DOE Project DE-FC26-04NT42270: Systematic Engine Uprate Technology Development and Deployment through Increased Torque

“Engine Uprates”

DOE/NETL Project Kickoff
April 21, 2005
Outline

• Executive Summary (Ted)
• Previous Work done with GTI Funds (Dan)
• DOE Year 1 Results To-Date (Dan)
• Planned Research Activities (Dan)
The overall objective of this project is to develop new engine up-rate technologies that will be applicable to a large inventory of existing pipeline compressor units for the purpose of increasing pipeline throughput with the same footprint of existing facilities.

- Increase Output by 10%
- Target Cost ~ $500/HP

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<th>Family</th>
<th>#Units</th>
<th>Total HP</th>
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Objectives by Year

• Year 1: Laboratory Demonstration of Candidate Technologies
  – Demonstrate that the technologies developed during the background research phase to achieve the performance targets under controlled, laboratory conditions and using the Engines and Energy Conversion Laboratory's (EECL's) Clark TLA research engine.

• Year 2 (Phase 2): Demonstration of Optimal Technologies
  – Demonstrate that the technologies tested under phase 1 can migrate to an operating engine in pipeline service with similar, or better, performance and that the durability of the retrofit equipment will be acceptable.
Issues to Keep in Balance

- OEM Business Strategy
  - Dresser-Rand
  - Cooper Compression
- Enabling Technologies
- Air Emissions Permits
- FERC Capacity Certification
Project Team

- Engine Manufacturer, Dresser-Rand (Doug Bird)
- PRCI CAPSTC Project Lead: Ken Gilbert, Dominion Pipeline

Colorado State University PI: Dan Olsen

Guidance from manufacturer perspective

Guidance from user perspective

Reporting

Department of Energy
## Year 1 Project Schedule

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Expenditures

DOE Project DE-FC26-04NT42270
CSU Expenditures of DOE Funds

Cumulative Funds, $

Budgeted
Actual

Months

0 1 2 3 4 5 6 7 8 9 10 11 12
Outline

• Executive Summary
• Previous Work done with GTI Funds
• DOE Year 1 Results To-Date
• Planned Research Activities
Identify Potential Engines: Engine Candidates

Desired Engine Candidate Requirements
• BMEP vs. Quantity

Want to find engines with:
• Low BMEP
• Significant Installed Base
• 2-Stroke
## Identify Potential Engines: Engine Uprates Survey Table

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<th>Manufacturer</th>
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<th>#Units</th>
<th>Total HP</th>
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<th>Cylinder Configurations</th>
<th>Air Delivery</th>
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Identify Potential Engines:
Target Engines

Based upon the engine survey table, the following engines meet the requirements:

• Clark HBA
• Clark TLA
• Cooper-Bessemer GMV series
Technical Considerations: Potential Technologies

- Turbocharger Upgrade or Installation
- High Pressure Fuel Injection
- Micro Pilot Injection
- Pre-Combustion Chambers
- Intercooling
- Piston Crown Re-design
- Exhaust Tuning
Block Diagram

Uprate Strategy

Increase Trapped Air → Increase Fuel Flow → Increase BHP → Emission Reductions

- Increase Boost
- Improved Scavenging
- Mixing Enhancements
- Ignition Improvements
- Exhaust Tuning

- Enhanced Intercooling
- Piston Crown Re-Design
- Water Injection
Projected Reduction In NOx After Uprating Methods

B.S. NOx vs Load

- MGAV @ 7.5"
- HPFI @ 7.5"
- HPFI @ 12"
- Adv. Ign. Sys. @ 16"

Overall Reduction in NOx

Turbo Upgrade
MGAV -> HPFI
Increased Load
Final Operating Point

Projected Reduction In NOx After Uprating Methods
Projected Fuel Savings with Uprating Methods

Brake Specific Fuel Consumption

- MGAV @ 7.5" 440 bhp
- HPFI @ 7.5" 440 bhp
- Adv. Ign. Sys. @ 12" 440 bhp
- Adv. Ign. Sys. @ 16" 440 bhp
- Adv. Ign. Sys. @ 20" 440 bhp
- Adv. Ign. Sys. @ 16" 484 bhp

Potential Fuel Savings After Increased Boost & Load
The Effect of Combustion Stabilization

Potential increase in average peak pressure without increasing maximum peak pressure

Combustion stabilization through enhanced ignition
Micro Pilot Ignition System

Using a micro-liter quantity of a compression ignitable pilot fuel as the ignition source
Micro Pilot Ignition System

