Industrial Advanced Turbine Systems Program Overview[1]

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Introduction

Early in this decade, the U.S. Department of Energy (DOE) recognized the fact that gas turbines were playing an ever-expanding role in the power generation industry. Despite the fact that such machines have been in existence for more than 50 years, their improvements in efficiency, emissions, cost and reliability have been largely incremental, having typically followed improvements in materials and other enabling technologies. In response to this dichotomy, DOE initiated the four phase Advanced Turbine Systems program in 1990 and chartered the program with the following goals relative to then state-of-the-art industrial turbine products:

- 10% improvement in busbar cost of electricity.
- 15% improvement in efficiency.
- Single-digit NOx emissions.
- Reliability equal to or greater than currently available products.

Now, more than 8 years into the future, the development program undertaken by this unprecedented public-private partnership is entering its fourth and final phase. The design phase of the program is behind us and the comprehensive field evaluation phase of Solar Turbines' ATS program is now well underway and will continue for the next year. With one field evaluation machine in operation and 5 more scheduled to follow in short order, we will address the status of the Solar's Mercury 50 program and its progress vs. the four fundamental goals that were set forth more than 8 years ago.

The Mercury 50™ was introduced to the public in December 1997 at the ASME Turbomachinery symposium in Orlando, Florida as a single shaft, optimized recuperated engine, nominally sized at 4.3 MWe with better than 40% efficiency at the busbar. This environmentally superior system incorporates a highly flexible combustion system that can be configured for either ultra-lean premixed or catalytic combustion. The Mercury 50™ is targeted to meet the rapidly expanding demand for highly efficient, environmentally superior turbine-based power systems in the industrial power generation and emerging distributed generation markets.

Development Efforts

Formal development of the Mercury 50™ began in September 1995 and emphasized the use of system-level design solutions that take advantage of a wide variety of demonstrated technological advancements, each providing sufficient margin to assure the superior durability and availability that are required by industrial gas turbine users. A combination of innovative

[1] Research sponsored by the U.S. Department of Energy's Federal Energy Technology Center, under contract DE-FC21-95MC31173 and the Chicago Operations Office, under contract DE-AC02-92CE40960 with Solar Turbines Incorporated, 2200 Pacific Highway, P.O. Box 85376, San Diego CA 92186-5376.

primary and backup design solutions have been carefully blended to offer maximum cycle efficiency and emissions reductions with minimal risk, as adequate design margin is maintained within each selected technology. The materials used in the manufacture of the Mercury 50™ turbine are a key element in the durability equation and represent a mix of current turbine materials as well as next-generation alloys that are relatively new to industrial turbines. One of the most significant Mercury 50™ innovations is the layout of the core engine, around which the package has been synergistically designed. The resulting design offers significant advantages in terms of cost, performance and maintainability and is central to its ability to meet the key product goals stated at the beginning of the program.

Solar's Mercury 50™ engineering design activities were concluded in July 1998. The engine test phase of the program commenced in December 1998 to evaluate the performance and durability capabilities of this unique engine prior to the commencement of field evaluation tests. The fourth and final industrial system demonstration phase of the program begins in December 1999 and will be marked by startup of the DOE Host Site demonstration machine at Rochelle Municipal Utilities. This machine is scheduled to run for 8,000 hours, during which time it will demonstrate its capability to meet the four fundamental goals of the program. As a precursor to this milestone event, evaluation of an early pre-commercial version of the Mercury 50 began in September of 1999, coincident with startup of the machine at a remote mining site in Australia.

Summary

Solar's Mercury 50™ is the culmination of a development effort that has been more than 8 years in the making and represents a revolutionary approach in an industry that has long depended upon evolutionary solutions. It has been designed to offer superior performance and operating flexibility at a price that is competitive with alternative power generating technologies. It represents a balanced approach to the tradeoff between the benefits of new technology, low cost and high reliability that is targeted directly at the needs of the industrial power generation marketplace. This report highlights Solar's ATS program progress over the past year and will discuss the design activities, test results and field evaluation preparations along with a brief overview of future plans, commercialization efforts and marketplace activities.

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Dave Esbeck

Vice President, Engineering

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Program Sponsorship

ATS Program Management
DOE Office of Industrial Technology

- Chicago Operations Office
  - Steve Waslo - Contracting Officer's Technical Representative
- Washington Headquarters
  - Denise Swink - Deputy Assistant Secretary, Industrial Technology
  - William Parks - Director, Cross-Cutting Technologies
  - Patricia Hoffman - ATS Program Manager
- FETC - Morgantown
  - Mary Gabrielle - Contracting Officer

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Introduction

- Introduction & Overview — *Dave Esbeck*
- Review of Accomplishments — *Steve Gates*
  - Mercury Engine Design
  - 2nd Generation Hardware
  - Package Design
  - Summary of Test Results
- Commercialization Activities
  - Overview
- Update - Rochelle Site Preparations — *Mr. Ray Schwartz, Rochelle Municipal Utilities*

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Mercury 50 Layout

- Industrial Single-Shaft Generator Set
- Optimized Recuperated Cycle
- Modular Construction
  - 10-Stage Axial Compressor
  - 2-Stage Axial Turbine
  - Annular Combustor
- 4.2 MWe
- 40% Busbar Efficiency

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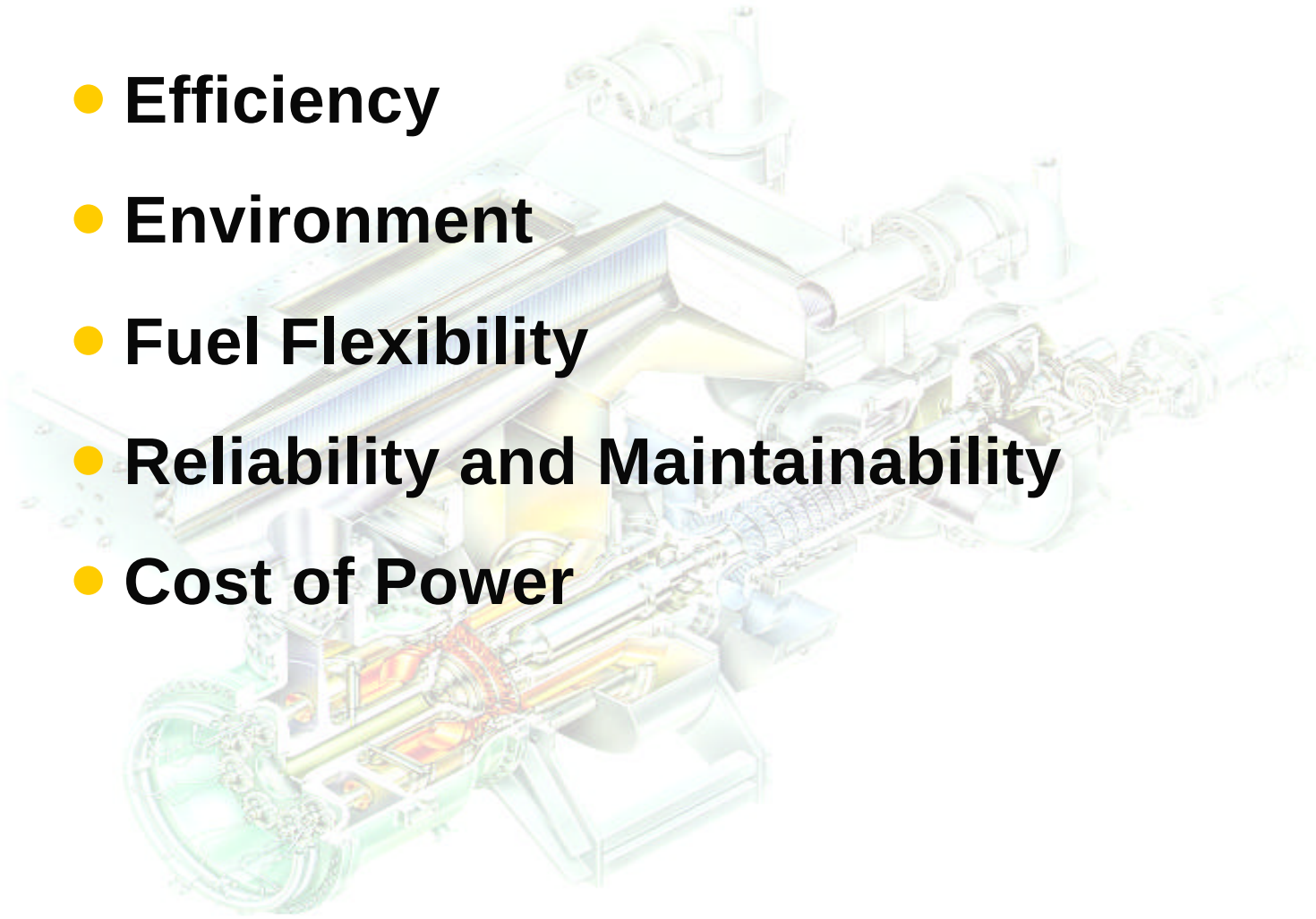
Program Goals



