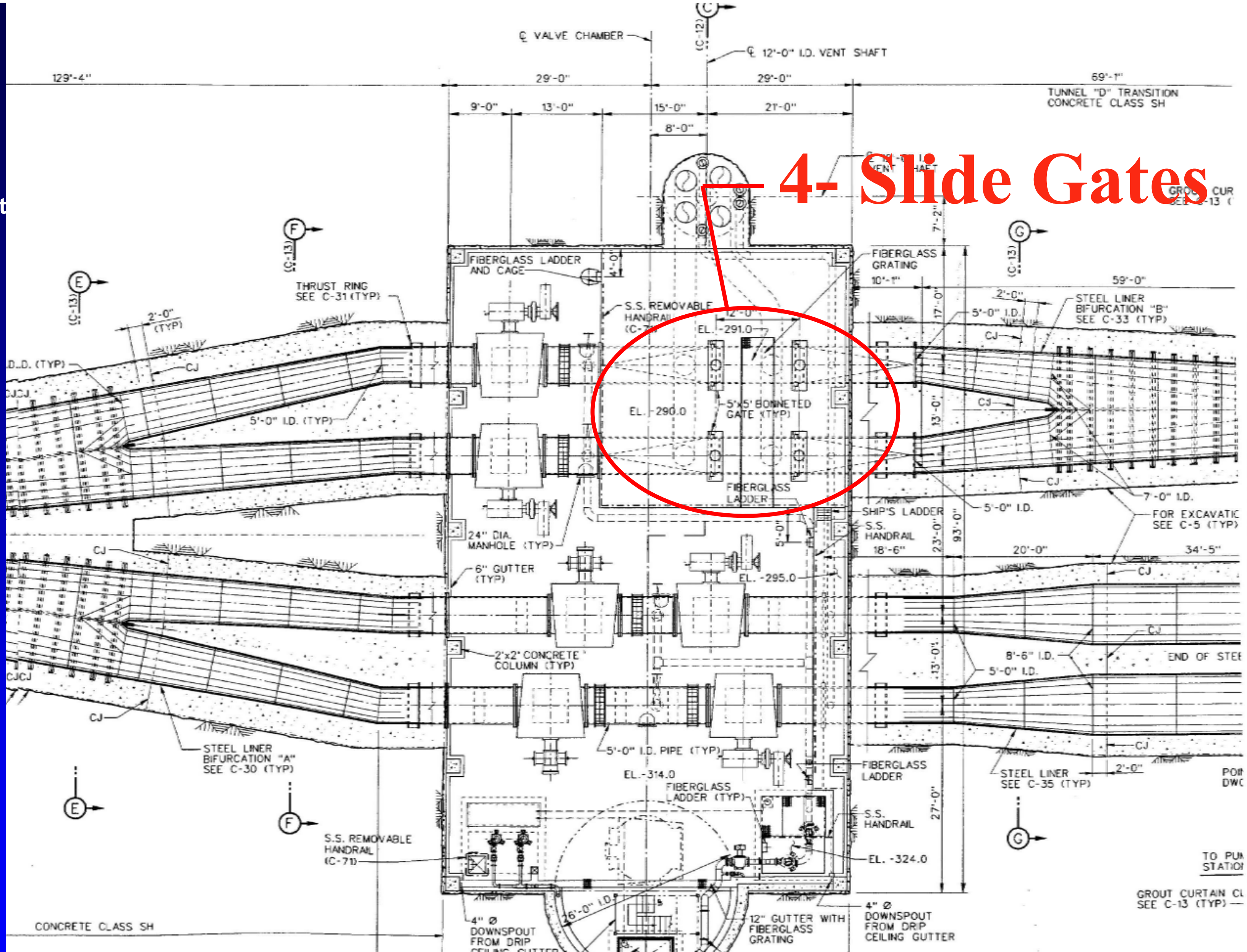

Distribution Chamber

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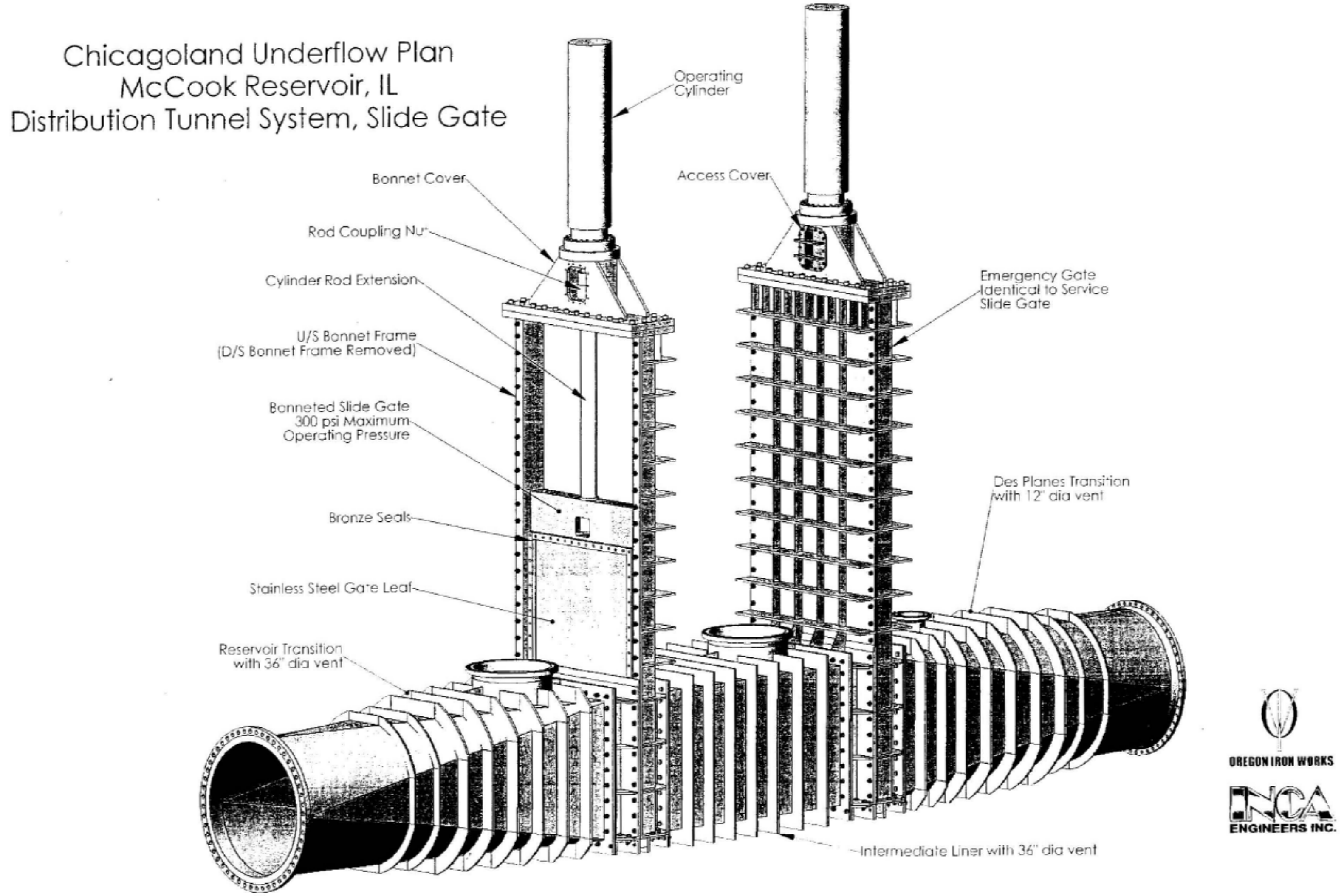

Bonneted Slide Gates – 5'x 5'

CONTRACT COST/SCHEDULE

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Total contract	$60 million
Completed	85%
Anticipated Completion Date:	Jan 2006

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Design of Circular Tunnel Lining

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EM 1110-2-2901
30 May 1997

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ENGINEERING AND DESIGN

Tunnels and Shafts in Rock

ENGINEER MANUAL

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Tunnels General

- **3100 Lineal Feet of 11.5' DIA. Tunnel**
  800 Lineal Feet of 8.5' DIA. Tunnel
- **Approximately 310' below grade**
- **Excavation by Drill and Blast - Creating a horseshoe shaped excavation**

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Tunnel Excavation – Drill and Blast

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Tunnels General (con't)

- Final Tunnel cross sections are Circular except at bifurcations.
- At bifurcations cross sections are oblong or vary between circular and oblong

