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Engineering Reliability Analysis for Prioritizing Investment Decisions

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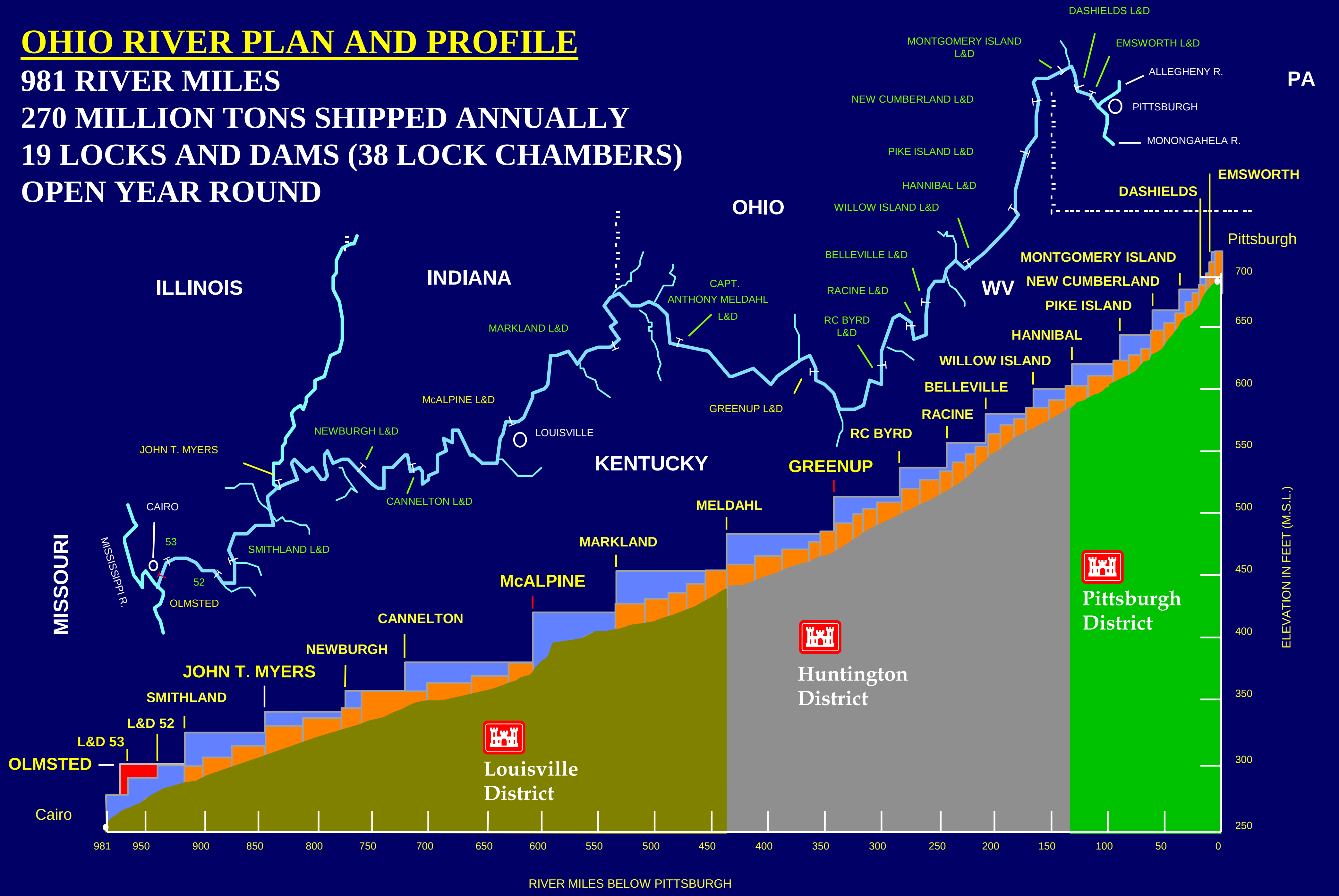
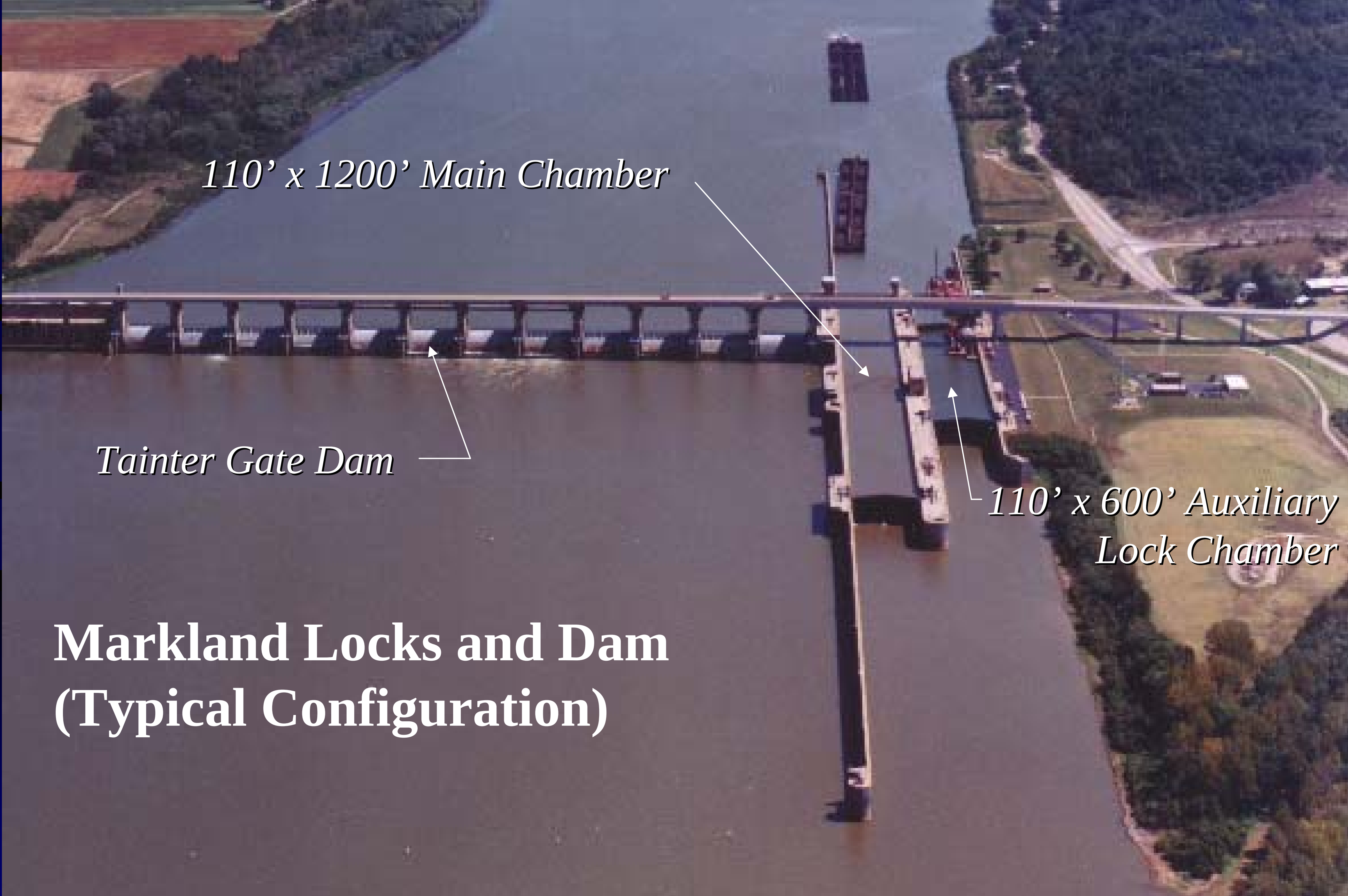
Outline of Presentation

- Existing System of Ohio River Locks and Dams
- Ohio River Mainstem Systems Study
    - *Engineering Reliability Features*
    - *Integration with Economics*
- Ohio River Navigation Investment Model
    - *Capabilities and Uses*
- Future and On-Going Studies
    - *Great Lakes/St. Lawrence Seaway & Panama Canal*

OHIO RIVER PLAN AND PROFILE

981 RIVER MILES
270 MILLION TONS SHIPPED ANNUALLY
19 LOCKS AND DAMS (38 LOCK CHAMBERS)
OPEN YEAR ROUND




110’ x 1200’ Main Chamber
Tainter Gate Dam
110’ x 600’ Auxiliary
Lock Chamber
Markland Locks and Dam
(Typical Configuration)

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Ohio River Project Details

Project	District	Year Built	Annual Tonnage	Annual Tows	Annual Number Recreational Vessels
Emsworth	LRP	1921	23,000,000	5,300	4,000
N.Cumberland	LRP	1959	37,000,000	4,600	1,800
Hannibal	LRP	1972	46,000,000	4,300	900
Willow Island	LRH	1972	44,000,000	3,800	1,600
RC Byrd	LRH	1993	59,000,000	5,400	700
Greenup	LRH	1959	70,000,000	6,400	700
Markland	LRL	1959	55,000,000	5,200	4,100
John T. Myers	LRL	1975	72,000,000	6,600	2,500
Olmsted*	LRL	2014	94,000,000	9,900	1,700 (* Current Level)

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Ohio River Mainstem Systems Study

Assessing the Condition of All Project Features

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Engineering Reliability Analysis

What is it? Why is it used?