- Efficiency
- Environment
- Fuel Flexibility
- Reliability and Maintainability
- Cost of Power

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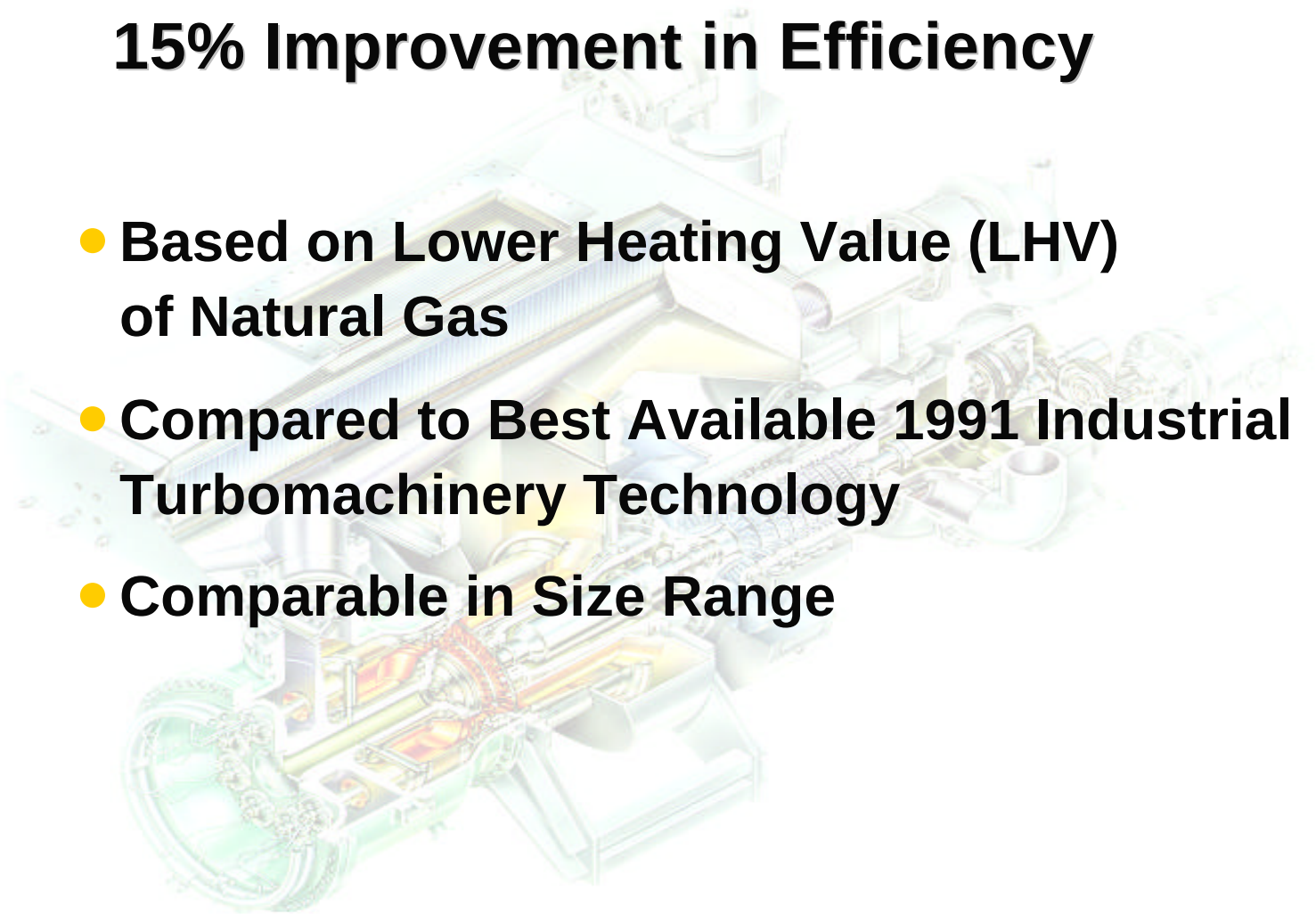
Program Goals - Efficiency

15% Improvement in Efficiency

- Based on Lower Heating Value (LHV) of Natural Gas
- Compared to Best Available 1991 Industrial Turbomachinery Technology
- Comparable in Size Range



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Program Goals - Environment

- Environmental Superiority Under Full- and Part-Load Conditions
- No Post-Combustion Cleanup Devices
- Emissions Acceptable in Severe Non-Attainment Areas - NOx, CO, UHC
- “Single-Digit” NOx

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Program Goals - Fuel Flexibility

- Natural Gas Fired ATS Systems
- Adaptable to Biomass and Coal-Derived Fuels

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Program Goals - Reliability

- Reliability and Maintainability
  - Equivalent to Best Available Circa 1991
- Addressing “RAM-D”