Success with Cooper-Bessemer GMV

- No Misfires
- Lower THC
- Lower BSFC
- Achieved <1% pilot fuel energy
- Worked with stock compression ratio
Micro Pilot Ignition System

Misfire Elimination

Load (%)

Misfires (%)

Pilot Ignition

Spark Ignition

φ = 0.85
φ = 0.85
φ = 0.78
φ = 0.78
φ = 0.73
φ = 0.73
φ = 0.71
φ = 0.67
φ = 0.67
φ = 0.67
φ = 0.67
Micro Pilot Ignition System

THC Reduction

Load (%)

Spark Ignition

Pilot Ignition

THC (g/hp-hr)

φ = 0.85

φ = 0.85

φ = 0.78

φ = 0.78

φ = 0.73

φ = 0.73

φ = 0.71

φ = 0.67
Micro Pilot Ignition System

BSFC Reduction

Load (%)

7000 7500 8000 8500 9000 9500

BSFC (BTU/hp-hr)

Spark Ignition

Pilot Ignition

φ = 0.85
φ = 0.78
φ = 0.73
φ = 0.67

0.8% Pilot

Engines and Energy Conversion Laboratory
Currently, key components are provided by Woodward and Delphi.
Micro Pilot Ignition System

The current injectors used will work better for the Clark engine than for the GMV Micro Pilot Ignition System. Impinging Sprays were shown to reduce pilot fuel quantity with custom fuel injector testing.
Clark TLA Piston Crown
Re-Design Example
Clark TLA Exhaust Tuning Example

- Developed using **Ricardo WAVE**
  - Engine simulation software
  - Models compressible flow effects (1-D)
  - Computes emissions
  - 2-zone combustion model
- Engine is first modeled under nominal operating conditions, matching efficiency, cylinder pressure profile, NOx emissions, and other parameters
- Manifold is optimized using 7 variable Design of Experiments technique, adapted for this application
Tuned Exhaust Manifold for Clark TLA Engine

Original Exhaust Manifold

New Exhaust Manifold Design
Tuned Exhaust Manifold for Clark TLA Engine
### Tuned Exhaust Results

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<td>8.45</td>
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- The first optimized case produced NO$_x$ reduction of 34%
- The modified optimized case produced NO$_x$ reduction of 17.3%
CFD Modeling of D-R Research Engine, K5X
Cost Analysis

- Project target cost was to achieve <25% of new unit cost
- New unit (engine & compressor) with installation is estimated at $2,000/HP
- Cost reductions are thought to be attainable by use of a single installation contractor (example assumed three separate contractors)

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<th>Cost for 500 BHP (25%) Increase</th>
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EECL’s Clark TLA Engine – Donated by Dresser-Rand

- Currently being modified from 3-cylinder to 6-cylinder configuration
## Engine Specific Uprate Strategy

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<th>Enhanced Mixing</th>
<th>Improved Air Delivery</th>
<th>Improved Ignition</th>
<th>Exhaust Tuning</th>
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<td>BA</td>
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<td>HPFI TC</td>
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**Note:**
1. If CR > 8.5:1 Then pilot injection
2. If CR < 8.5:1 Then PCC's

**TC = Turbocharger**
Industry Involvement

• Dresser-Rand support – TLA engine donation, engineering drawings, and commitment for some conversion parts
• Altronic, Enginuity, and Hoerbiger commitment for hardware support/donations
• Industry personnel assistance – interviews, documentation, etc.
Industry Experience (Summary)

- Large bore NG 2-stroke engines are believed to have large safety factors.
- Field data demonstrates safe operation at greater than 100% load.
- Many of the large bore NG 2-stroke engines capable of increased speeds and loads without structural modifications.
- No increase in failures noted for these engines.
Industry Experience (Interviews)

Chevron-Texaco - Clark RA Series

- Power Cylinder Porting Change
- New Heads & Pistons
- Scavenging Air Elbow
- No Turbo Upgrade
- 110% of Rated Load
- Ran Better, No Increased Failure Rates
SoCal Gas – Clark TLA-6 (7)

- Installed ABB Marine Turbocharger (19” Hg Boost)
- Intercooler w/ Wet Cooling Tower – Intake Air Temp. of 97°F
- Peak Pressure Balance w/ Std. Dev. < 30 psi.
- 115% of Rated Load Since 1958 w/ No Increase in Failure Rates or Maintenance
Williams Pipeline – Clark TLA-6 (12)

- Std. Turbocharger
- Intercooler Upgrade w/ Cooling Towers
- 105% of Rated Load for 20 yrs w/ No Increase in Failure Rates
Industry Experience

Terry Smith – Industry Field Repair Expert

• Reviewed TLA-6 crankcase and upper block solid models
• Provided feedback on common TLA-6 failure modes and locations
• Will provide similar input for GMV and HBA engines
• Memo from Clark to Texaco (1959) communicated results from a vibration analysis for an RA-6.