- Required by USACE Guidance for the Justification of Specific Types of Investments
  - Major Rehabilitation Projects (Markland, Emsworth, J.T. Myers)
  - New Project Authorization Based Upon Deteriorated Condition of Existing Project (Chickamauga)
  - Systems Studies Recommendations (ORMSS and GLSLS)
- Recognizes and Captures Uncertainty in Engineering and Economic Analyses
  - Engineering Uncertainties – Loads, Material Properties, Corrosion, Fatigue
  - Economic Uncertainties – Traffic Forecasts, Rate Savings
- Shows Economic Justification and Risks Associated with Multiple Future Investment Alternatives
  - Fix-as-Fails Maintenance, Advance Maintenance, Major Rehab
- Allows an Unbiased Method to Rank Projects Based Upon Risks and Economic Merit

Ohio River Mainstem Systems Study

Forecasting the Future

- Traffic Forecasts
- Lock Capacity
- Lock Reliability
  - Structural condition of lock and dam components
  - Cost of repairing lock components compared to replacing components ahead of failure
  - Operational effect of lock repairs (do they cause significant impacts to navigation, pool levels, and/or other impacts)

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Ohio River Mainstem Systems Study

Introduction to Systematic Evaluation

- Investment Plan for Ohio River Navigation System for 2005 - 2065
- Multi-Project, Multi-District, Multi-Discipline
  - Pittsburgh, Huntington, and Louisville Districts
  - Engineering, Economics, Plan Formulation, and Environmental
- Prioritization Among Maintenance, Rehabs, New Construction for All 19 Projects
  - Projects ages vary from 80+ years to under construction
  - Traffic levels and lock chamber dimensions vary
- Reliability Had Significant Impact on Economic Analysis and was used to Time Improvements

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Engineering Reliability Integration

- Aging System of Locks and Dams
  - Most projects approaching original design life of 50 years
  - Most projects will be near 100 years old by end of study
- Older, Deteriorated Projects Need Condition Upgrades
- High Traffic Projects Need Capacity Enhancements
- Reliability Used to Justify and Time Project Upgrades
- Most Critical System Components Analyzed
  - Excessive repair cost and/or excessive down time
- Bottom Line – Where is Best Place to Put Limited Funds???

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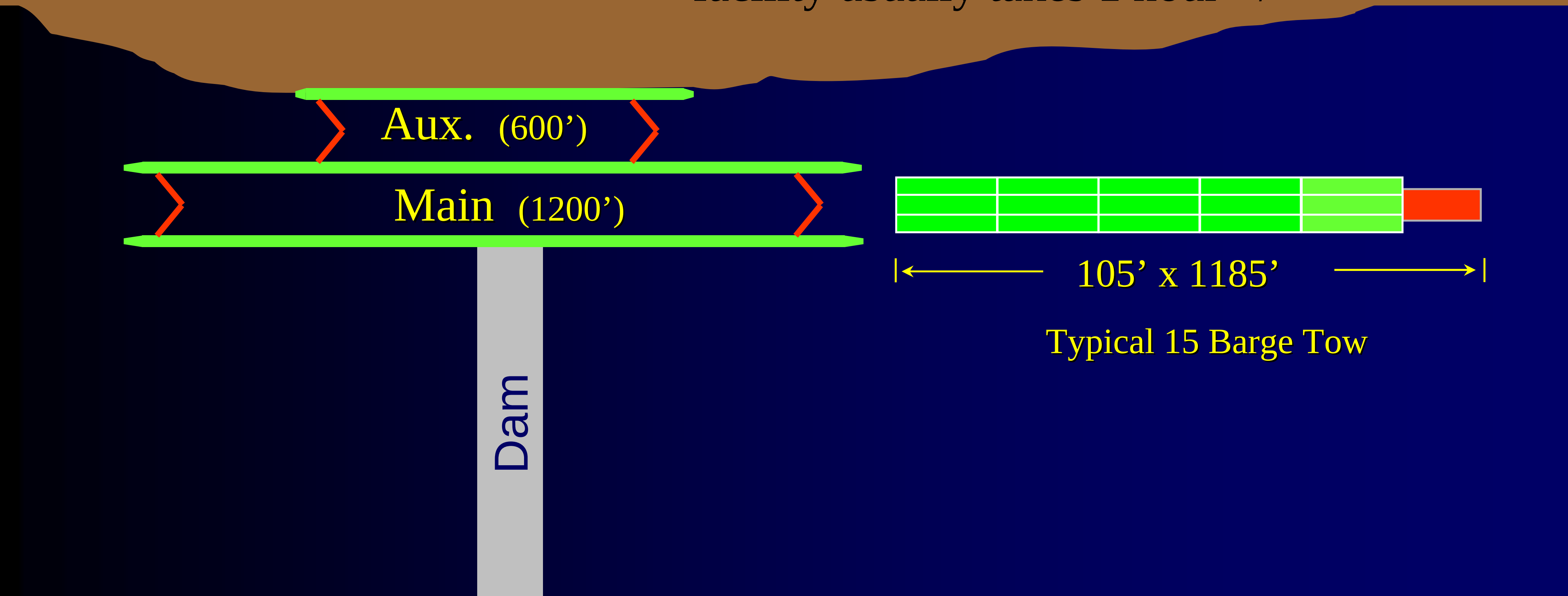
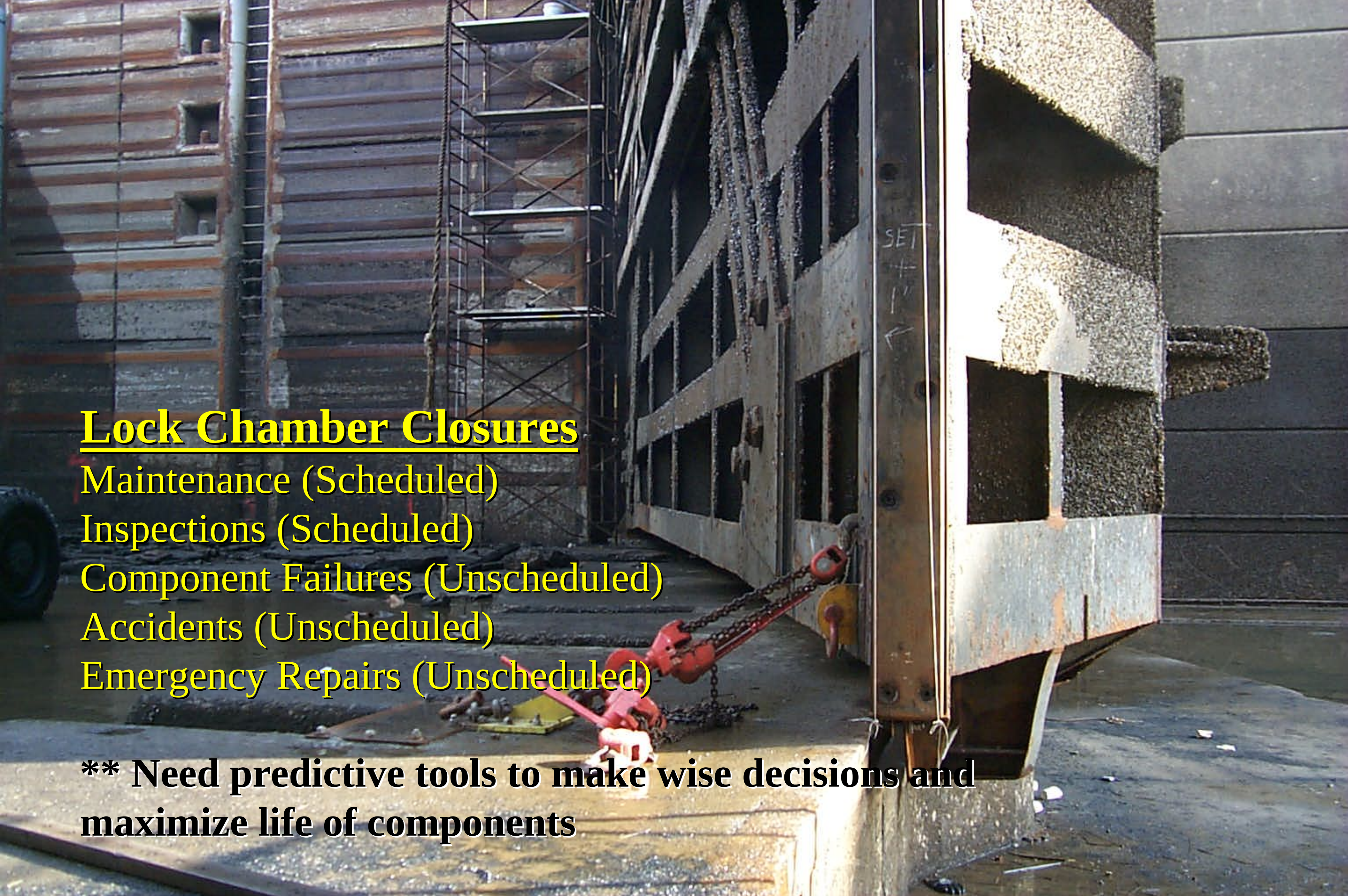
Typical Ohio River Main & Auxiliary Locks