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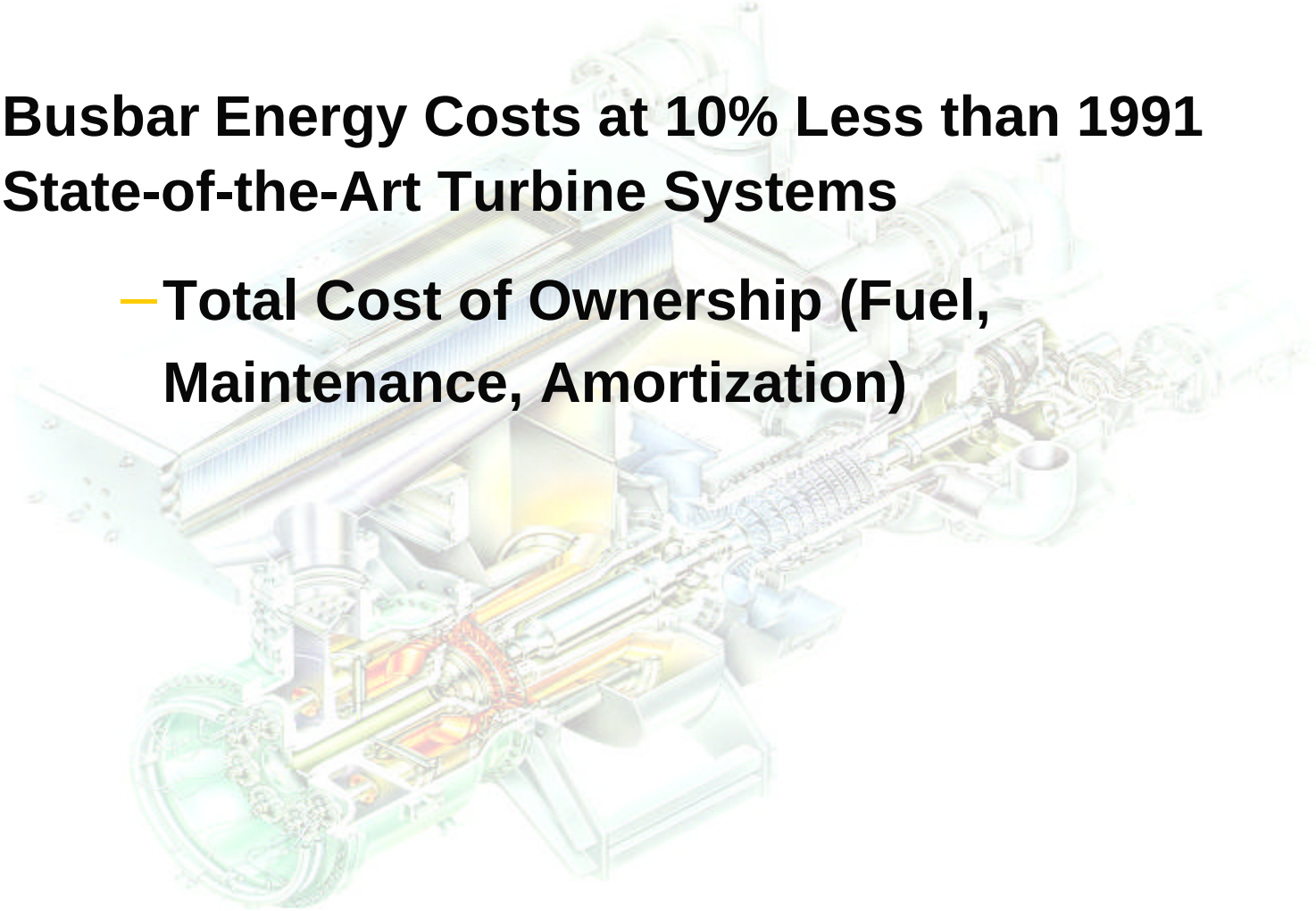
Program Goals - Cost of Power

- **Busbar Energy Costs at 10% Less than 1991 State-of-the-Art Turbine Systems**
  - **Total Cost of Ownership (Fuel, Maintenance, Amortization)**



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Steve Gates
Director,
Developmental Engineering

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Mercury 50 Engine Design Overview

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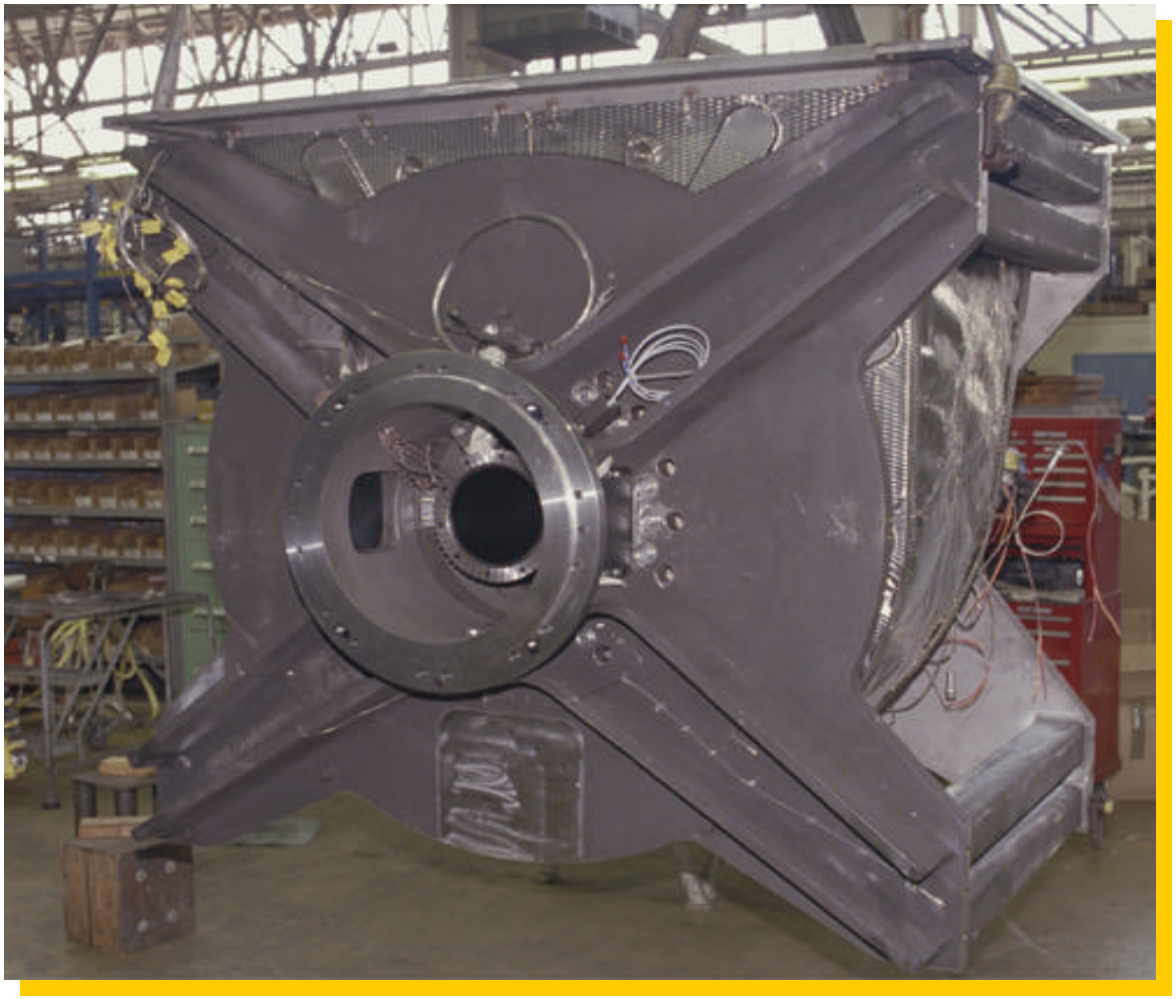
Mercury 50 Layout
Center Frame



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Mercury 50 Layout Combustor Module

- 8 ULP Injectors
- Augmented Backside-Cooled (ABC) Combustor Liner
- Closed-Loop CO Control
- Compensating Geometry Design

- Flexible Design
  - Accommodates Either Ultra Lean-Premixed (ULP) or Catalytic Combustion
- Extension of SoLoNOx Technology

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Mercury 50 Layout
Turbine Module

2nd-Stage Design, 2125°F TRIT
1st-Stage Bladed Disk

- Vortex-Cooled Leading Edge Cooling Circuit
- Film / Impingement Cooled
- Unshrouded; Highly Loaded