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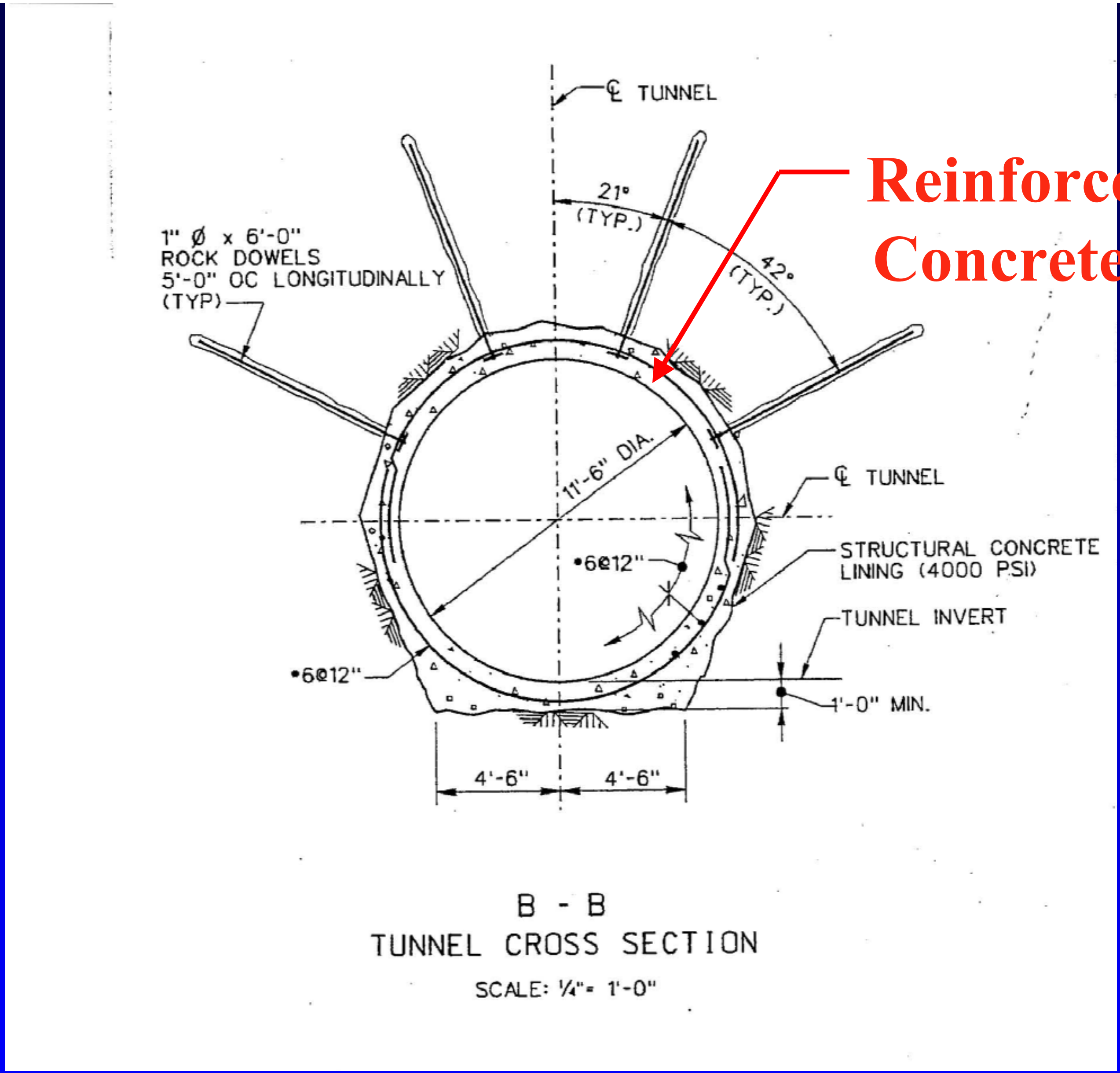

Typical Tunnel Cross Section

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Why Reinforced?

- Most of the Chicago TARP tunnels are not reinforced because;

  - Exfiltration is not a concern since external pressures from ground water exceed internal pressures

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Why Reinforced? (con't)

On Distribution tunnels reinforcement is provided because;

- The proximity of the reservoir draws groundwater down allowing exfiltration

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Hydraulic Design Considerations

- Velocities > 100 fps can occur around gates and valves in tunnels – those areas are steel lined and backed with 6000 psi concrete

- Tunnel C and D are low velocity gravity – 4000 psi concrete

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Design Loads
Circular Tunnel Liners

- Internal Pressures

  Max Hydraulic Dynamic Pressure of 160 psi

- External Pressure

  Hydrostatic Load from Ground Water

  head = 310 ft   or 132 to 134 psi

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Key Design Assumptions

- All rock loads are assumed to be fully supported by permanent rock dowels. No rock loads to the liner.

- Relaxation of the rock and stress redistribution is assumed to occur prior to installation of the lining

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Crack Width Limitation (Internal Pressure Design)

- Crack Width Limited to .008” for water tightness
- Tensile stresses in the reinforcing are limited to limit the crack width.

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Materials

- **Concrete strength:**

  4000 psi in tunnels

  6000 psi around steel liners

  10,000 psi at concrete bifurcation

- **Reinforcing:**

  ASTM A615, GR 60

Analyses Procedure

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Tunnel Lining is analyzed for Internal External pressure

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External Pressure Design Procedure

1. Determine and apply external pressures:

   132 psi for 11.5’ diameter tunnels

2. Determine Load Case(s):

   1.1 D + 1.4 H (EM 2901, Table 9-1)

3. Model tunnel Lining using STAAD

4. Design Concrete for Hoop Compression

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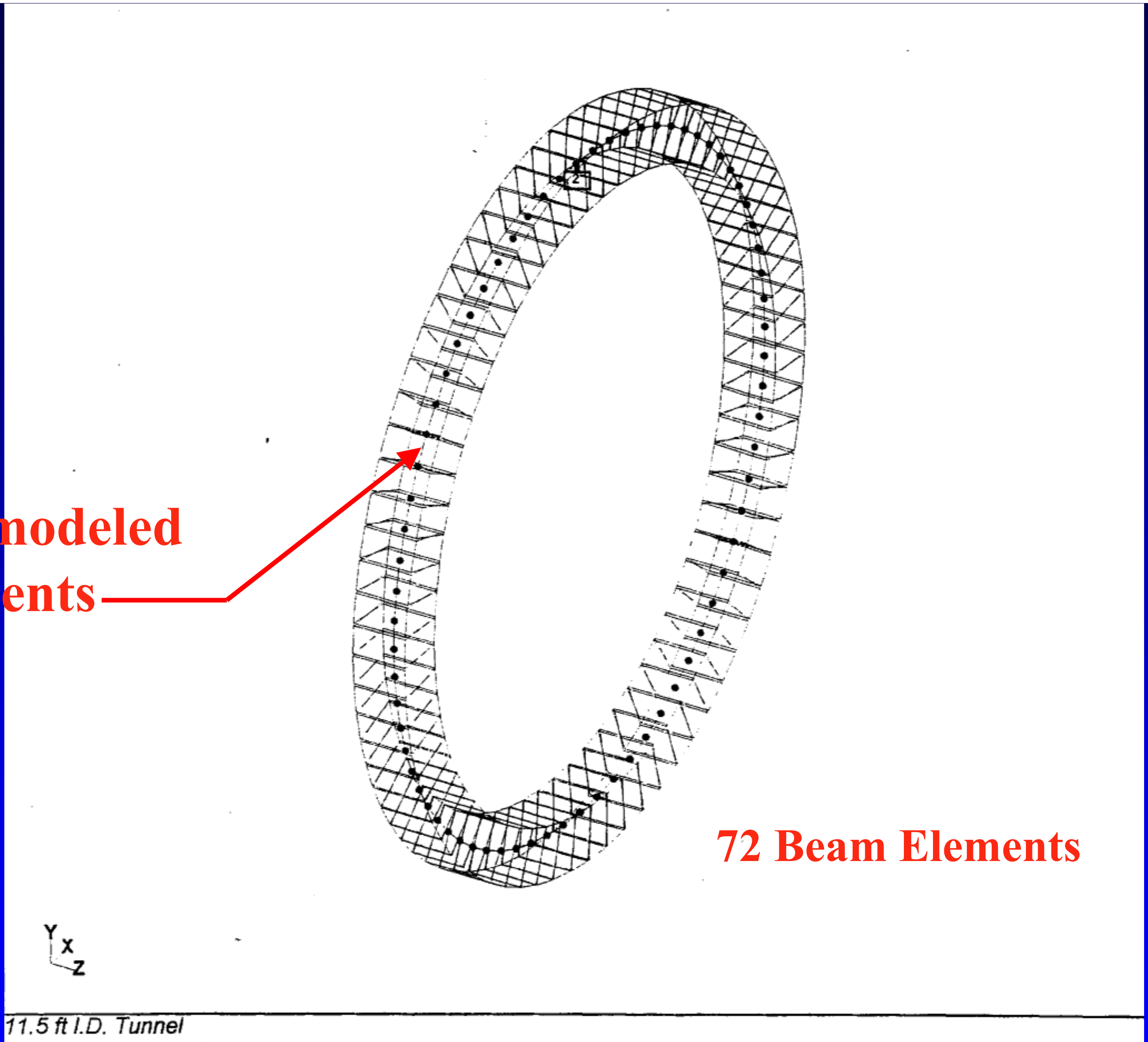
Tunnel Lining modeled with beam elements