When both chambers open transit thru facility usually takes 1 hour +/-





Lock Chamber Closures

Maintenance (Scheduled)
Inspections (Scheduled)
Component Failures (Unscheduled)
Accidents (Unscheduled)
Emergency Repairs (Unscheduled)

**** Need predictive tools to make wise decisions and maximize life of components**

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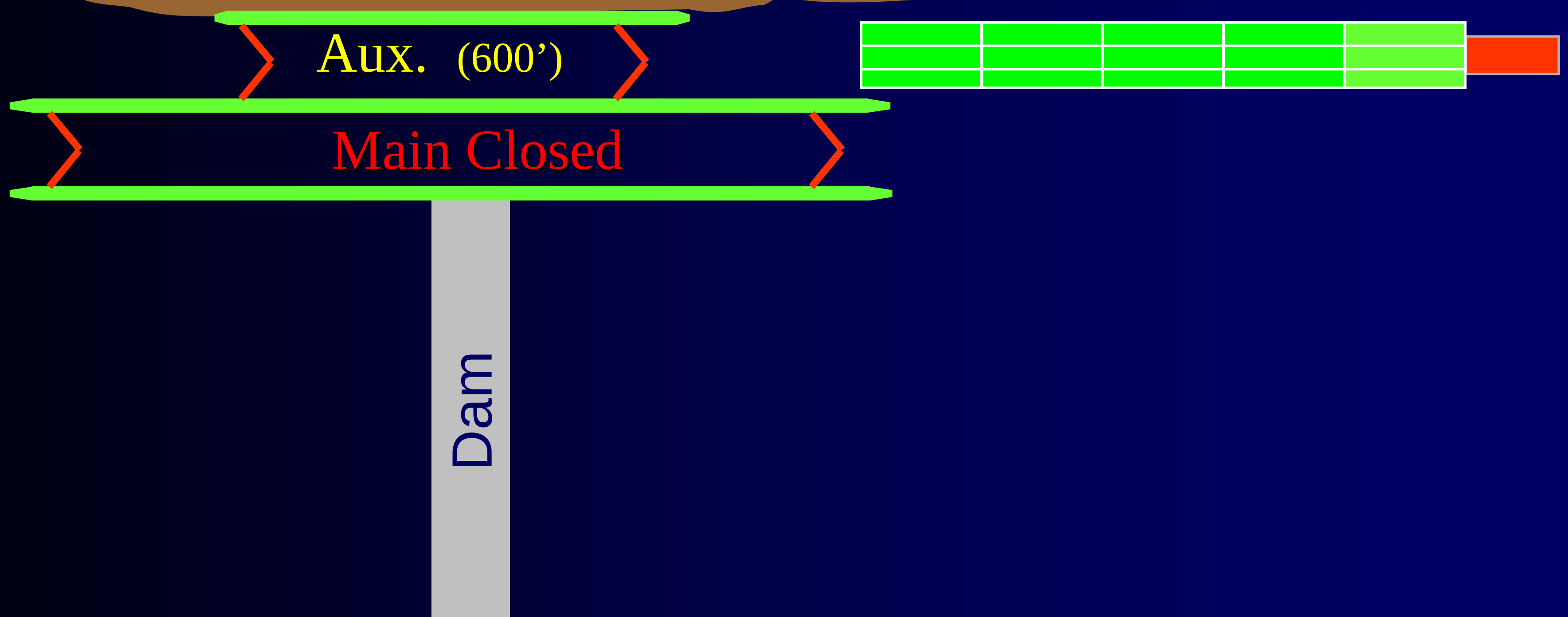
Typical Ohio River Use of Auxiliary Locks

Main chamber closed, transit time greatly increased due to short auxiliary chamber



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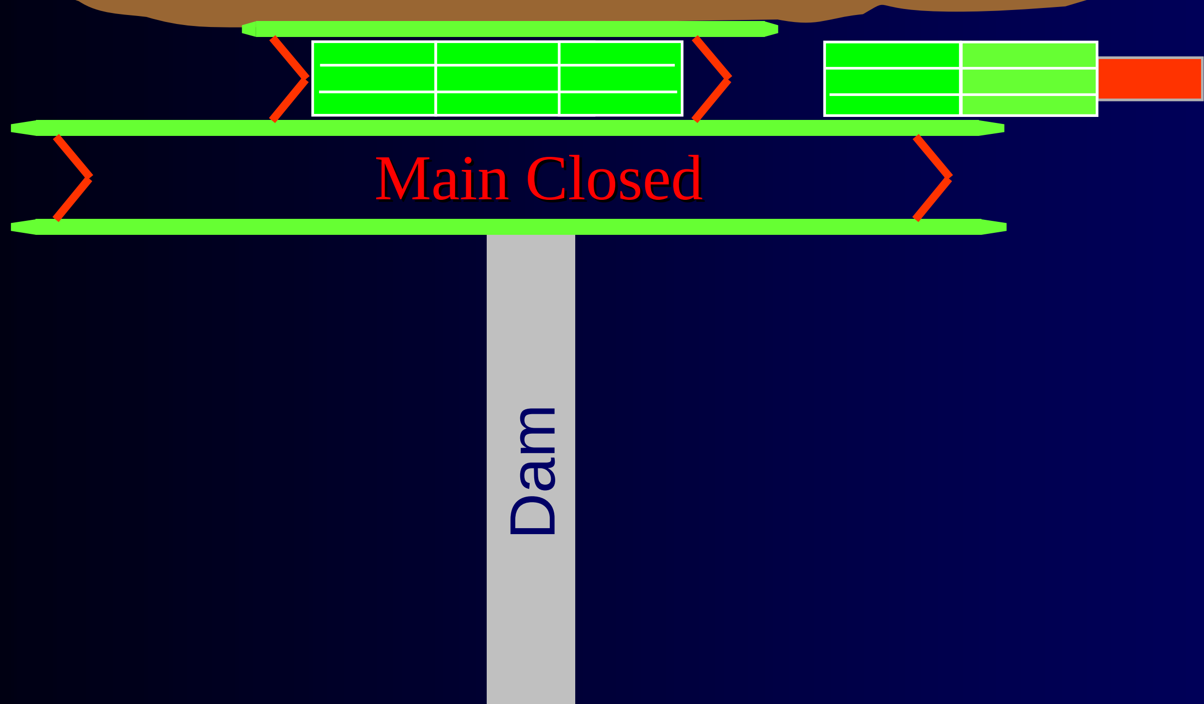
Typical Ohio River Use of Auxiliary Locks

Tow has to "double-cut" to process thru facility. Queue begins to build.