Uncooled 2nd-Stage Bladed Disk

- Shrouded Blade Design
- Nominal Stage Loading

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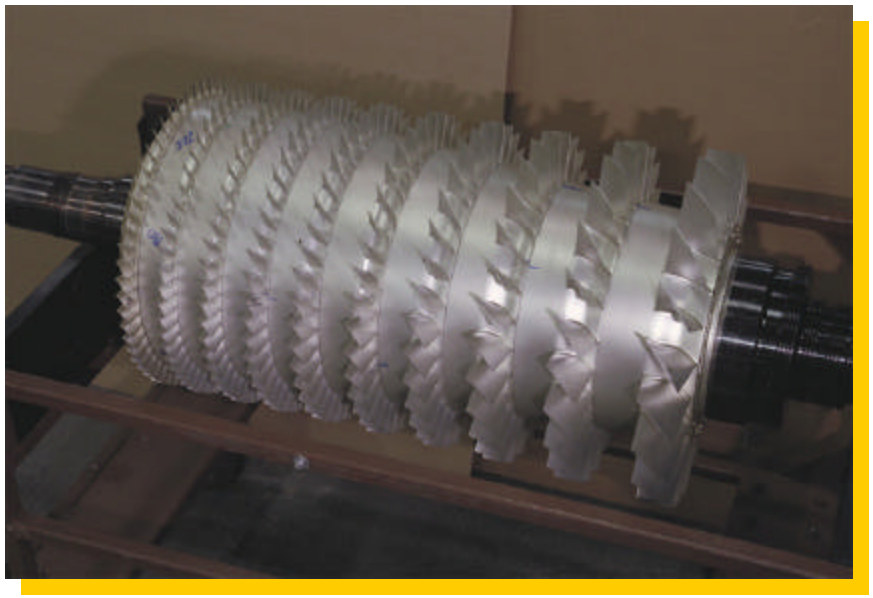
Mercury 50 Layout
ACE Compressor Module



- 10-Stage Axial Design
- 9.1 Pressure Ratio
- 3-D Wide Chord Airfoils
  - 40% Reduction in Blade Count

Variable Geometry Control

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Test Results

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ATS Mercury 50 Accomplishments

- Commissioned Dedicated Mercury 50 Development and Production Test Cells
- Completed 1st Round of Development Testing on Engines #1 & #2
- Completed On-site Package Serviceability and Installation "Kaizen" Review
- Created Significant Commercial Interest in ATS Product
- Built, Tested and Shipped First Commercial Unit on Schedule

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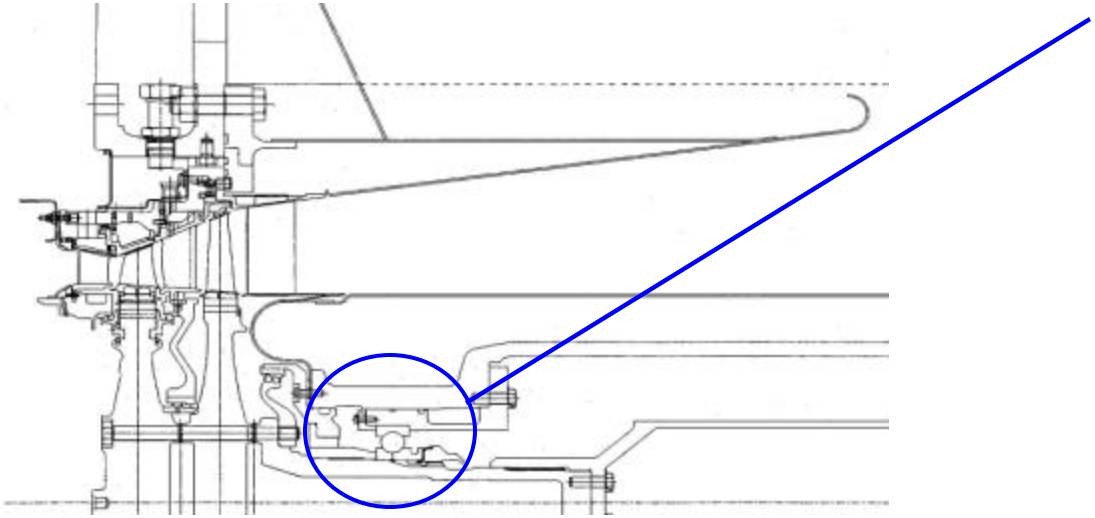
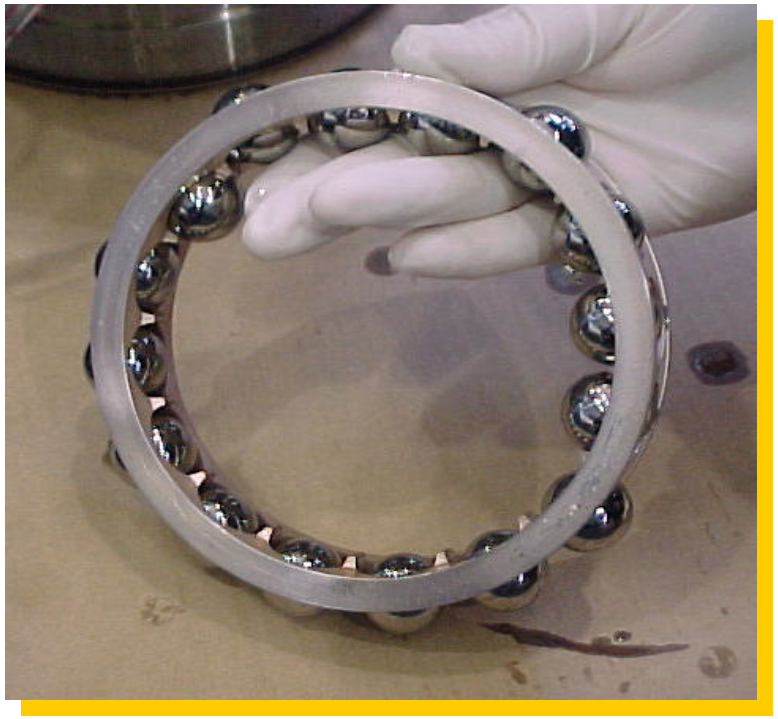
Rolling Element Bearings

- All Bearings in Excellent Condition
- Thrust Bearing Like New
- Skidding Non-Existent
- No Pitting or Contamination





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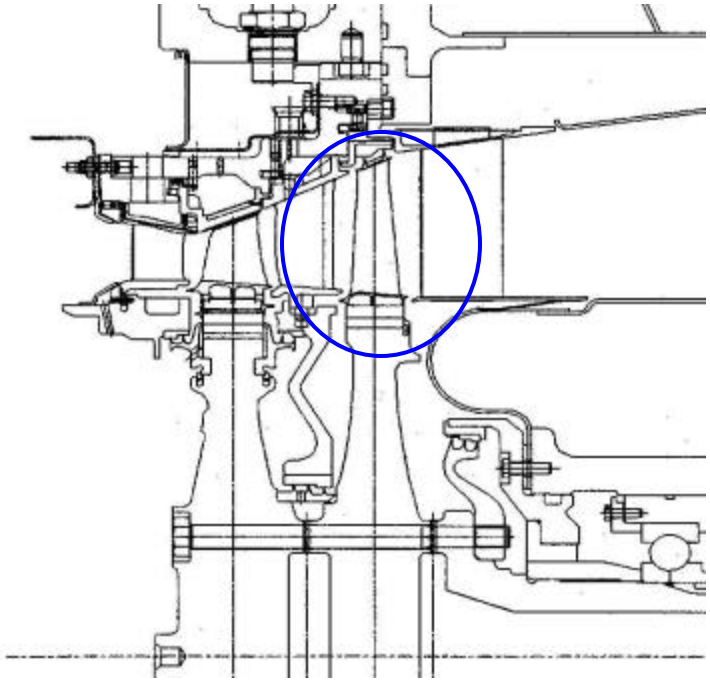
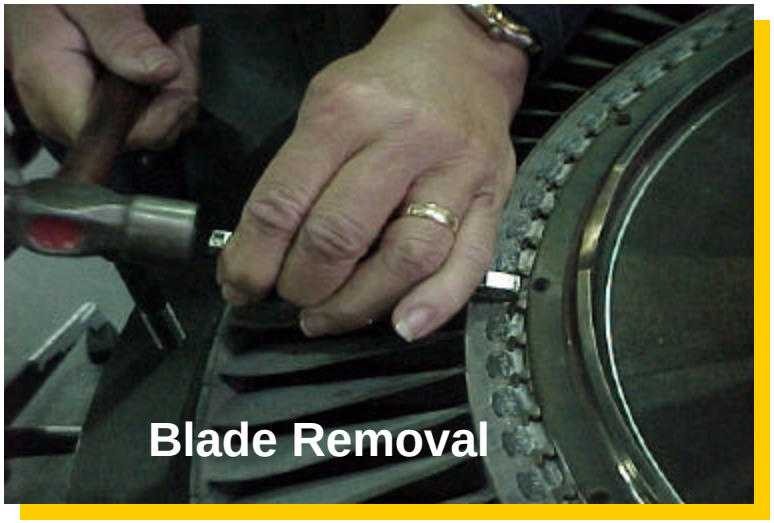
2nd Turbine Disk Assembly