• Results indicated a resonant frequency exists at 340-350 RPM with a 7° amplitude.

• Clark recommended a max. speed of 320 RPM or flywheel modifications.
OEM Communications

- Report from Cooper-Bessemer to Texaco (1989) regarding increasing speeds of GMV-6 (3) and GMVL-6 (1).
- Increased speed from 300 – 330 RPM.
- Balance study indicated that one of the GMV-6 engines needed to have additional reciprocating weight added.
Increasing torque, not speed, can avoid approaching critical speeds.

Industry data supports the conclusion that the engines have a large factor of safety, which will allow for the safe operation at the increased loads.

Improved air delivery has long been demonstrated to reduce fuel consumption and emissions through leaner operation.
GTI Project Conclusions (2/2)

- Enhanced mixing can help reduce emissions, increase combustion stability, extend the lean limit, and decrease fuel consumption.
- Improved ignition techniques can reduce emissions, improve combustion stability, extend the lean limit, and decrease fuel consumption.
- HPFI, micro pilot ignition, and increased boost are proven technologies and are planned for implementation in Year 1 of the DOE program.
- Exhaust tuning benefits are engine specific and would have to be analyzed for each case.
# Year 1 Project Schedule

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<th>J 05</th>
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- 1.1 Research Management Plan: complete
- 1.2 Technology Assessment: complete
Outline

• Executive Summary
• Previous Work done with GTI Funds
• DOE Year 1 Results To-Date
• Planned Research Activities
### Task 1.2: Technology Assessment Summary Table

<table>
<thead>
<tr>
<th>ENGINE MODEL</th>
<th>BA, HBA, HLA</th>
<th>TLA</th>
<th>KVG</th>
<th>KVS</th>
<th>GMV, GMVA</th>
<th>GMW, GMWA</th>
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</thead>
<tbody>
<tr>
<td>(Percent of Overall Fleet)</td>
<td>(7.5)</td>
<td>(7.1)</td>
<td>(3.1)</td>
<td>(4.4)</td>
<td>(5.1)</td>
<td>(9.3)</td>
</tr>
</tbody>
</table>

**UPRATE TECHNOLOGY**

- **Indicates Uprate Technology is applicable to engine model (subject to change per study)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>BA, HBA, HLA</th>
<th>TLA</th>
<th>KVG</th>
<th>KVS</th>
<th>GMV, GMVA</th>
<th>GMW, GMWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo Installation/ Upgrade</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
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</tbody>
</table>
- **Pro:** Can help reduce emissions, increase engine output and extend the lean limit.
- **Con:** May not be economical for units <1,500 HP

| High Pressure Fuel Injection | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Pro: Can extend the lean limit, increase combustion stability, and reduce emissions. Commercially available. | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Con: May require turbo to gain full benefits |

| Pre-Combustion Chamber | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Pro: Commercially available, extends the lean limit and increases combustion stability. | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Con: May require turbo to gain full benefits |

| Pilot Fuel Ignition | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Pro: Eliminates spark plugs, increases combustion stability, and reduction of emissions. Applicable to low-BMEP, non-turbocharged engines. | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Con: Require second fuel source. Commercialization efforts needed. |
Task 1.3: Optical Engine (1/15):
Description
Task 1.3: Optical Engine (2/15): PLIF Imaging Setup
Task 1.3: Optical Engine (3/15): CFD Validation

CFD – PLIF Comparison

Piston

Fuel jet (yellow) recirculation in cylinder volume near TDC

CFD – PLIF Comparison

Fuel Jet

Fuel jet (red, yellow) interaction with scavenging flow and piston top
Task 1.3: Optical Engine (4/15): Clark TLA CFD Analysis

- Optical engine has 14” bore; TLA has 17” bore
- Not practical to modify for larger bore
- Performed mixing studies using CFD, previously validated with optical engine results
  - Case #1 - OEM TLA with standard mixing model
  - Case #2 - TLA with enhanced mixing model and OEM piston
  - Case #3 - TLA with enhanced mixing model with modified crown piston
Task 1.3: Optical Engine (5/15): CFD Flow Field @ IGNITION
Task 1.3: Optical Engine (7/15): CFD Flame Propagation & Fuel Consumption
Task 1.3: Optical Engine (8/15): CFD Flame Propagation & Fuel Consumption
Task 1.3: Optical Engine (9/15): CFD Temperature & NO
Task 1.3: Optical Engine (10/15): CFD Temperature & NO
Task 1.3: Optical Engine (11/15): Mixing Comparison