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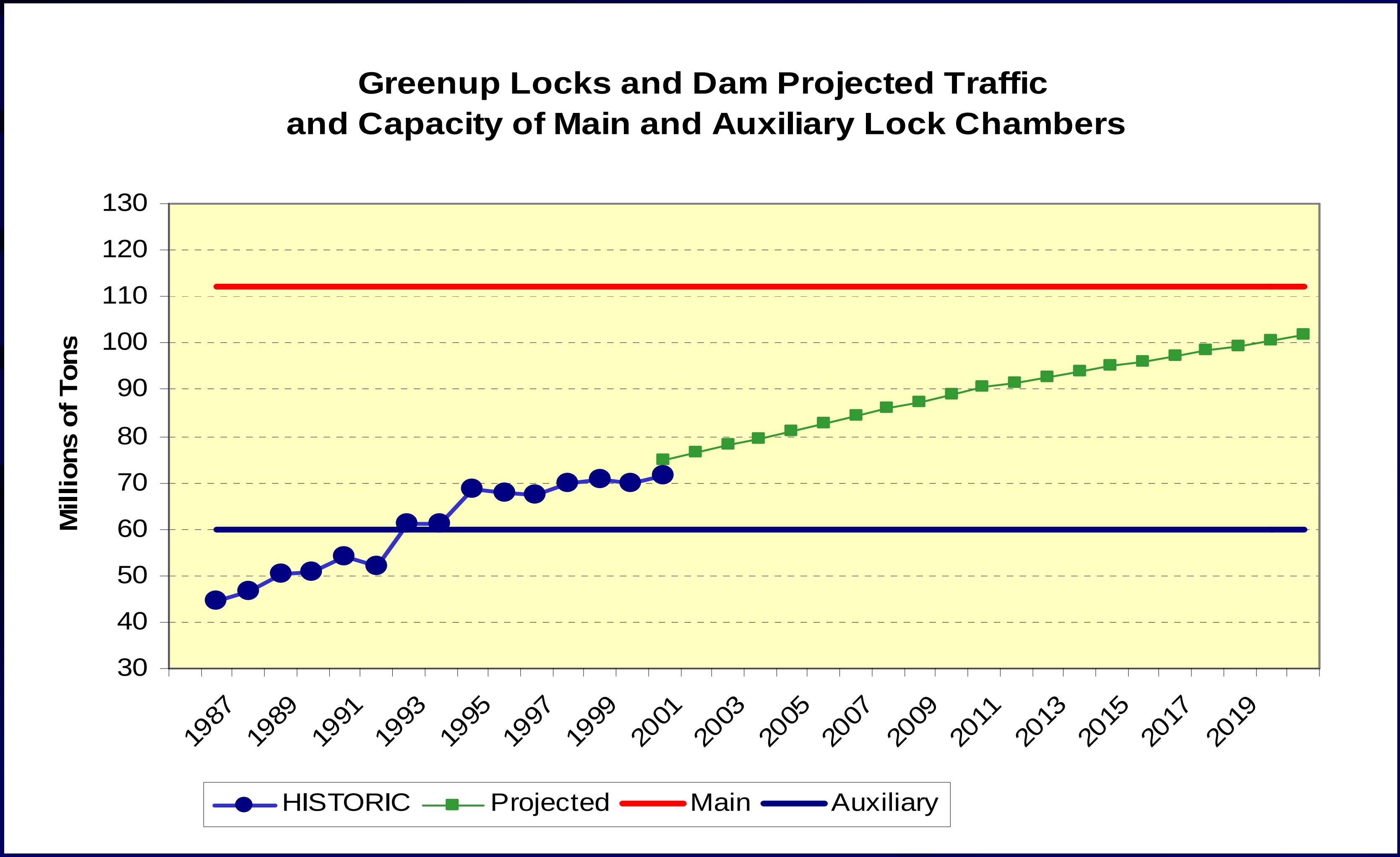
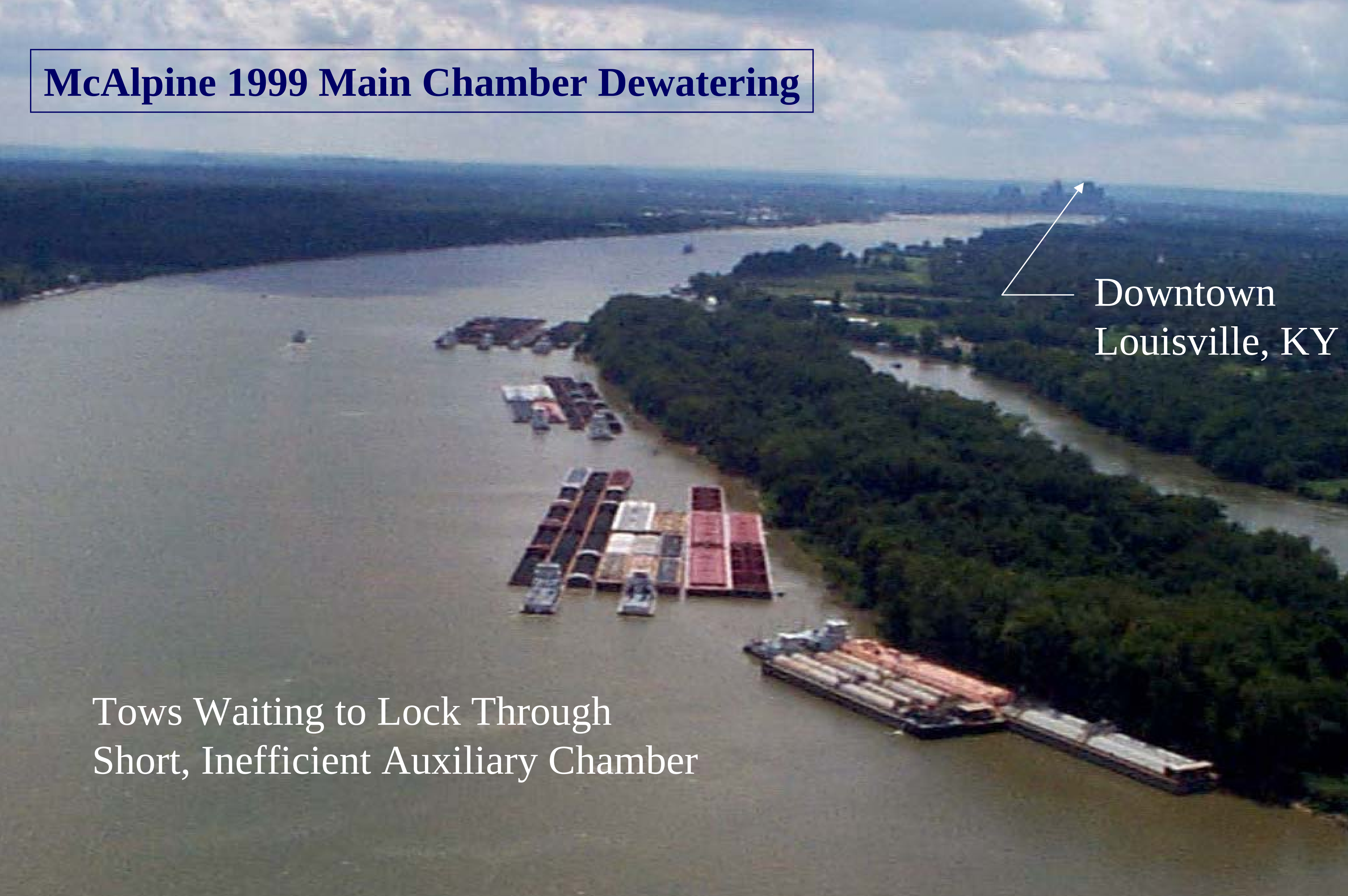
Assessment of Needs
Capacity & Traffic




McAlpine 1999 Main Chamber Dewatering
Downtown
Louisville, KY
Tows Waiting to Lock Through
Short, Inefficient Auxiliary Chamber

Economic Impacts of Main Closures

Event	Duration	Delay $	Repair $	Total $	Peak Delay
McAlpine* April 2005	2 days	1.0 M	Reimbursed by Barge Co	1.0 M	75 hours (3 days)
Greenup** Oct. 2003	52 days	13.2 M	1.5 M	14.8 M	93 hours (4 days)
Markland June 2005	13 days	0.6 M	0.8 M	1.4 M	33 hours
McAlpine Sept. 1999	15 days	3.1 M	0.8 M	3.9 M	86 hours (3 ½ days)

*** McAlpine was unscheduled closure due to a barge impacting a cofferdam at the site. The lock had to be closed for 2 days while emergency repairs were made.**

**** Greenup was partially scheduled. Originally scheduled for 21 days, gate condition required 52 days to make extensive repairs. Additional $30 million in costs to end users also identified.**