Shrouded Blade Design

Shroud "Z-Notch" Interlock Functioning per Design Intent

No FPI Indications at Attachments





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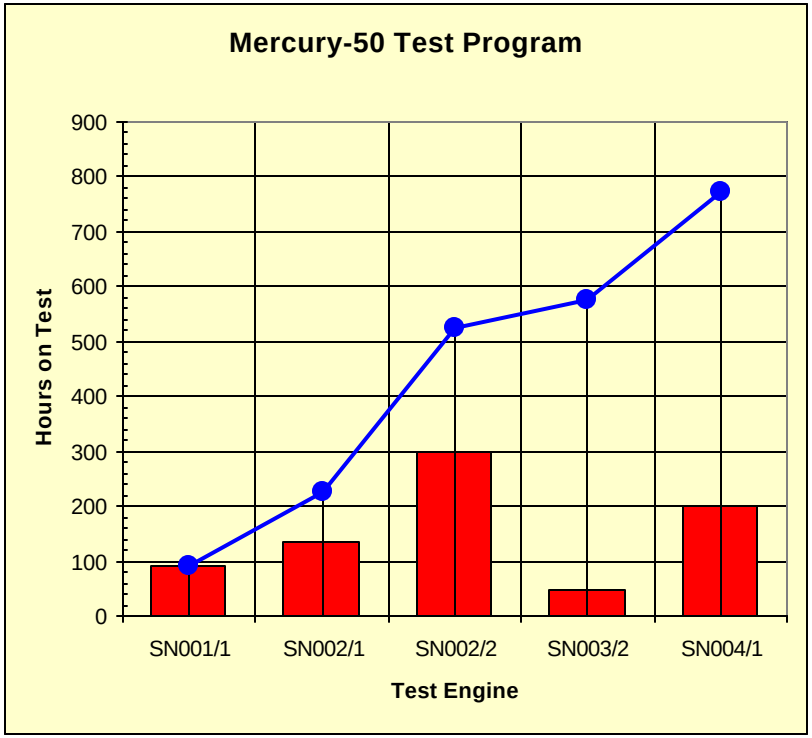
Mercury 50 Development Test Summary

- Over 700 Hours of Test
  - 2 Phases, 4 Engines, 5 Builds
  - 300+ Start Cycles
- Critical New Content Functioning As Designed

- Emissions: Exceeding Goal in Test Cell
- Engine Performance on Plan



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Mercury 50 Package Maintainability Kaizen Demonstration

- Service/ Maintenance/ Safety Audit
- Review Assembly/ Installation Plans
- Evaluate Field Tooling

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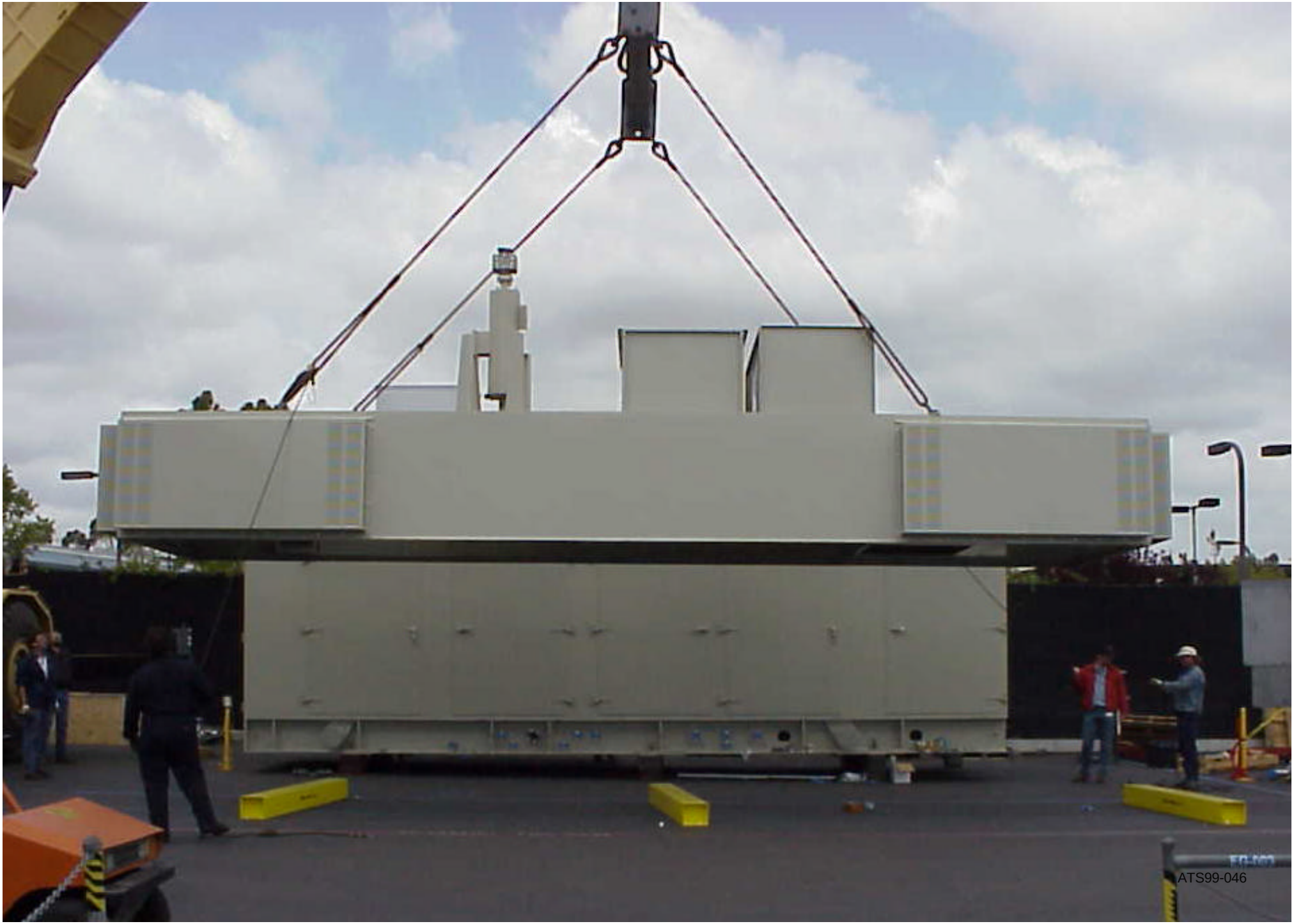
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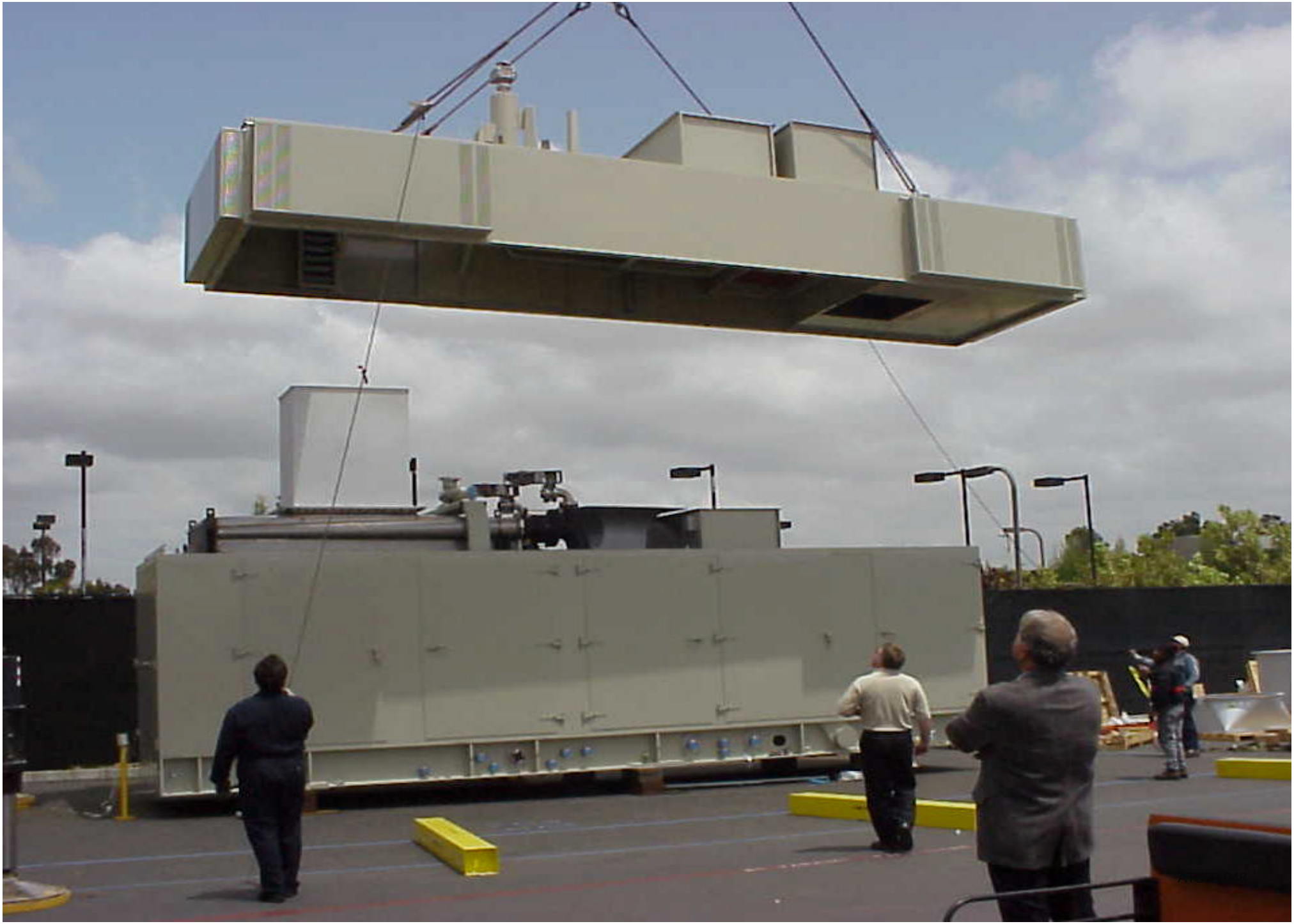