120° BTDC
Nominal TLA

110° BTDC
HPFI

100° BTDC
HPFI w/ modified piston

90° BTDC
Task 1.3: Optical Engine (12/15): Mixing Comparison

80° BTDC
Nominal TLA
HPFI
HPFI w/ modified piston

70° BTDC

60° BTDC

50° BTDC
Task 1.3: Optical Engine (13/15): Mixing Comparison

Nominal TLA

HPFI

HPFI w/ modified piston
Task 1.3: Optical Engine (14/15)

- CFD work provides required information on mixing
- To examine micropilot ignition, utilize combustion test chamber (CTC)
- CTC will allow imaging of pilot injection with new injectors prior to engine testing
Task 1.3: Optical Engine (15/15): Combustion Test Chamber
• Request for OEM components has been submitted to Dresser-Rand
• Hoerbiger and Enginiuity have offered to provide high pressure fuel injection systems
• Enginiuity is donating an Impact cylinder pressure monitoring system
• Altronic is donating CPU 2000 spark ignition system with add-on module for micropilot injection control
Task 1.4: Component Procurement & Fabrication (2/15): Modal and Dynamic Stress Analysis

- Modal analysis (Pro Mechanica) performed to assess possibility of utilizing speed increases
- Stress analysis performed to examine effects of increasing torque
- Dynamic forces accounted for by utilizing Working Model and simulation feature in Pro Mechanica
- High stress locations identified using Finite Element Analysis
Task 1.4: Component Procurement & Fabrication (3/15):
TLA Crankshaft Modal Analysis

- Added ‘mass’ (lobes) to crankshaft to simulate piston/connecting rod weight.
- Constrained bearing at non-flywheel end to 1 rotational DOF, all other bearing supports to 1 rotational and 1 translational DOF.
- Modal Analysis results indicate the first resonant frequency occurs at 34Hz (2040RPM).
  - The 5th, 6th, and 7th order critical speeds are 408, 340, and 291 RPM, respectively.
Task 1.4: Component Procurement & Fabrication (4/15): TLA-6 Stress Analysis

- Given the forces of the power and compressor pistons, the frame stresses are examined.
- The frame stresses of standard TLA configuration are compared to the frame stresses of the uprated TLA configuration.

GMV crankcase
Superior crankcase (Reynolds-French)
Task 1.4: Component Procurement & Fabrication (5/15):
TLA-6 Dynamic Analysis

• Developed dynamic model using Working Model 2D software
• Determined dynamic forces on crankshaft bearings
• These forces used as the loading forces for the crankcase FEA modeling
Task 1.4: Component Procurement & Fabrication (6/15): TLA-6 Dynamic Analysis
Task 1.4: Component Procurement & Fabrication (7/15): TLA-6 Dynamic Stress Analysis

- Motion added to Pro/E solid model using Pro/Mechanica’s Motion capability.
Task 1.4: Component Procurement & Fabrication (8/15):
TLA-6 Dynamic Stress Analysis

- Pro/Mechanism are used to determine the dynamic forces on crankshaft bearings
- These forces are compared to the Working Model simulation results and incorporated into the FEA stress modeling

..\..\..\..\General Lab\Movies and Simulations\TLA6_W_COMPR_VER4.
Task 1.4: Component Procurement & Fabrication (9/15):
TLA-6 Static Stress Analysis

• TLA Crankcase with bearing surfaces and block stud locations highlighted

• Simplified TLA Crankcase
• Meshed for Finite Element Analysis (FEA)
Task 1.4: Component Procurement & Fabrication (10/15): TLA-6 Static Stress Analysis

- TLA Crankcase with initial bearing loading conditions (from dynamic modeling)
- Loading conditions are based upon single cylinder at peak pressure (18° ATDC)
- Six cases evaluated, one case for each power cylinder at peak pressure
Task 1.4: Component Procurement & Fabrication (11/15):
TLA-6 Stress Analysis Results

- Most common locations of high stress
- Stress conc. factors could be artificially elevated due to ‘ideal’ nature of model
- Max. FEA stress results are ~22ksi - compression
- Class 30 gray cast iron has $S_{UC} = 109\text{ksi}$
Task 1.4: Component Procurement & Fabrication (12/15): Frame Stress Model Verification