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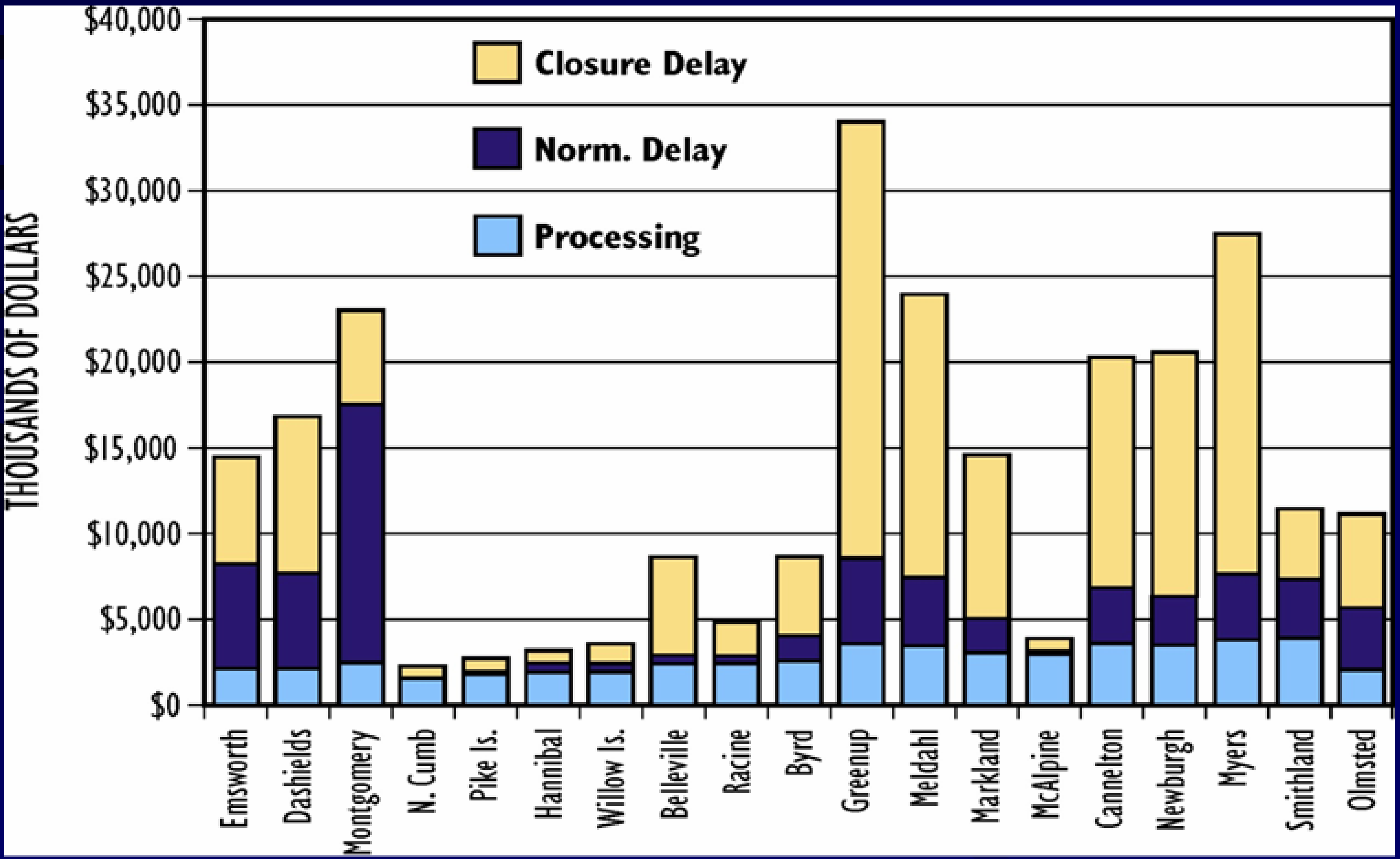
ORMSS Economic Impact

Average Annual Transit Costs by Category

FUTURE CONDITION W/O LARGE-SCALE IMPROVEMENTS



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ORMSS Reliability Integration

Selection of Critical Components

- Two Phase Screening Process Used to Select Components
  - Site Inspections, Interviews, Review of Plans Led to Global List of 170 Components
  - Phase 1 Screening Eliminated Components of Low Consequence (60 Survived)
  - Phase 2 Screening Used a Numerical Rating System (15 Survived)
- 15 Components Required Reliability Modeling
  - Non-Time Dependent Components
  - Time Dependent Components

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ORMSS Reliability Integration

Types of Components

- **Non-Time Dependent Components**
  - Typically Gravity Structures That Do Not Change With Time
  - Analyzed for Multiple Failure Modes
  - Multiple Load Cases
  - Reliability Model Produces PUP’s That Remain Constant

- **Time Dependent Components**
  - Structures That Degrade Over Time
  - Example - Steel Structures Subject to Corrosion and Fatigue
  - Reliability Model Produces Hazard Functions

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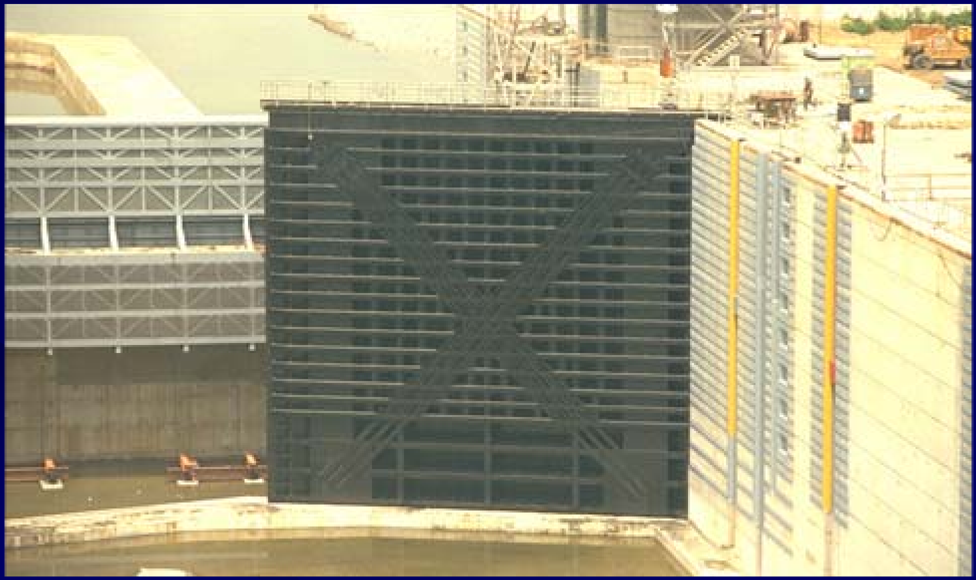
ORMSS Reliability Integration

Non-Time Dependent Components

STABILITY ANALYSIS OF UNANCHORED GRAVITY STRUCTURES

- Land, River, Middle Wall Monoliths
- Guide and Guard Wall Monoliths
- Miter Gate Monoliths
- Miter Gate Sills



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ORMSS Reliability Integration

Non-Time Dependent Components

LOAD CASES

Normal Operating

Maintenance Dewatering

LIMIT STATES

Sliding at the Base

Deep-Seated Sliding

Overturning

Bearing Capacity

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ORMSS Reliability Integration

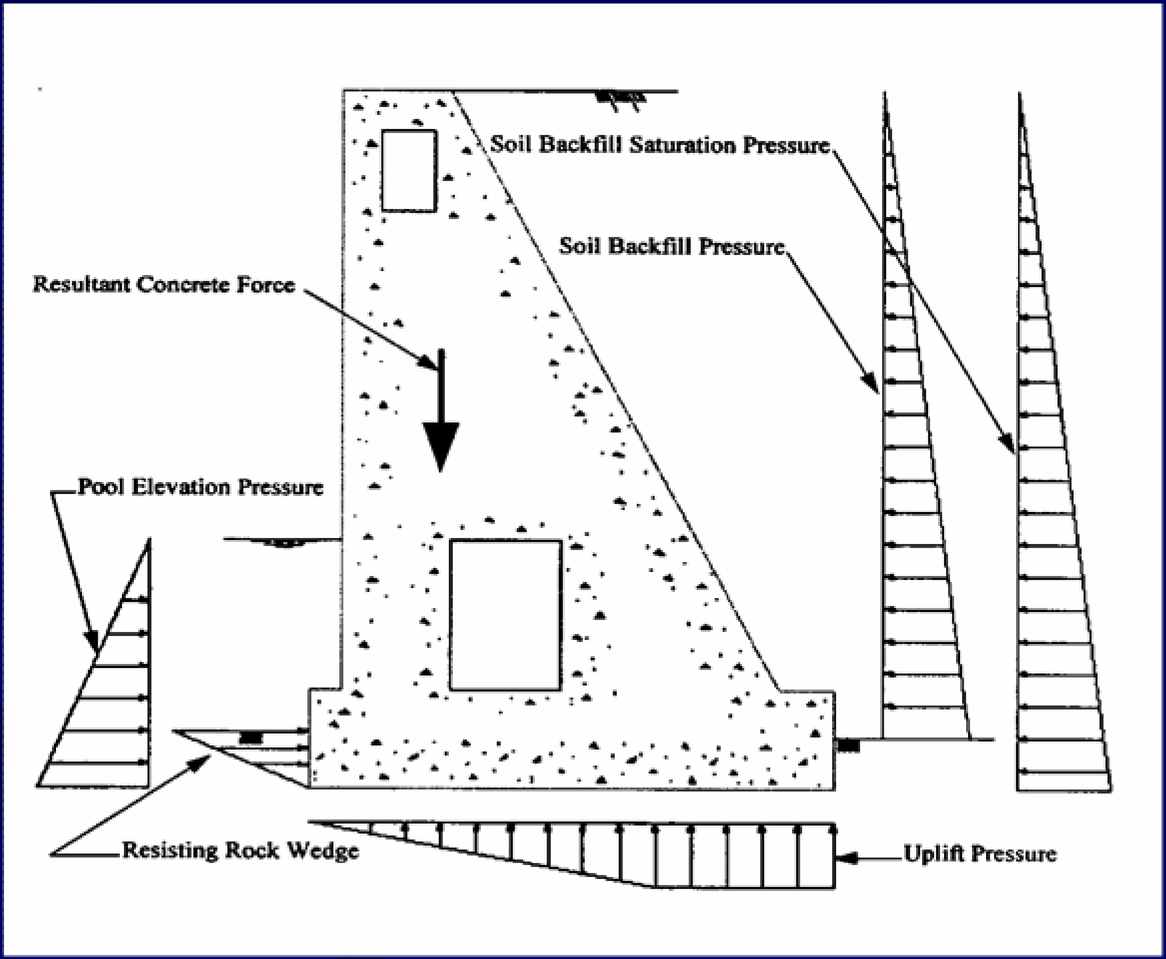
Non-Time Dependent Components

Random Variables

- Lower Pool Elevation
- Soil Unit Weights and Strengths
- Soil Backfill Saturation Level
- Rock Strengths
- Barge Impact Force
- Hawser Force