STAAD FE Model

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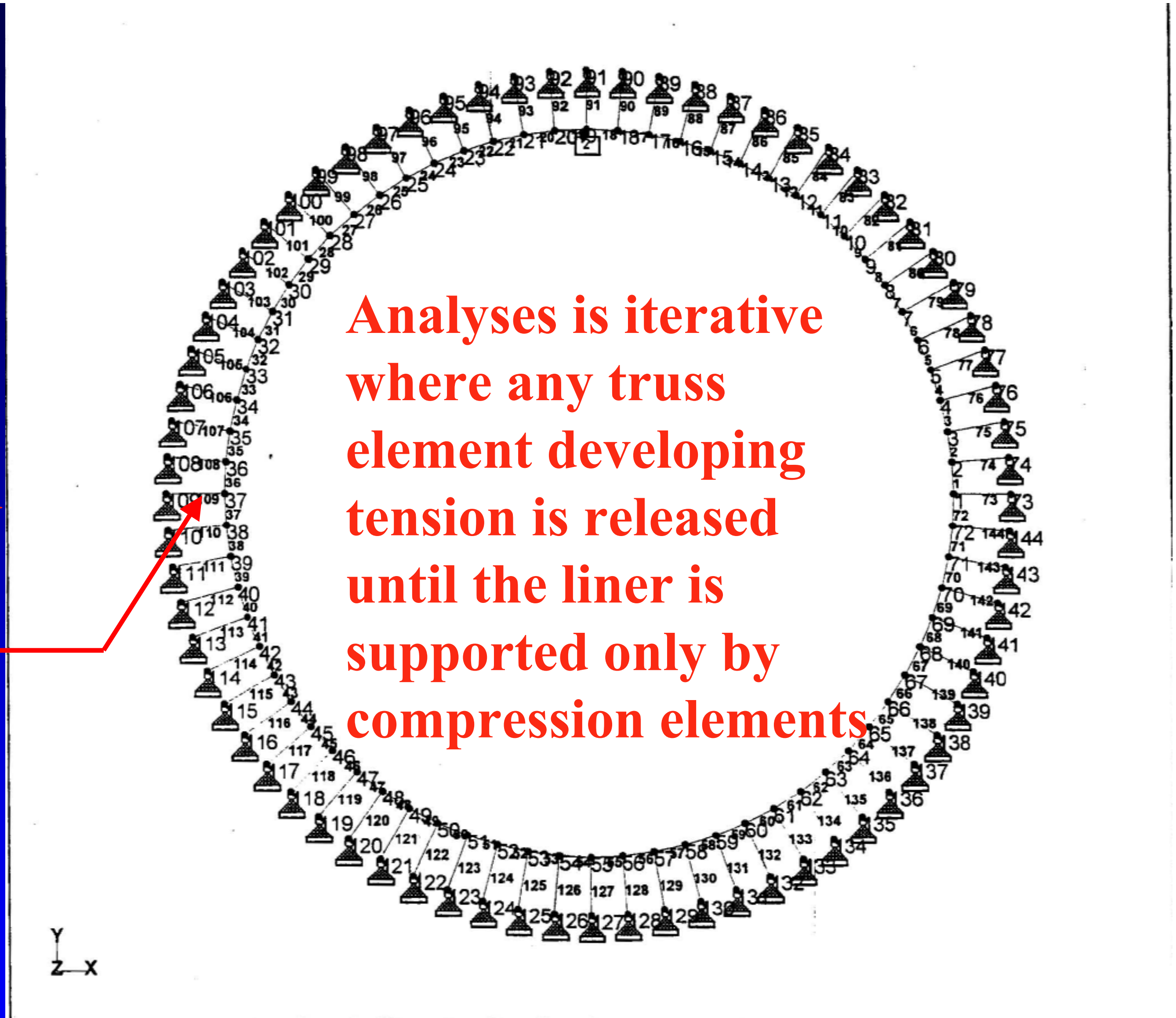
Rock Modeled
With truss
elements

Radial spring
Stiffness assigned
Per Equation 9-18,
EM 2901.



Analyses is iterative
where any truss
element developing
tension is released
until the liner is
supported only by
compression elements

11.5 ft I.D. Tunnel (Beam and Node Numbers)

STAAD Model

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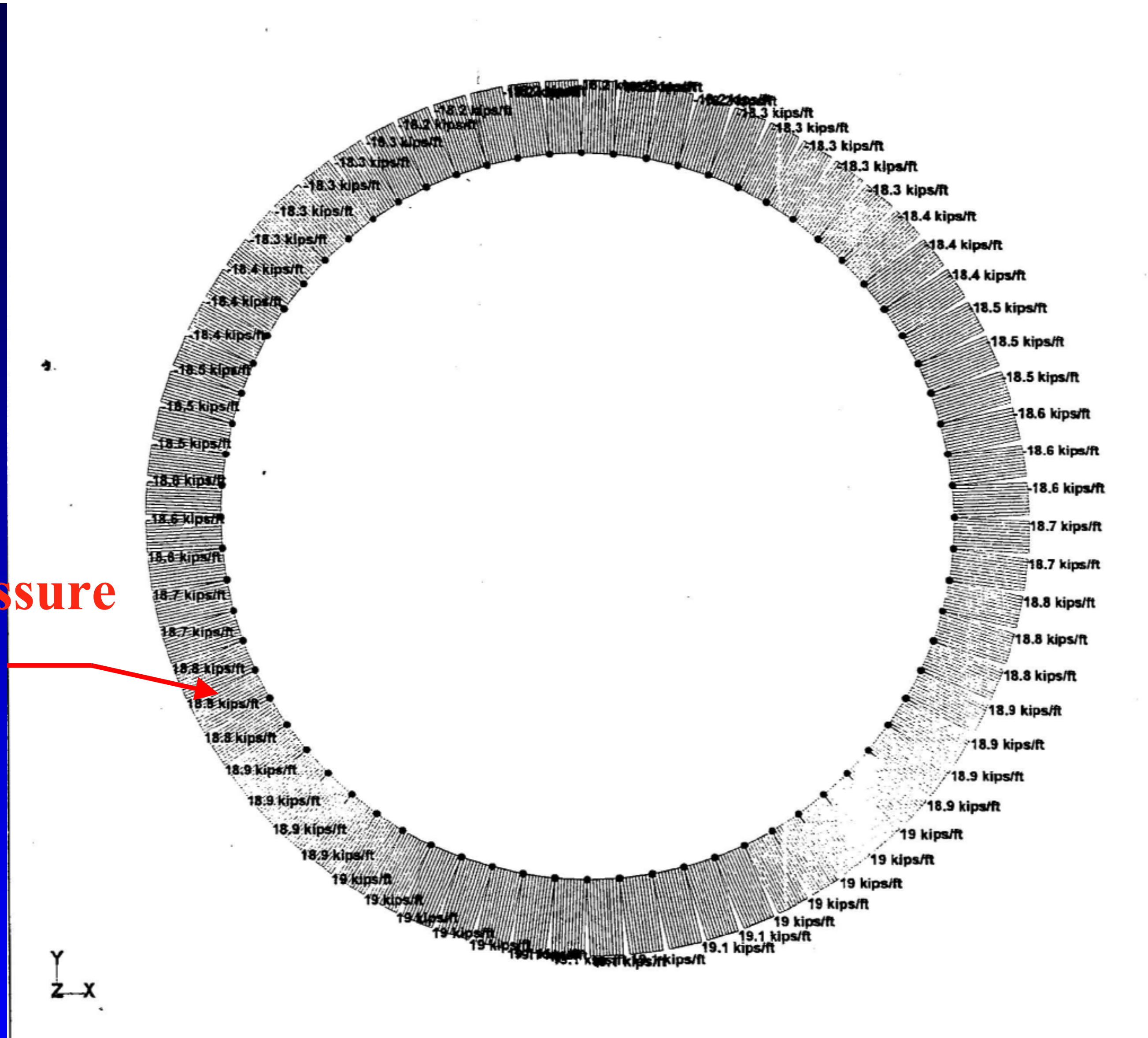
STAAD Model

External Pressure
Load 132 psi



11.5 ft I.D. Tunnel (Pressure Loads)

Results – External Pressure Design

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- Primary Load is hoop compression

  Pu = 164 K/FT   for 11.5’ Tunnels

- Moments and Shears are negligible

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Internal Pressure Design Procedure

1. Determine and apply internal pressures:

   160 psi …………..11.5' diameter tunnels

2. Determine Load Case(s):

   1.1 D + 1.4 H (EM 2901)

3. Model the tunnel using Program "TUNNEL" developed by MWH.

4. Design Reinf. to Limit crack width to .008"

Model Features
(Internal Pressure Design)

1. Surrounding Rock Mass was modeled as a thick walled cylinder

2. Deformation properties of the concrete lining and sound and fissured rock were modeled.

3. Strain compatibility was performed to determine % of load carried by the rock and the lining.

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Rock Properties
(Internal Pressure Design)

- A 40” ring of fissured rock was modeled – due to drill and blast excavations.