- Stress models are being duplicated for the EECL’s Cooper-Bessemer GMV-4
- The results from the stress models are to be verified against measured frame stresses on the GMV-4
- Strain gages (donated by Kistler) will be attached to the crankcase
- High stress locations will be determined by analyzing the FEA modeling results
Task 1.4: Component Procurement & Fabrication (13/15): Frame Stress Model Verification

- Rosette strain gages will be used
- Purchased Omega strain gage signal conditioning system
- Will integrate with the EECL’s existing networkable data acquisition hardware
Task 1.4: Component Procurement & Fabrication (14/15):
Future Analysis Efforts

- The frame stress analysis process is to be applied to other candidate engines
- Analysis on other candidate engines planned:
  - Clark HBA Series
  - Cooper-Bessemer GMV Series
Task 1.4: Component Procurement & Fabrication (15/15): Preliminary Conclusions

- Uprating may be successfully accomplished by a combination of increased torque and speed
- Modal analysis results indicate critical operating speeds are above targeted operating speeds
- Modal analysis results fit within reasonable range of historical resonant speeds of other similar engines
- Frame stress analysis predictions indicate a 10% to 15% increase in frame stresses with a 20% increase in engine power
- Frame stress results indicate a negligible reduction in factor of safety (TLA-6)
- Frame stress modeling still needs to be validated
## Task 1.5: System Test Plan

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<thead>
<tr>
<th>Configuration</th>
<th>Operating Conditions</th>
<th>Measures</th>
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<td>Stock</td>
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<td>Std. Temperatures, Pressures, Combustion Stats., HAPS, &amp; Criteria Pollutants</td>
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<tr>
<td>Enhanced Mixing</td>
<td>Equivalence Ratio Map, Speed Map</td>
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<tr>
<td>Enhanced Mixing and Ignition</td>
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<tr>
<td>Optimal Control Methodology</td>
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<tr>
<td>Uprated</td>
<td>Variation of Load &amp; Speed (up to 20% BHP ↑)</td>
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</tbody>
</table>
Outline

• Executive Summary
• Previous Work done with GTI Funds
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Task 1.4: Component Procurement & Fabrication

- Engine Manufacturer, Dresser-Rand (Doug Bird)
- PRCI CAPSTC Project Lead: Ken Gilbert, Dominion Pipeline

Guidance from manufacturer perspective

Colorado State University PI: Dan Olsen

Guidance from user perspective

Reporting

Department of Energy
Task 1.4: Component Procurement & Fabrication: Advanced Controls

- National Instruments Field Point Unit 1
- National Instruments Field Point Unit 2
- CPU 2000
- Output Module
- Diagnostics Module
- Impact System
- GOV - 10
- Control Valve
- Ethernet Hub
- RS-485/232 to Ethernet

Components:
- Diesel PILOT Injection
- Hyper Fuel
- Output Module
- TDC Clock
- Output Module
- Fuel Valves
- Output Module
- DPI Injectors
- Clock
- TDC Clock
- Up-rated Technology

Networks:
- Ethernet Hub
- RS-485
- Impact System

Pressure Sensors:
- PP, SDPP, LPP, SDLPP

Other Components:
- RS-485
- 3 Cylinder Pressure
- Hyper Fuel CPU 2000
- Output Module
- Diagnostics Module
- Control Valve
- GOV - 10
- TDC Clock
- Output Module
- Fuel Valves
- Output Module
- DPI Injectors
- Clock
- TDC Clock
- Up-rated Technology

Engines and Energy Conversion Laboratory
Colorado State University
Knowledge to Go Places
Task 1.4: Component Procurement & Fabrication:

- Bi-weekly conference calls with CSU, Dresser-Rand, and Dominion
- Report on project at PRCI CAPSTC, May 10-12 in San Diego; will get input from entire committee
- Planned on-site focus meeting at D-R in Painted Post, NY – May 19
- At meeting will select technology develop technology commercialization plan
Task 1.4: Component Procurement & Fabrication:

Candidate Technologies for D-R Commercialization

Tuned Exhaust Manifold

Inwardly Opening Supersonic Mechanical Fuel Valve
Task 1.5: System Test Plan

• Expand simplified test plan presented earlier
• Detailed plan will include specific operating conditions, list of measured parameters, and list of test points
Task 1.6: Uprate Systems Installation

- Installation of uprate systems will begin once hardware is delivered.
- Installation will be performed by CSU personnel with direction from manufacturers.
Task 1.7: Uprate System Test

- Testing will commence once uprate systems are installed
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