Constants in Analysis

- Upper Pool Elevation
- Concrete Unit Weight
- Water Unit Weight



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ORMSS Reliability Integration

Non-Time Dependent Model Details

- **10,000 Iterations for Normal Load Case**
  - Monte Carlo Simulation of Random Variables Used
  - @Risk™ Software Used for Simulation
  - Spread Sheets Used for Computations
  - Analysis Produces Single PUP for Normal Load Case
- **10,000 Iterations for Maintenance Case**
  - Lock Chamber Dewatered Every 5 Years On Average
  - Typically Represents Worst Load Case for Lock Wall Stability
  - Analysis Produces Single PUP for Maintenance Load Case
- **Event Tree Formatted for Both Load Cases**

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Time Dependent Components

STRUCTURAL MODELS

HF Miter Gates
VF Miter Gates
Anchored Monoliths
Anchored Sills
HF Culvert Valves
VF Culvert Valves

MECHANICAL/ELECTRICAL

MG Machinery
CV Machinery
Lock Hydraulic
Lock Electrical

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ORMSS Reliability Integration

Establish the Current Condition of Structure

CULVERT VALVE FAILURES

MITER GATE FAILURES

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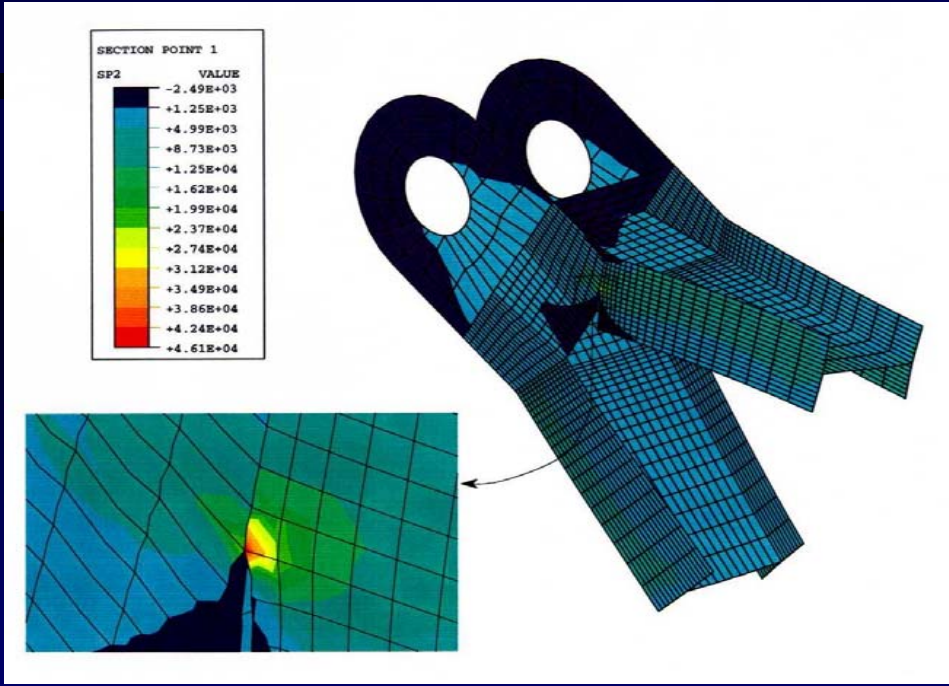
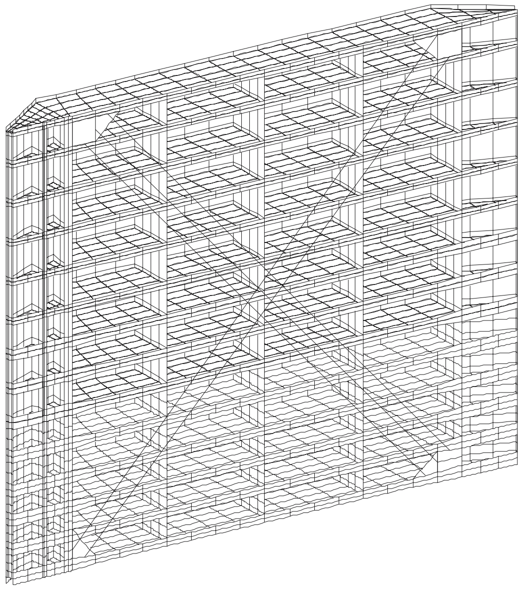
ORMSS Reliability Integration

Advanced Modeling for Realistic Failure Modes

LOCAL F.E. MODELING

- Establishes Residual Stress Distribution
- Crack Initiation and Propagation
- Benchmark with Field Cracking/Measurements





GLOBAL F.E. MODELING

- Load Distribution on Global Structure
- Stress Distribution for Varying Ops
- Determination of Areas of High Stress

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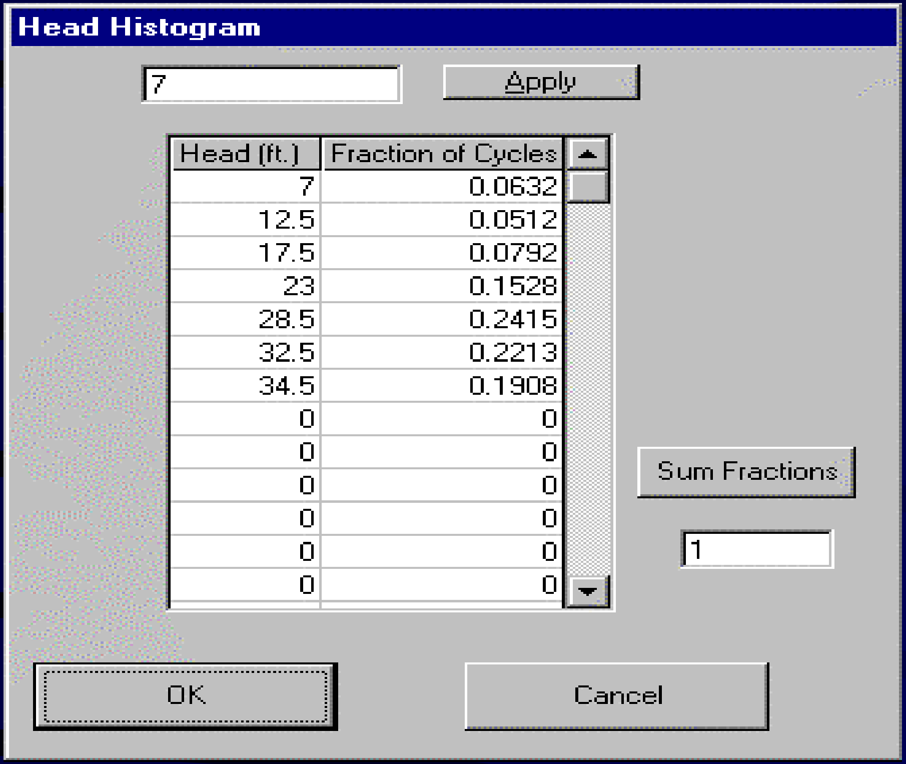
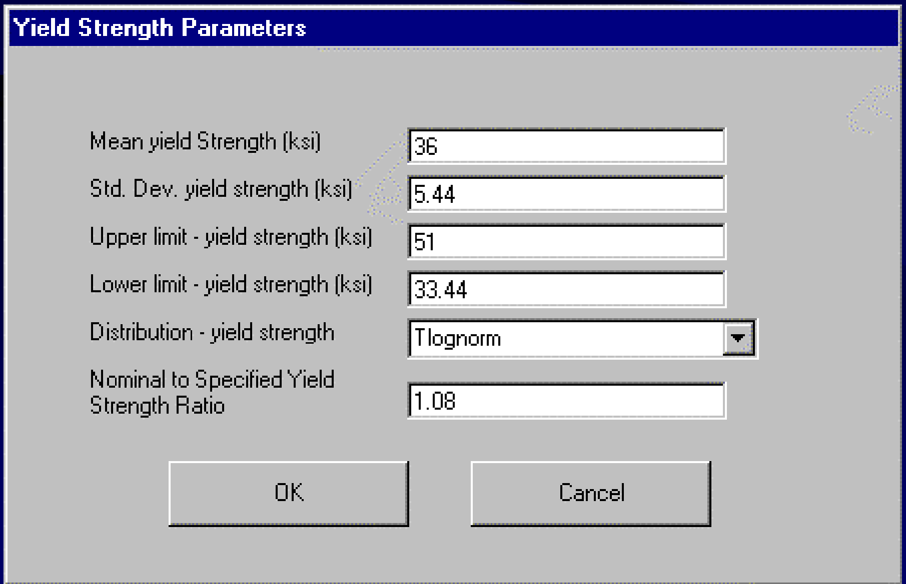
Time Dependent Reliability Modeling