- Then, sound rock was modeled beyond the fissured zone

Fissured Rock (grouted) …….Erock = 480,000 psi

Sound Rock ……………………..Erock = 1,300,000 psi

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Results
(Internal Pressure Design)

- Primary Load was tensile stress in the Concrete.

  Maximum Tensile Stress = 600 psi

- Reinforcement was sized to limit crack width to .008 inches

- Resulted in #6 @12 inches

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Setting Forms

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Window in Forms for Concrete Placement

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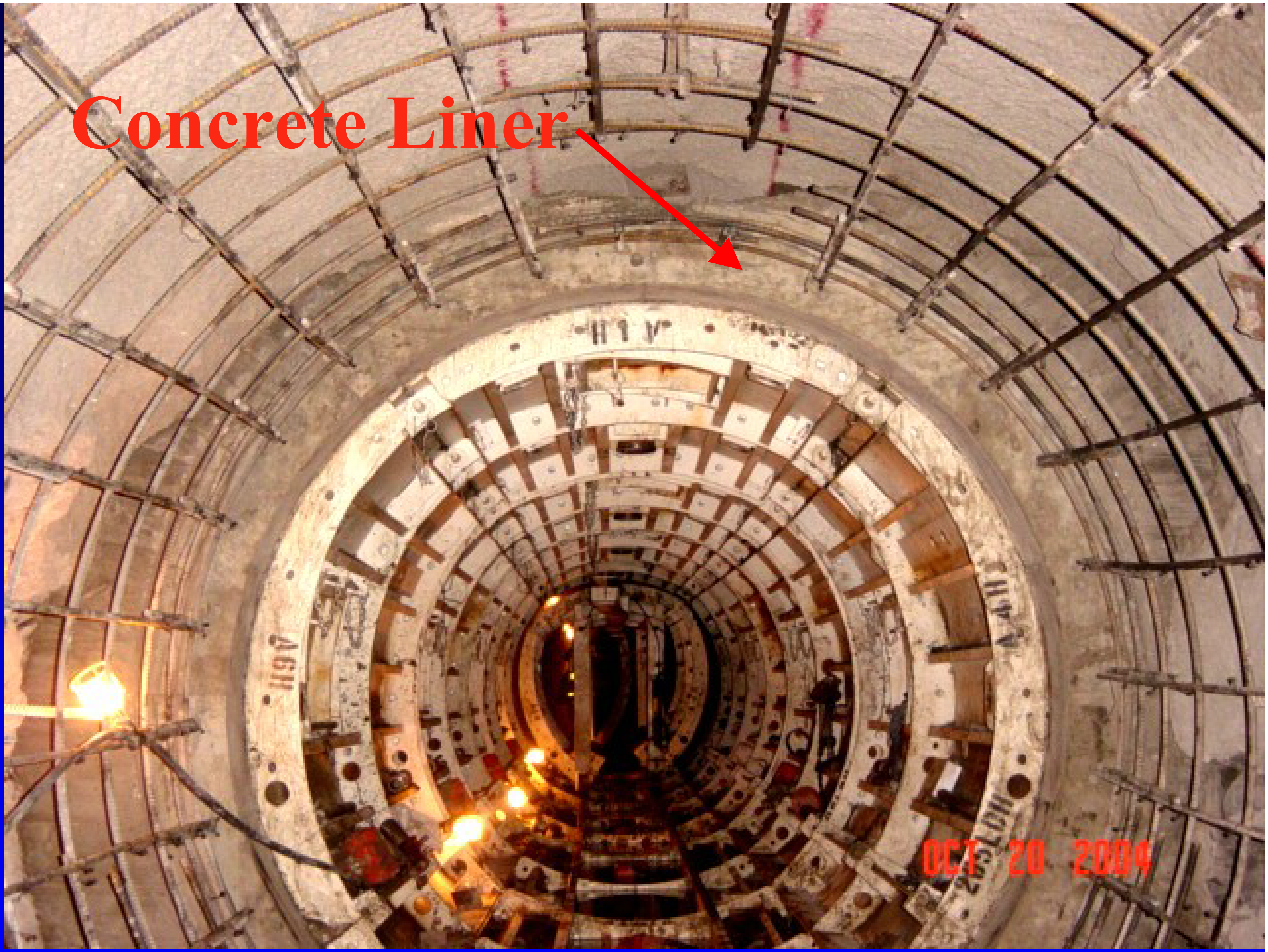

Tunnel Lining Formwork

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Design of Concrete Bifurcations

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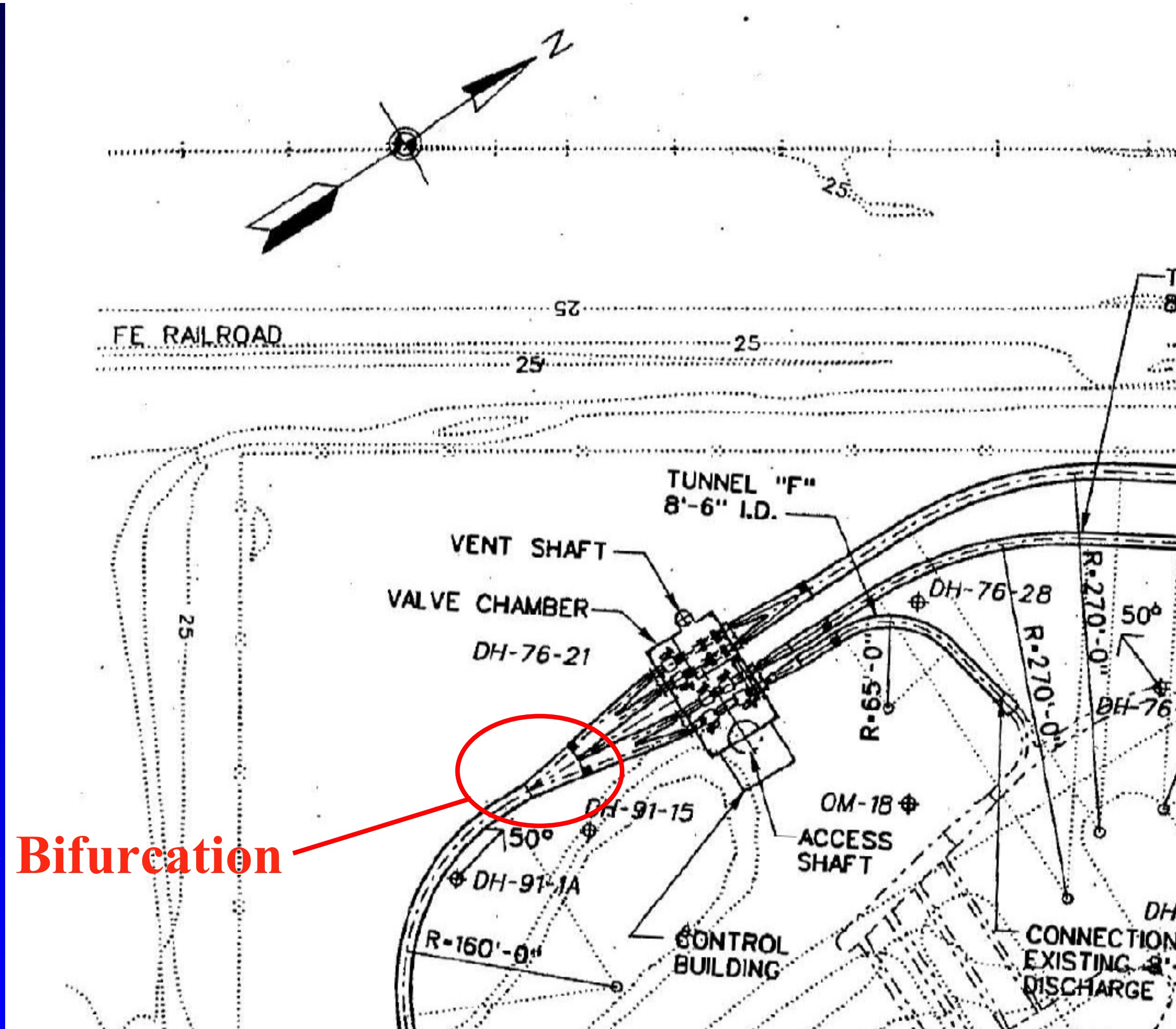