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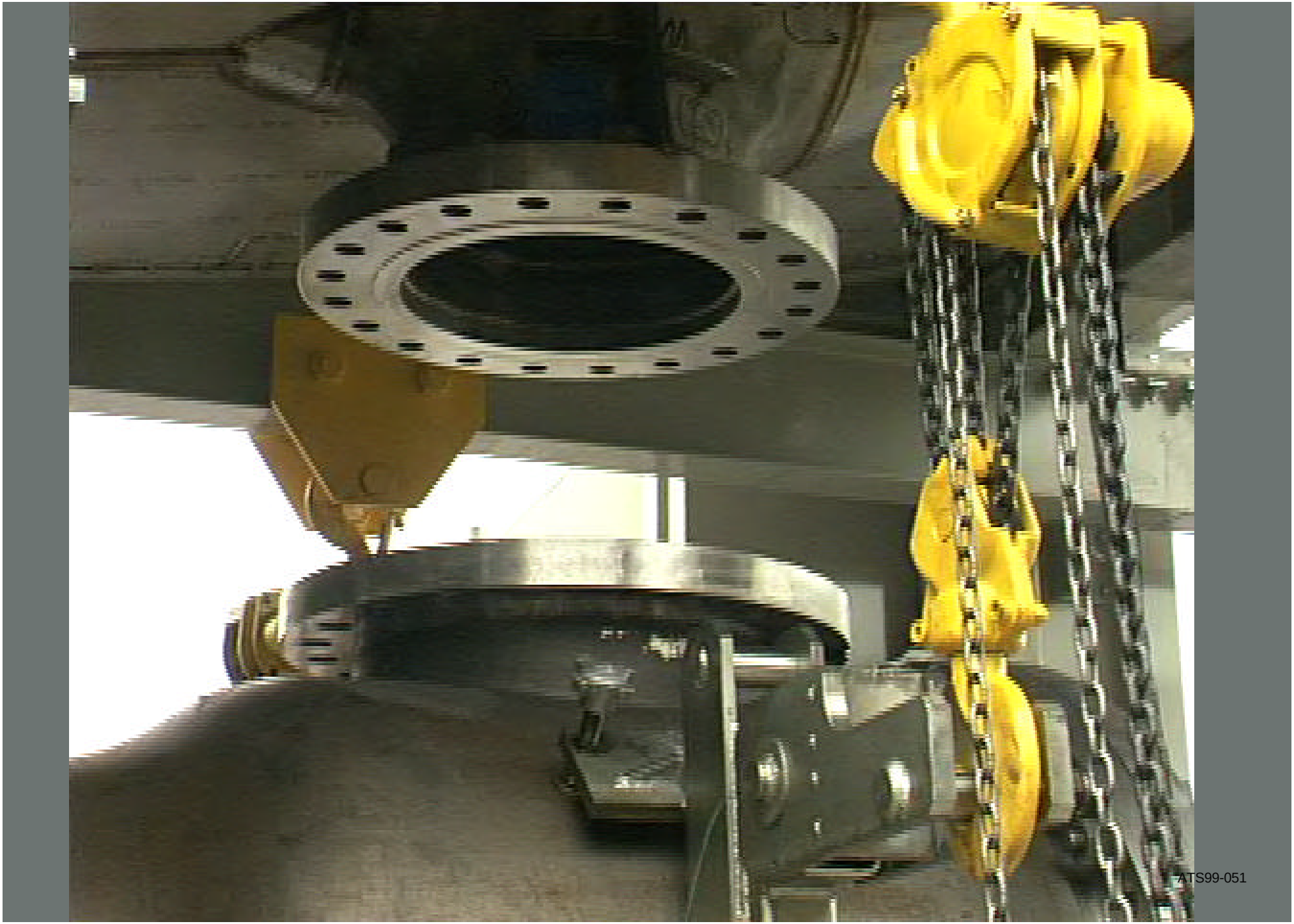
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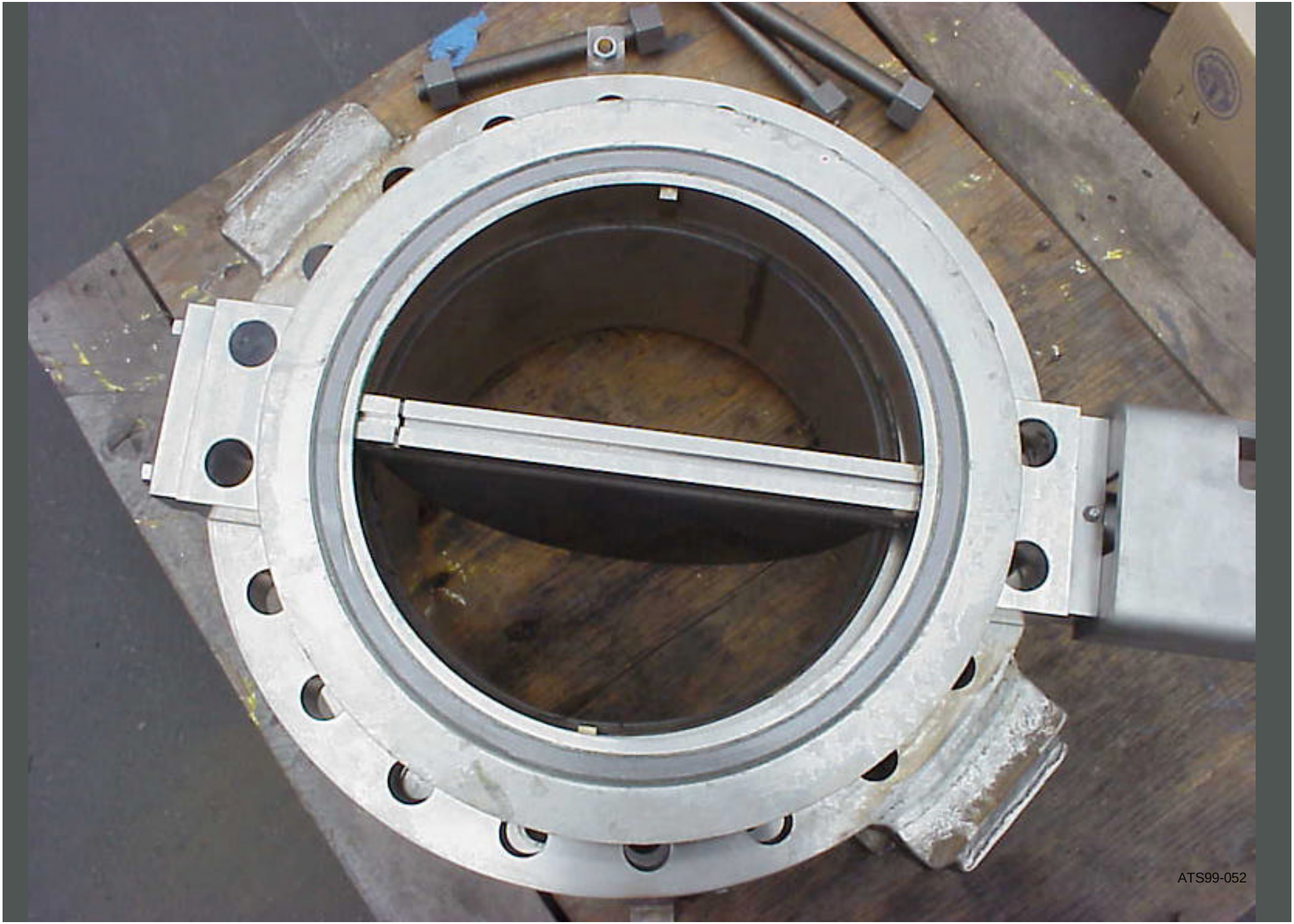