Summary of Model Features

- Miter Gate and Culvert Valve Reliability
  - F.E. Modeling Used as Basis for Reliability Model Input
  - Calibration and Limit State Developed Using F.E. Modeling
  - Custom Coded Reliability Model Developed in Visual Basic
  - Monte Carlo Simulation (Speed Allowed 50,000 Iterations)

- Mechanical and Electrical Models Were Developed using Failure Rates from Established Publications Within MS Excel Spreadsheet





Example HWELD Input Menus

- Miter Gate Properties
  - Girder Spacing, Length
  - Skin Plate Properties
- Girder/stiffener properties
  - Flange, Web Thickness
- Operating Cycles
  - Historic and Projected
- Yield Strength of Steel (Random)
- Corrosion Parameters (Random)
- Stress Concentration Factors (Random)
  - Determined from F.E. Modeling
- Pintle Wear / Misalignment Factor (Random)
  - Determined from F.E. Modeling
- Head Histogram (Acts Random)
  - Determined from LPMS Data
- Maintenance Strategy
  - Fix-As-Fails, Adv. Maintenance, etc.

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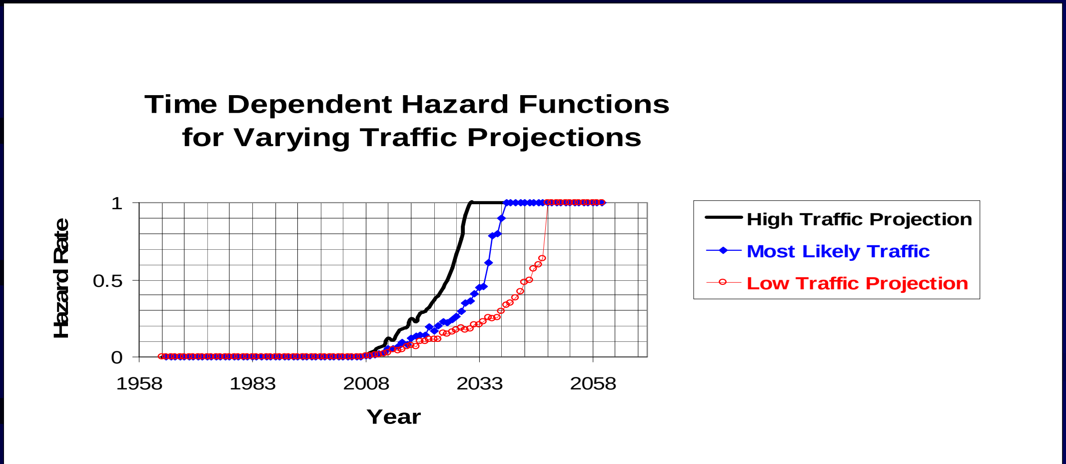
Model Outputs and Integration with Economics



Time dependent probabilities of failure for various alternatives through study period

Component	Annual Hazard Rate	Level of Repair	Closure Time	Repair Cost	Effect on Overall Component Reliability
	Annual Reliability Value (1 - Annual Hazard Rate)				
Horizontally-framed Miter Gate		New Gate 5%	365 days in year 1 90 days in year 2	$13,150,000 $3,150,000	Assume R = 1.0 for All Future Years
	Annual Hazard Rate	Major Repair 35%	45 days in year 1 45 days in year 2	$1,575,000 $1,575,000	Move Back 5 Years
		Temporary Repair 60%	45 days in year 1	$3,575,000	Assume R = 1.0 for All Future Years
		Replace 1st Set of Gates	45 days in year 2	$3,575,000	
		Replace 2nd Set of Gates	30 days in year 3	$5,050,000	

SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION

Year 1 -- 30 Days of Closure @ $5,050,00 Year 2 -- 30 Days of Closure @ $5,050,000

Future Reliability Will Equal 1.0 Throughout Remainder of Study Period

Consequence event tree given the limit state is exceeded in the reliability analysis

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Optimized Timing of Component Replacement

- Economic Model (ORNIM)
  - C+ Model Written to Integrate Engineering & Economics
  - Uses Hazard Rates & Event Tree Information
  - Computes Average Annual Costs Associated with Failures
  - Accounts for Component Repair & Navigation Delay Costs
- Different Alternates Tested Consistent with Formulation
  - Fix-As-Fails Baseline Condition
  - Other Maintenance Scenarios (Advance Maintenance)
  - Scheduled Rehabilitations or New Projects

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Example of Reliability-Based Economic Evaluation

MAIN CHAMBER GATE RESULTS FOR OHIO RIVER LOCK

Scenario	Average Annual Cost
Fix-As-Fails	$8,746,700
Advance Maintenance	$3,728,400
Replace in 2000	$1,603,100
Replace in 2001	$1,566,500
Replace in 2002	$1,531,600
Replace in 2003	$1,509,200
Replace in 2004	$1,491,800
Replace in 2005	$1,494,600
Replace in 2010	$2,195,100
Replace in 2020	$6,275,100

OPTIMUM TIME TO REPLACE

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Greenup Locks – Main Chamber Miter Gates

- **What Did Original Analysis Predict?**
  - ORMSS hazard rates and economic analysis indicated the optimal time to replace main chamber miter gates by 2004 without a major repair to these gates ahead of that time
  - Analysis was completed in 1999 based upon field performance of similar miter gates on Ohio River system and future traffic trends

- **What Actually Happened?**
  - Routine inspection dewatering of Greenup main chamber in fall 2003 planned for 21 days, no significant deterioration expected
  - Significant damage to gates found that emergency repairs required
  - Closure extended to 54 days (cost to industry and power companies estimated to be in $15 to $25 million range). Thus, gates suffered an “economic” failure.

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ORMSS Reliability Integration

Deterioration of Ohio River Miter Gates

Cracking Near Quoin Block

Cracking Through Thrust Plate

Plan Development

Alternatives

- Maintenance Alternatives
  - Fix major components as they fail
  - Plan for major repairs and fix before they fail
- Operational Alternatives
  - Helper boats, schedule arrivals
  - Congestion fees
- New Construction Alternatives
  - Construct new 1200’ lock
  - Extend auxiliary lock so it is 1200’ long

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ORNIM

Ohio River Navigation Investment Model

- Identify Optimal Investment Strategies Considering Probabilistic Analysis of Engineering, Economic, and Environmental Features
  - Multiple maintenance scenarios tied to reliability
  - Effectiveness of various repair scenarios
  - New construction versus sustaining existing system
  - Traffic management