Concrete Bifurcation

Plan - Concrete Bifurcation

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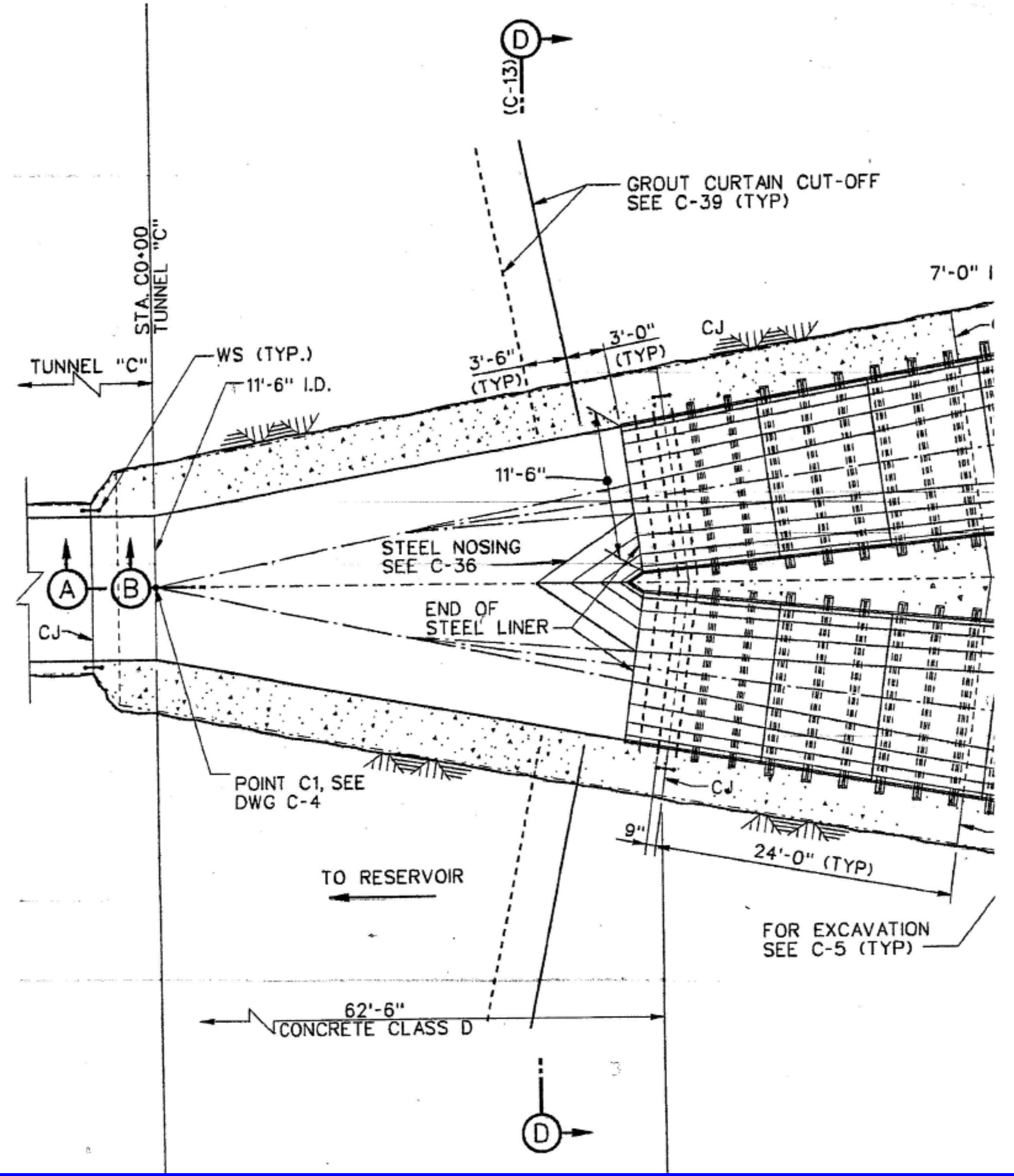

Plan of Concrete Bifurcation

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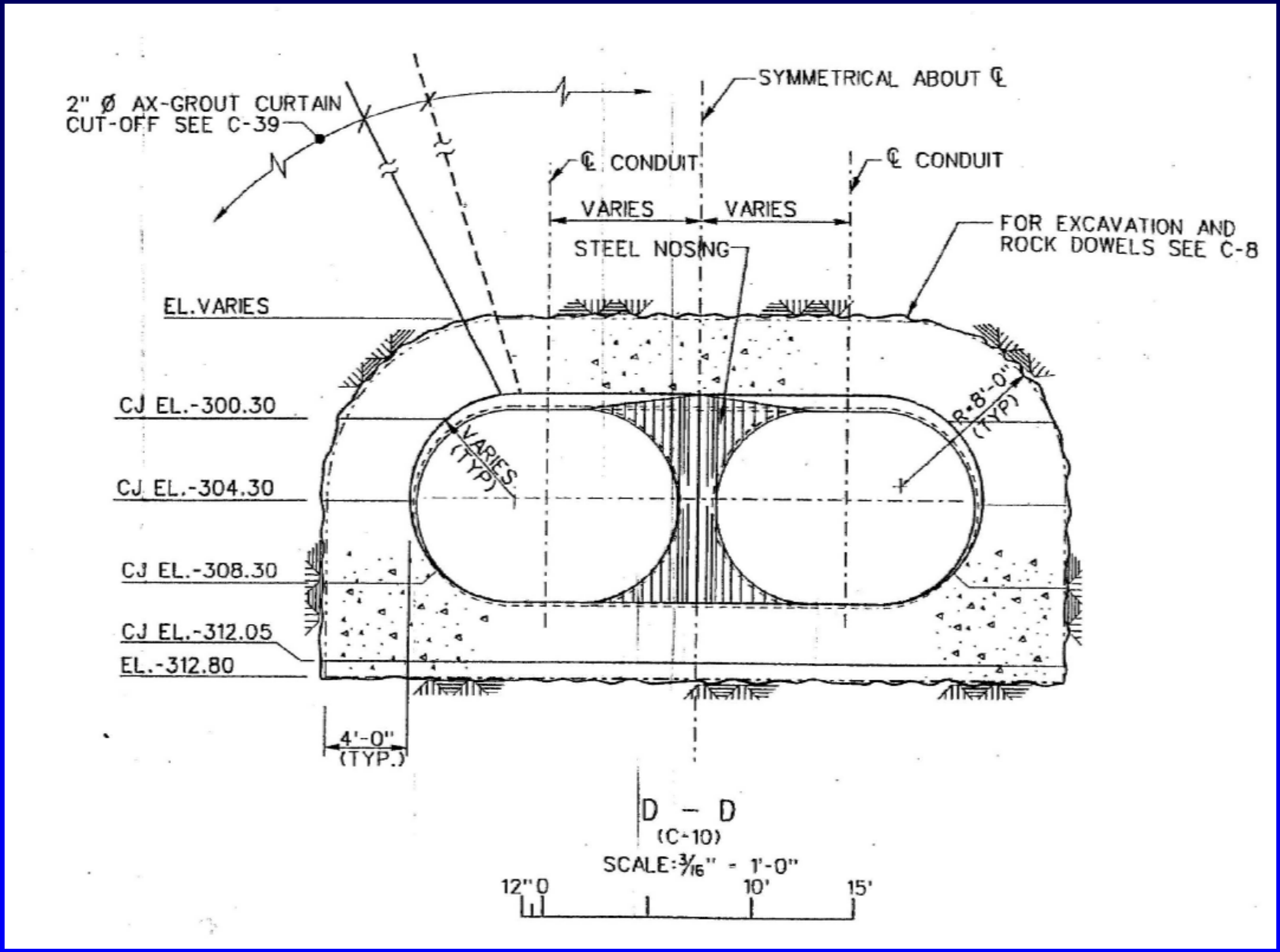

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Hydraulic Design Consideration

- Concrete Bifurcation is subjected to moderate turbulence - 10,000 psi concrete

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External Pressure Design

- Designed for external pressure of 136 psi
- External Pressures are resisted by the use of rock anchors on all sides
  - necessary due to non-circular shape
- Concrete sections are designed per ACI 318.