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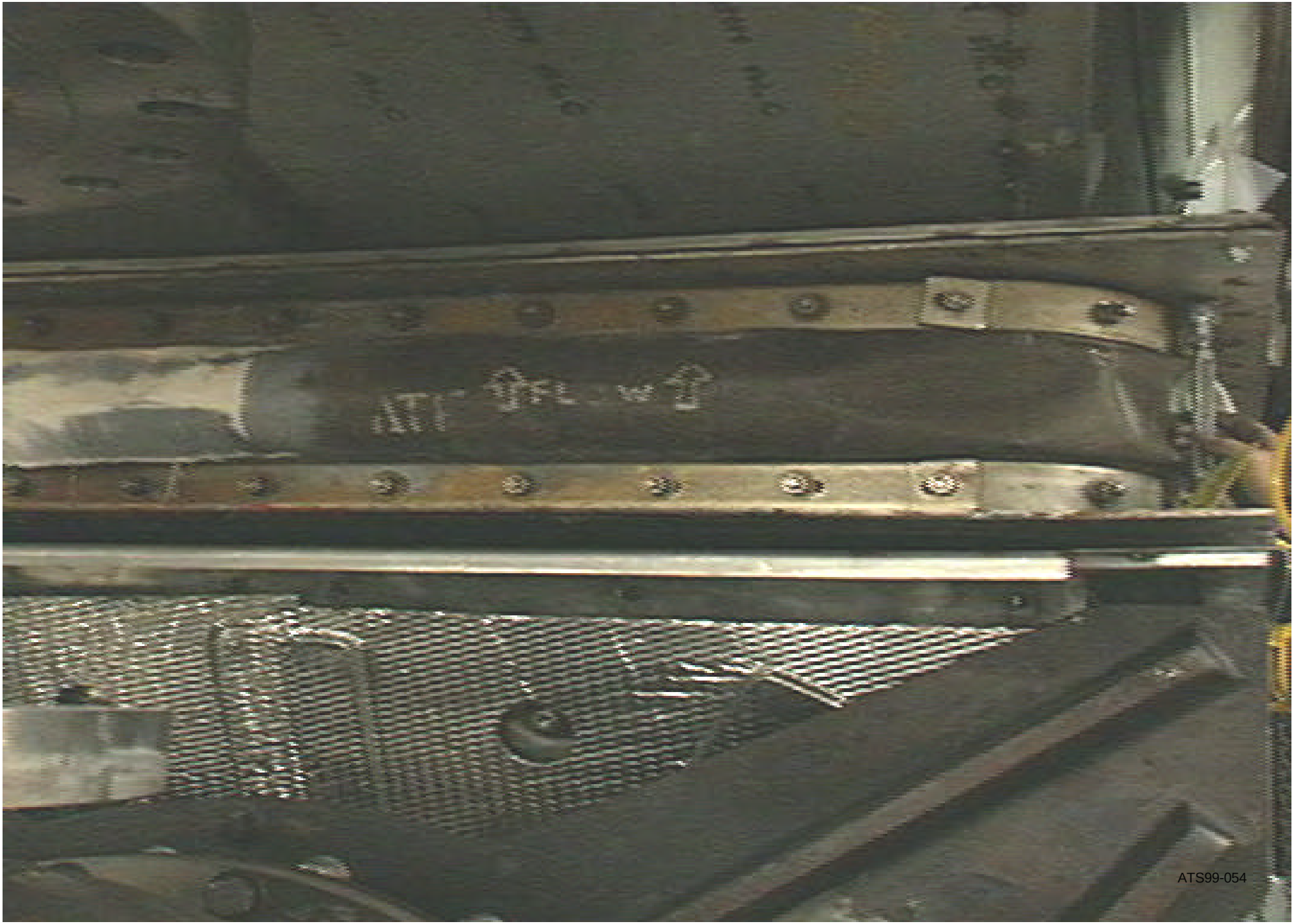
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