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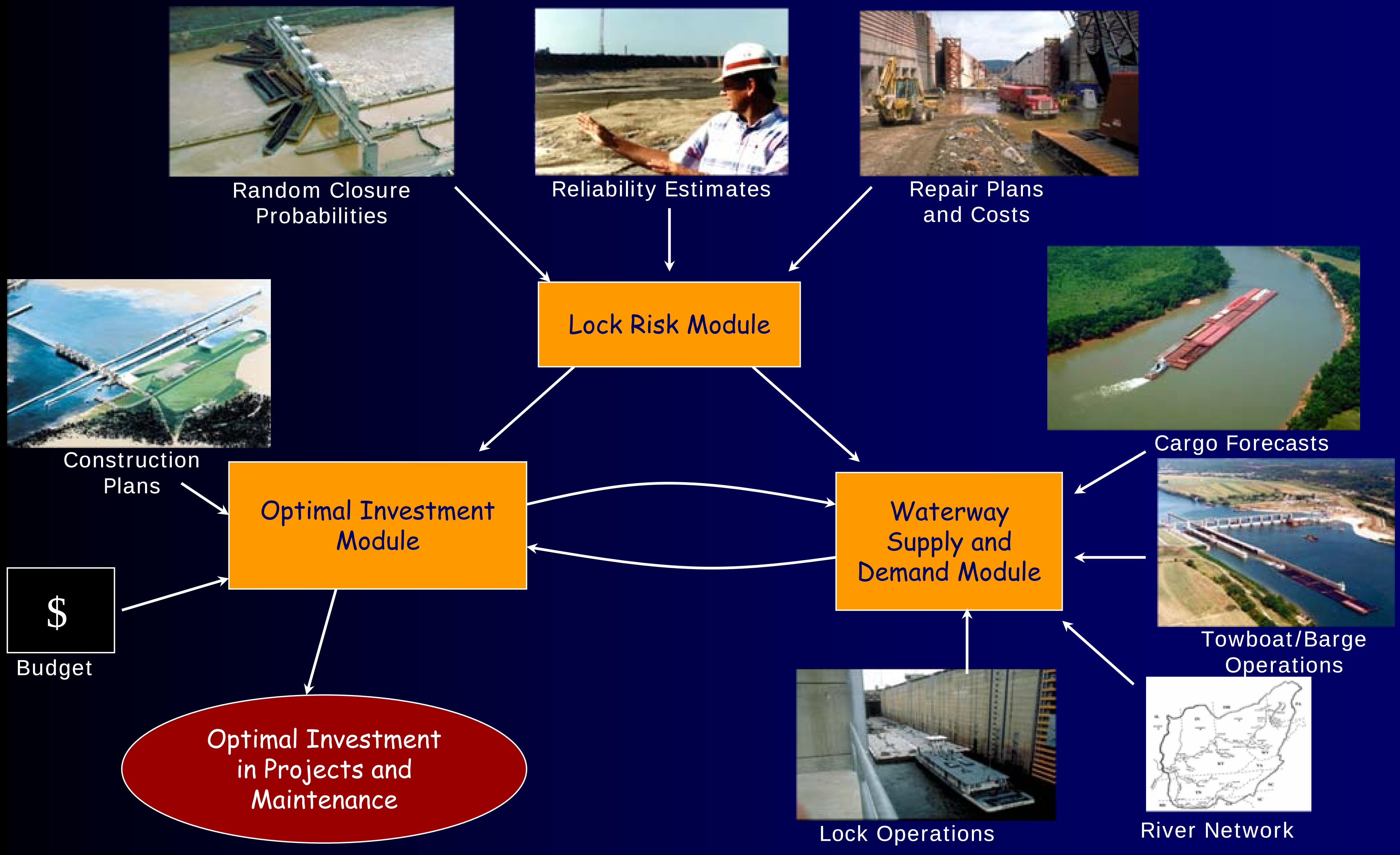
ORNIM

Analysis Capabilities of ORNIM

- System-wide benefits
- Handles engineering reliability
- Tradeoffs among projects over time
- Tradeoffs between new construction, repairs/maintenance, and traffic management
- Multi-year horizon

The ORNIM System



Optimal Investments for Single Component

Main Chamber Miter Gate Replacement

Scenario	Avg. Annual Cost
Current Maintenance	$5,746,700
Aggressive Maintenance	$3,728,400
Replace in 2006	$1,603,100
Replace in 2007	$1,566,500
Replace in 2009	$1,531,600
Replace in 2009	$1,509,200
Replace in 2010	$1,491,800
Replace in 2011	$1,494,600
Replace in 2012	$2,195,100
Replace in 2015	$5,275,100

OPTIMUM TIME TO REPLACE

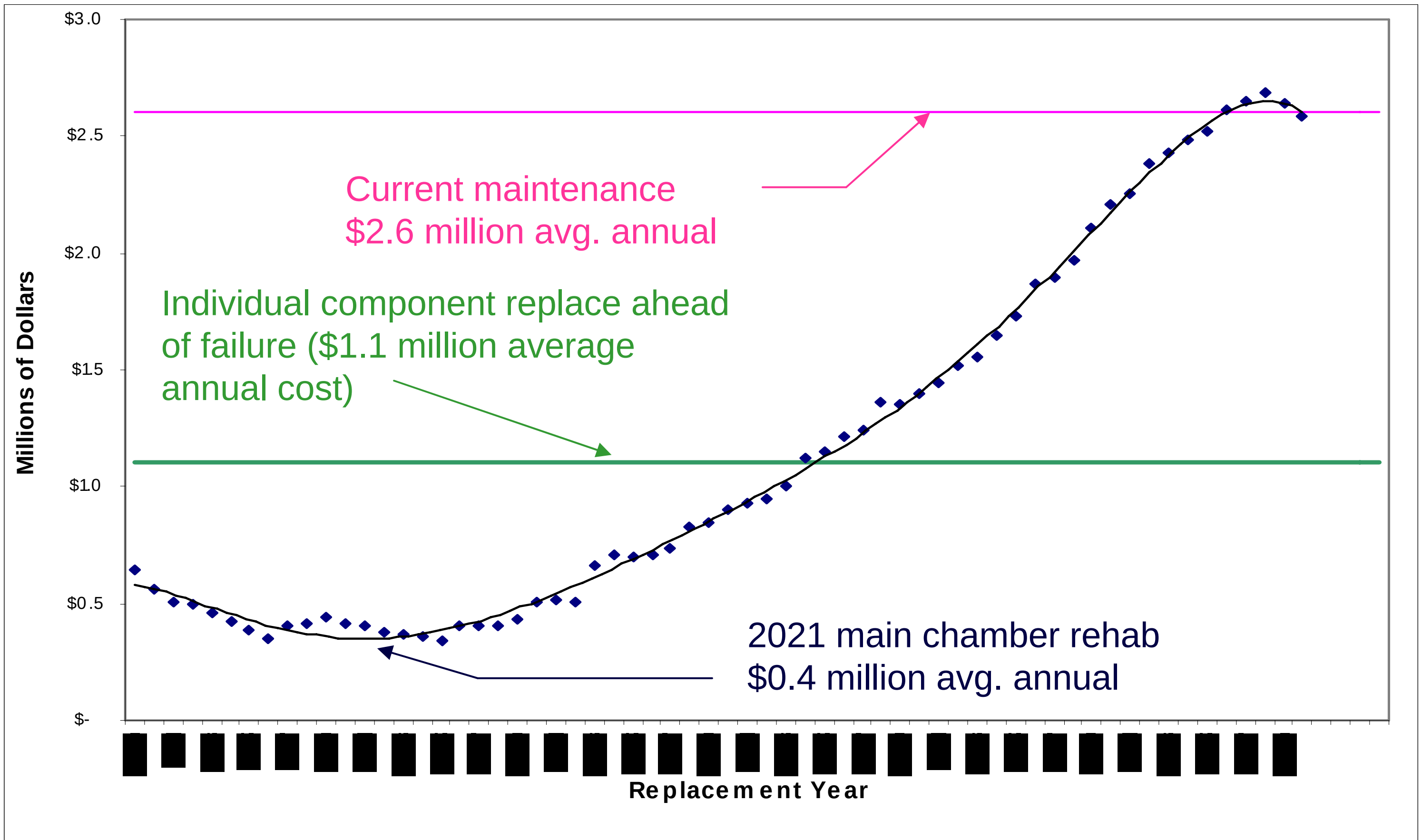
Optimal Replacement Timing

All Critical Components for One Lock Chamber

Feature	Future Traffic 1	Future Traffic 2	Future Traffic 3	Future Traffic 4
Miter Gates	2010	2008	2011	2014
Culvert Valves	2014	2012	2017	2019
Miter Gate Machinery	2020	2019	2018	2020
Hydraulic System	2018	2017	2017	2018
Electrical Controls	2015	2014	2014	2015

<u>*Optimal Replacement Timing*</u>

Major Rehab vs. Individual Components



Optimization of Newburgh Main Chamber Rehab

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Other Recent Applications

- Chickamauga Lock Replacement Study (Nashville)
  - Navigation lock on Tennessee River near Chattanooga
  - Mass concrete deterioration due to AAR
  - Reliability models for AAR-effected monoliths, including critical lower miter gate monolith
- Markland Major Rehabilitation (Louisville)
  - High traffic navigation lock on Ohio River
  - Fatigue and fracture of steel miter gates and culvert valves
  - Rehab approved at HQUSACE in FY00. Awaiting CG funds.

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Studies Spurned from ORMSS

- Great Lakes and St. Lawrence Seaway Study
  - Joint effort between USACE, USDOT, and Transport Canada
  - 18 locks, multiple ports, bridges, and tunnels
  - 4 year study evaluating long-term operation of system considering reliability, maintenance, future traffic trends
- Panama Canal Infrastructure Risk and Reliability Study
  - Phase I proposal being reviewed by ACP
  - Multiple year study looking at long-term reliability for various maintenance scenarios, risks associated with seismic events, flood analysis, and potential 3rd lane alternatives
  - Economic aspects include varying rates, traffic trends, etc…

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THANK YOU

QUESTIONS ???

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