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Internal Pressure Design

- Designed for internal pressure of 160 psi
- SAP 2000 was used for the Analyses to include the effects of the surrounding rock mass. Similar to tunnel design.
- Concrete designed for watertightness and allowable crack width of .008 inches

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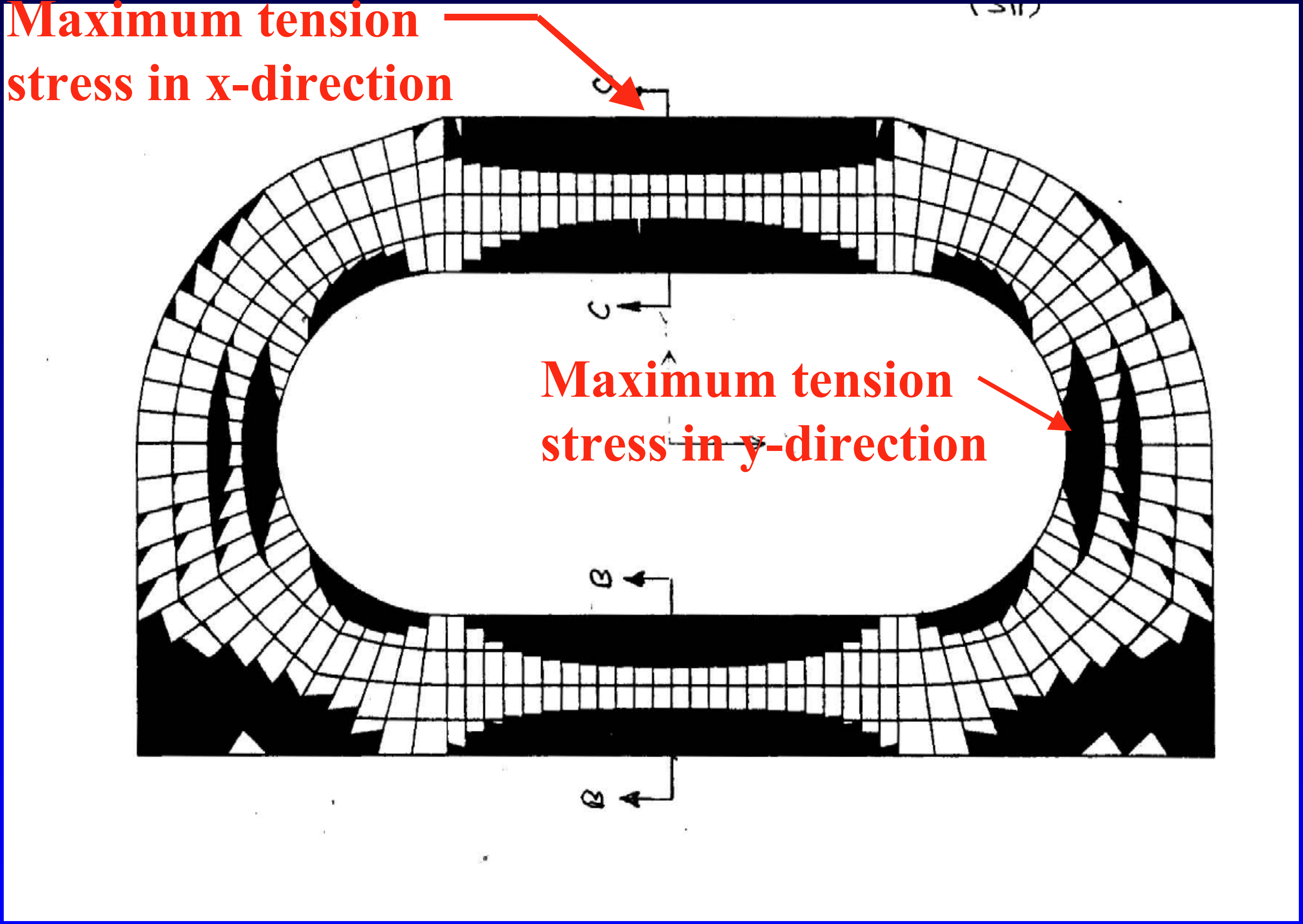

Maximum Stresses – (Internal Pressure)

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Overview of Steel Liner Design

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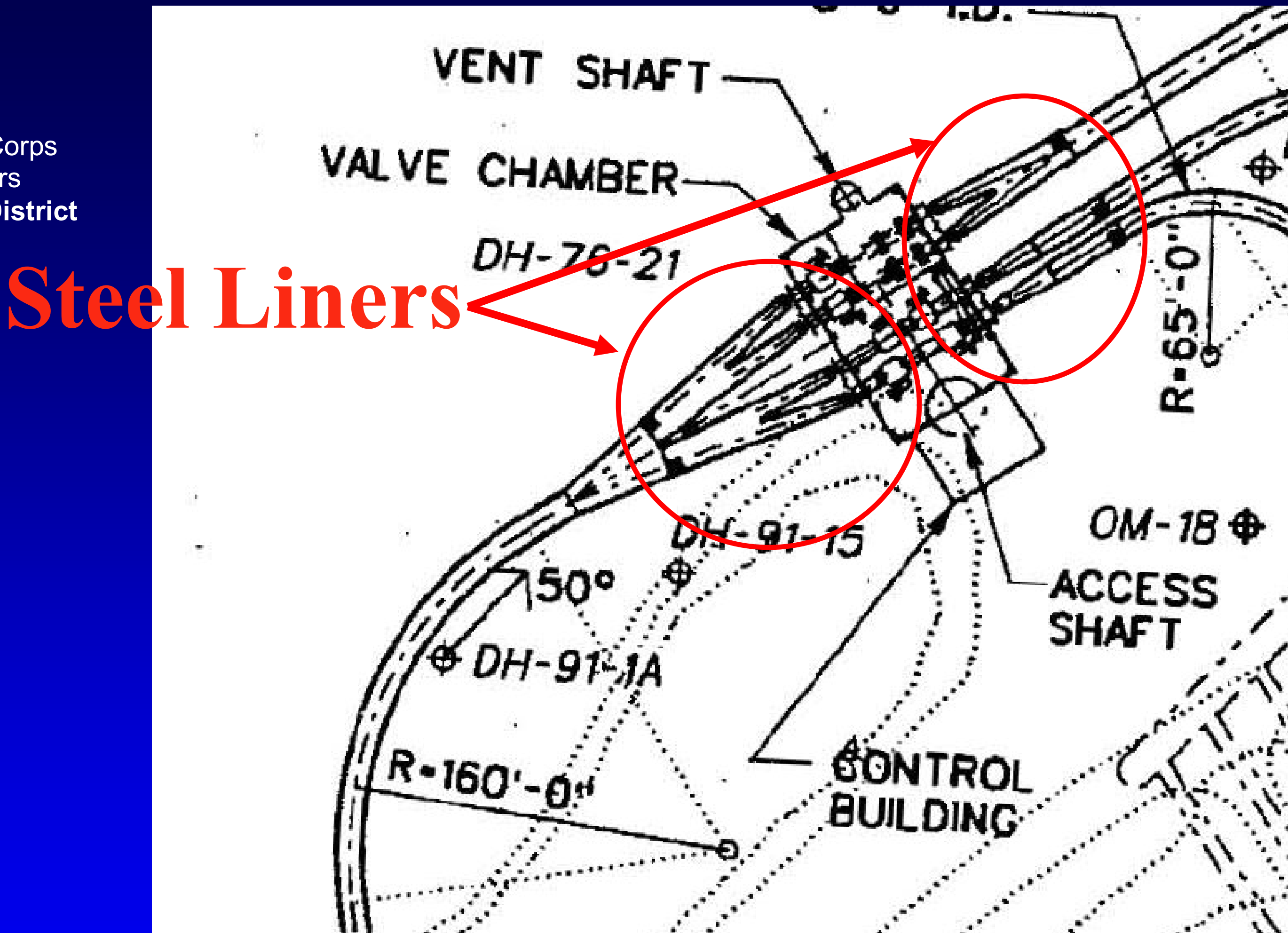

Steel Liners Located at Distribution Chamber

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Purpose of Steel Liners

- Provide erosion protection in areas around Distribution Chamber

  - Velocities > 100 fps

- Form the bifurcation geometry

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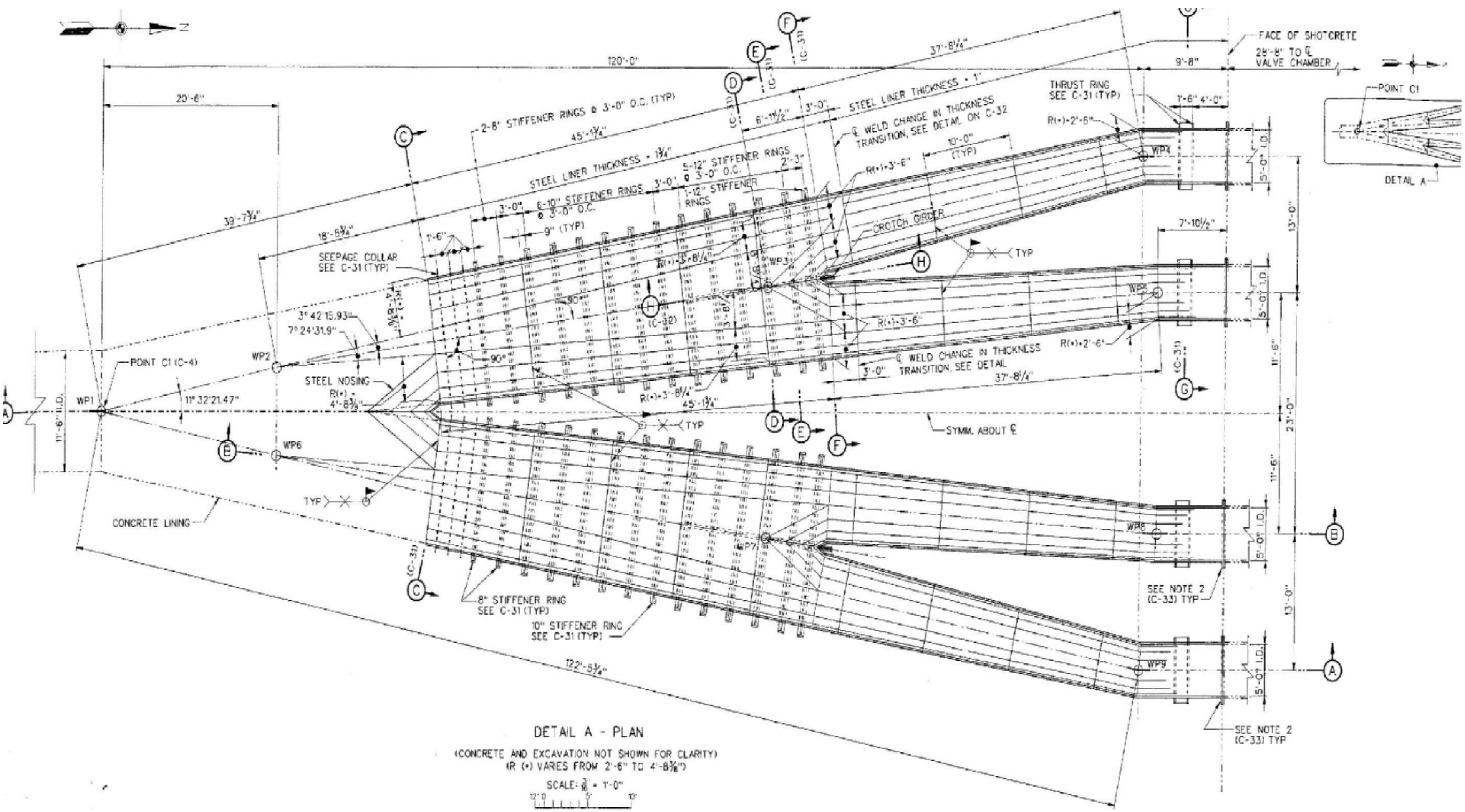
Design of Steel Liners

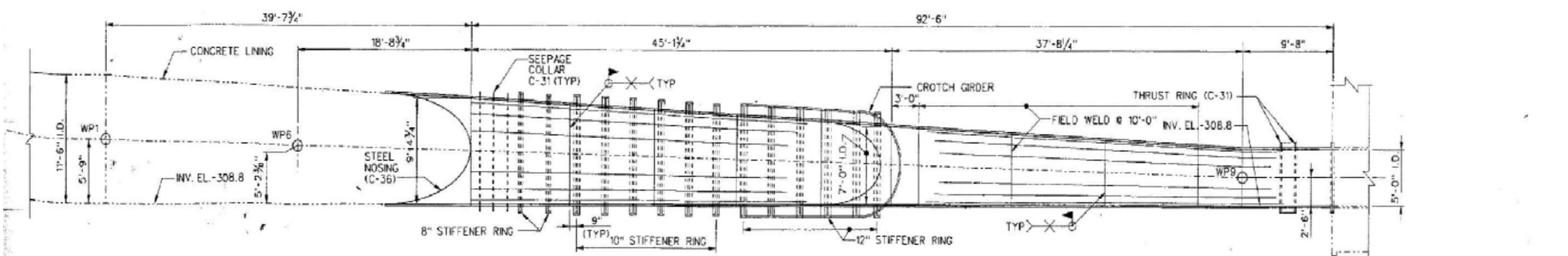
- Designed for internal and external pressures
- Circular Section designed per EM 2901 Section 9-5d.
- ASME Pressure Vessel Code, Section VIII used for design of noncircular sections
- Stiffeners are provided on obround liner sections to resist buckling
- In areas of geometric discontinuities, 3-D STAAD Model used to design the cross sections.



DETAIL A - PLAN

(CONCRETE AND EXCAVATION NOT SHOWN FOR CLARITY)
(R (•) VARIES FROM 2'-6" TO 4'-8⅜")

SCALE: ⅜" = 1'-0"



A - A

REFERENCE DRAWINGS:

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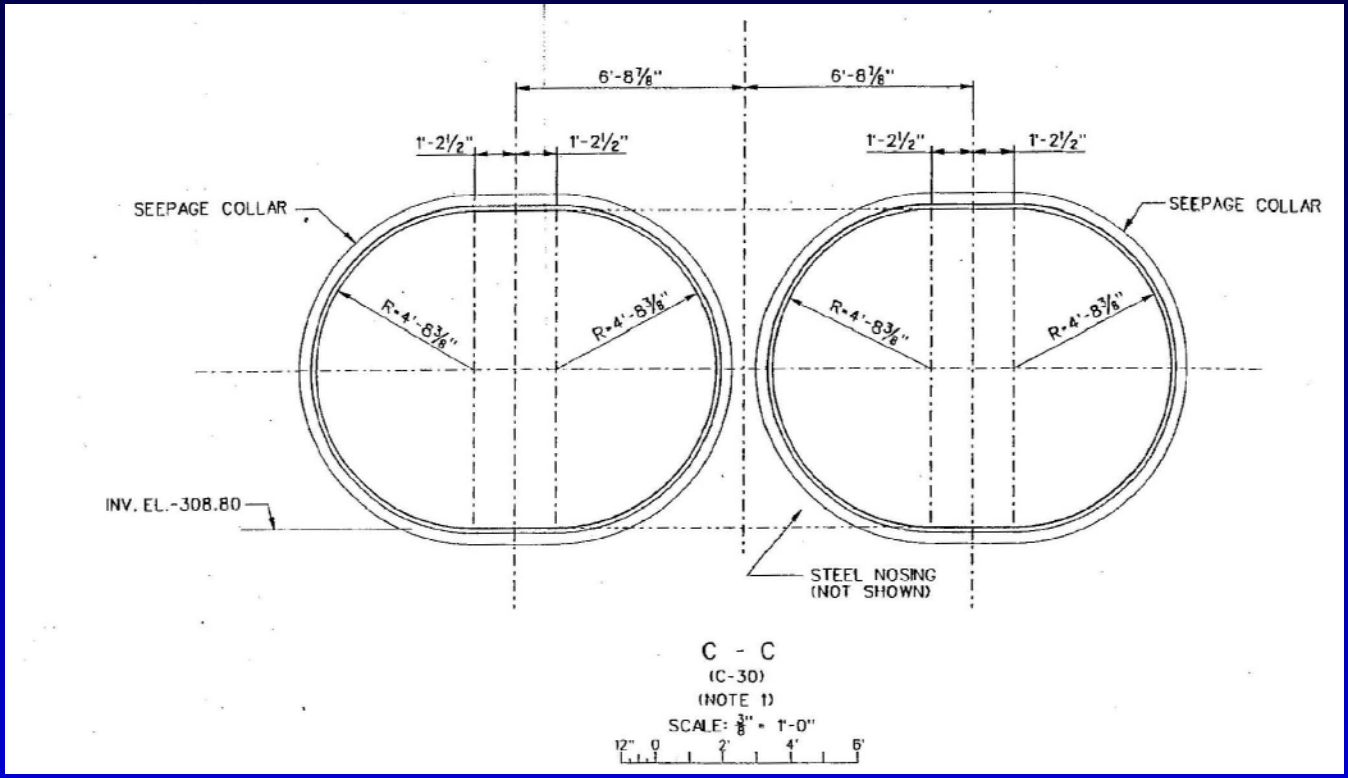

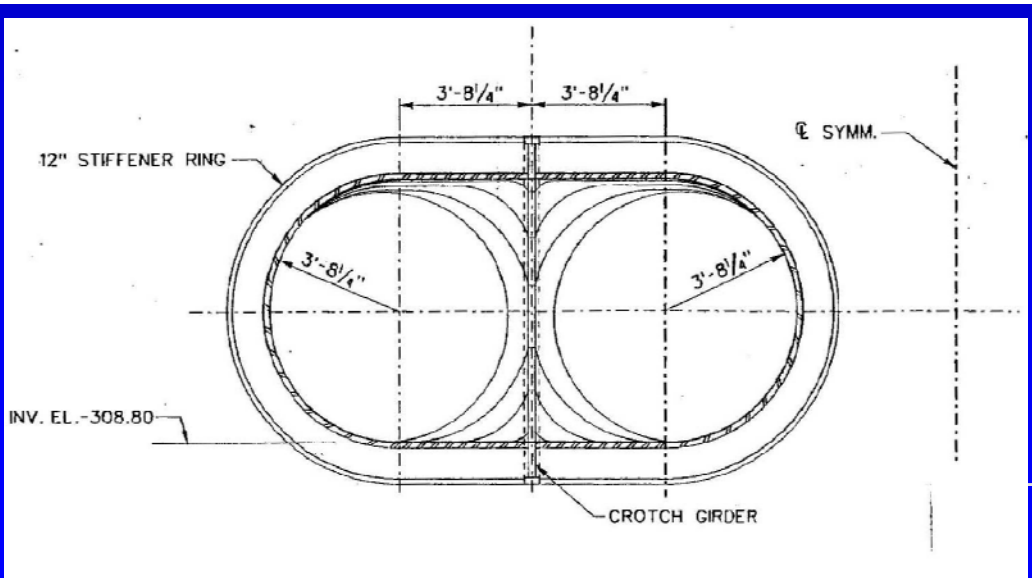

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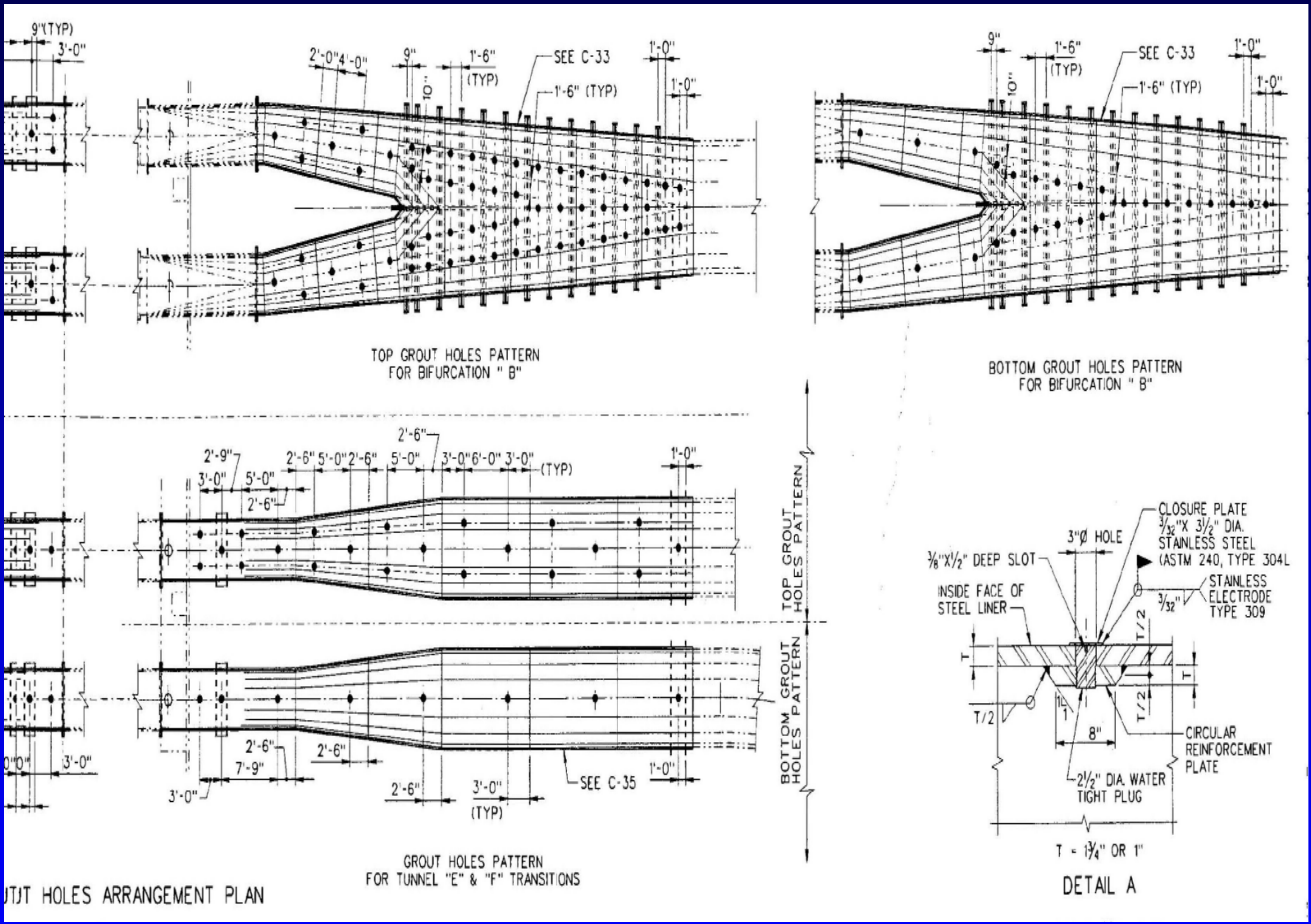

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Steel Nosing being lowered into 26' dia. Access shaft

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View From Inside Steel Liner

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Steel Liner Being Welded – Oblong Section

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Positioning Steel Nosing

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Thank You

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Machine-bored Tunnel
(the new way)

Intersection of Machine-bored Tunnels

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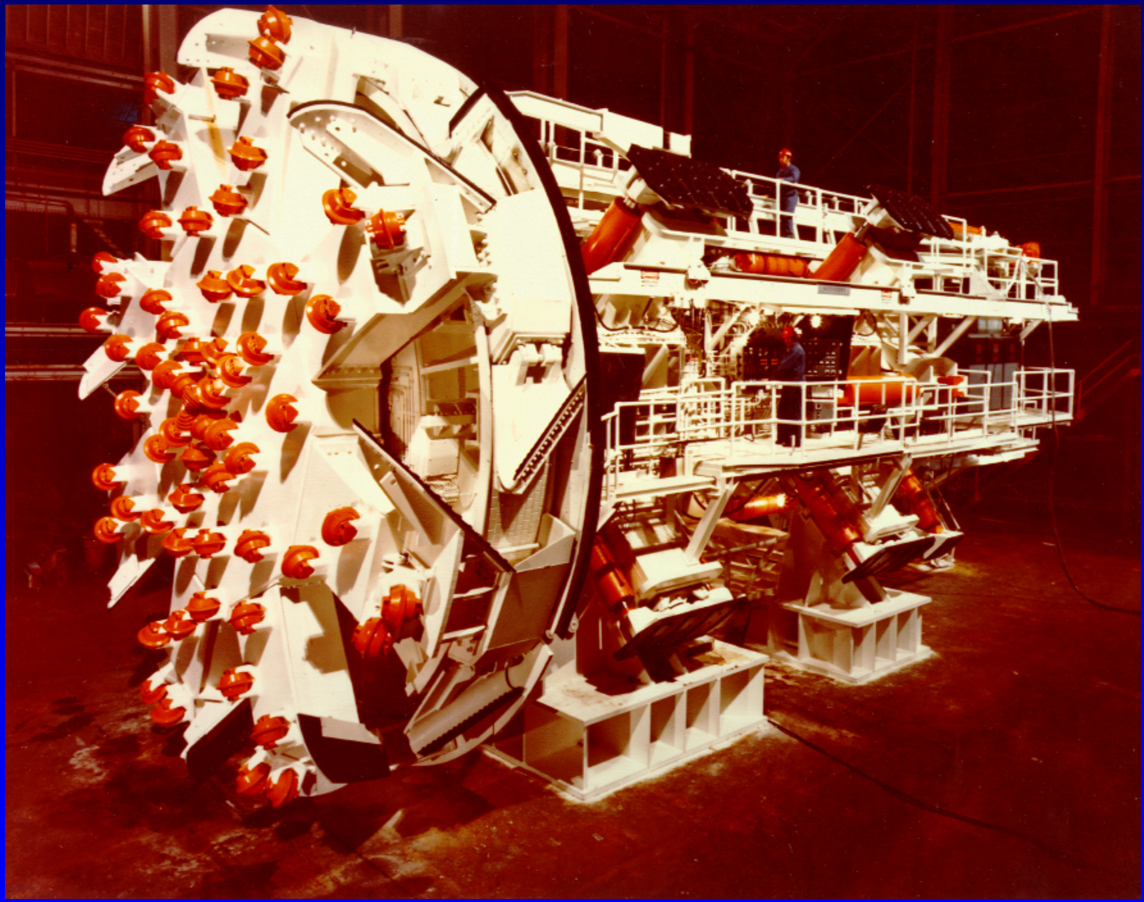
TUNNEL BORING MACHINE



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27-ft Diameter Machine-bored Tunnel – Before Lining

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Placing Concrete for Tunnel Lining

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LINED TUNNEL