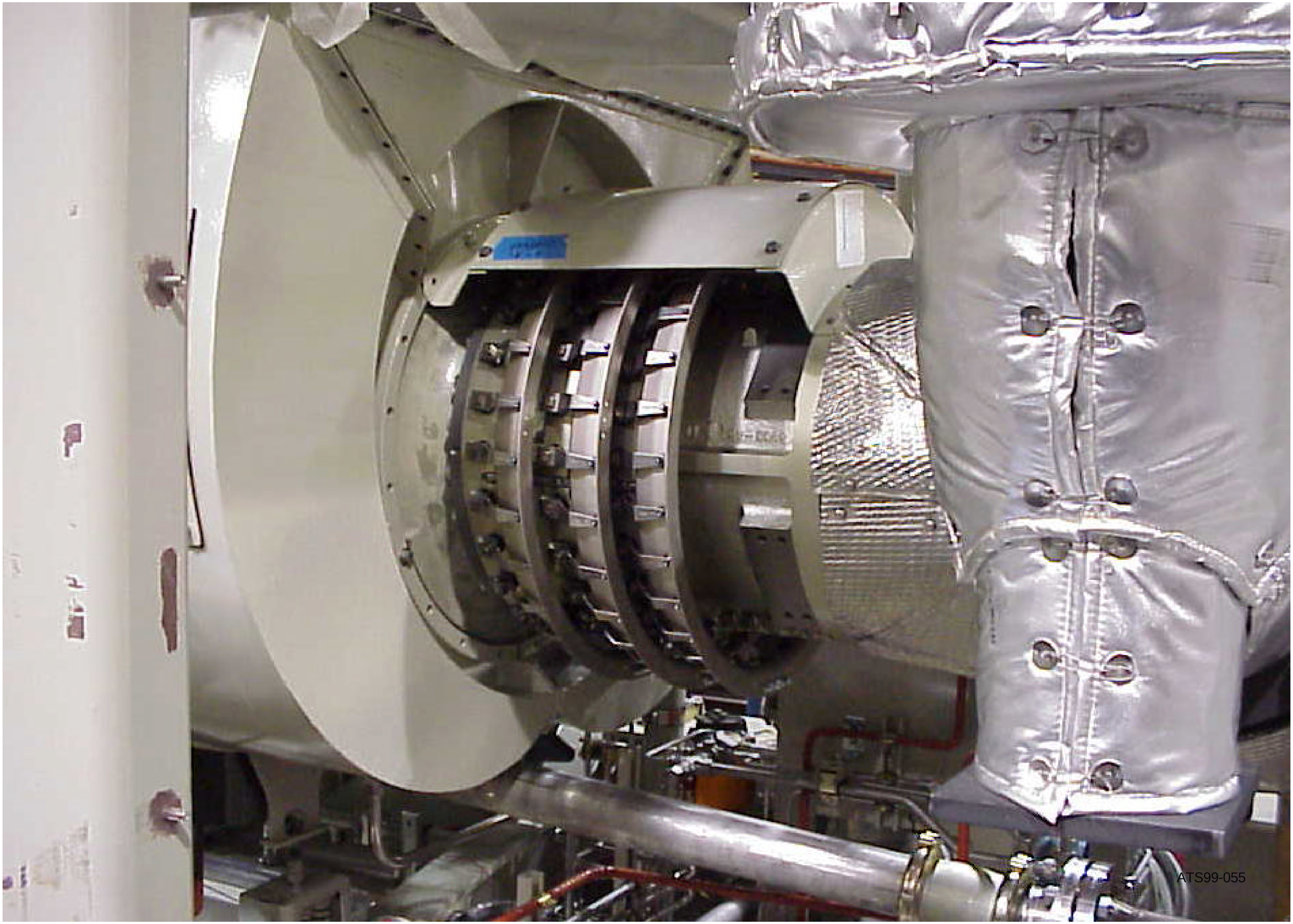
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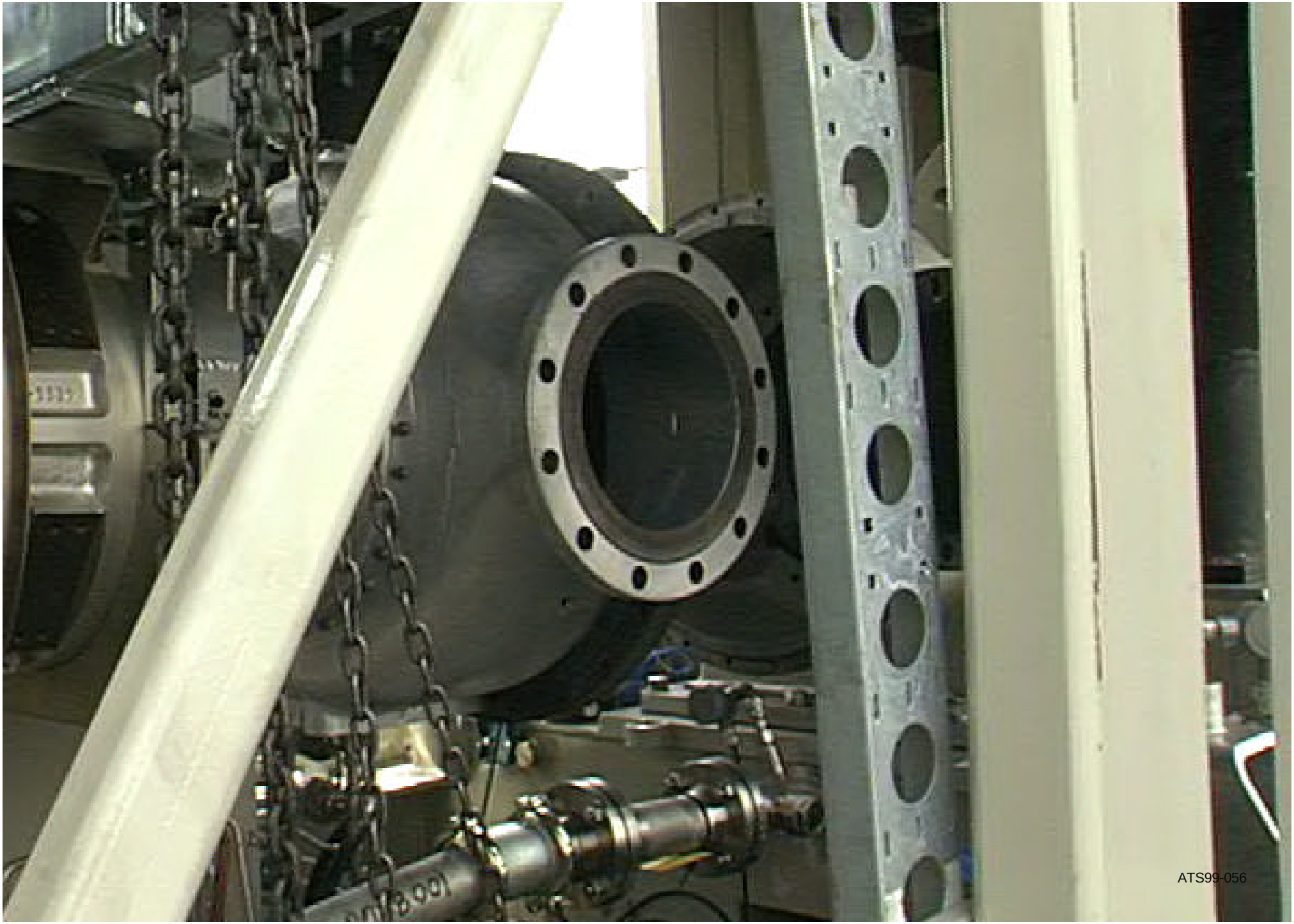
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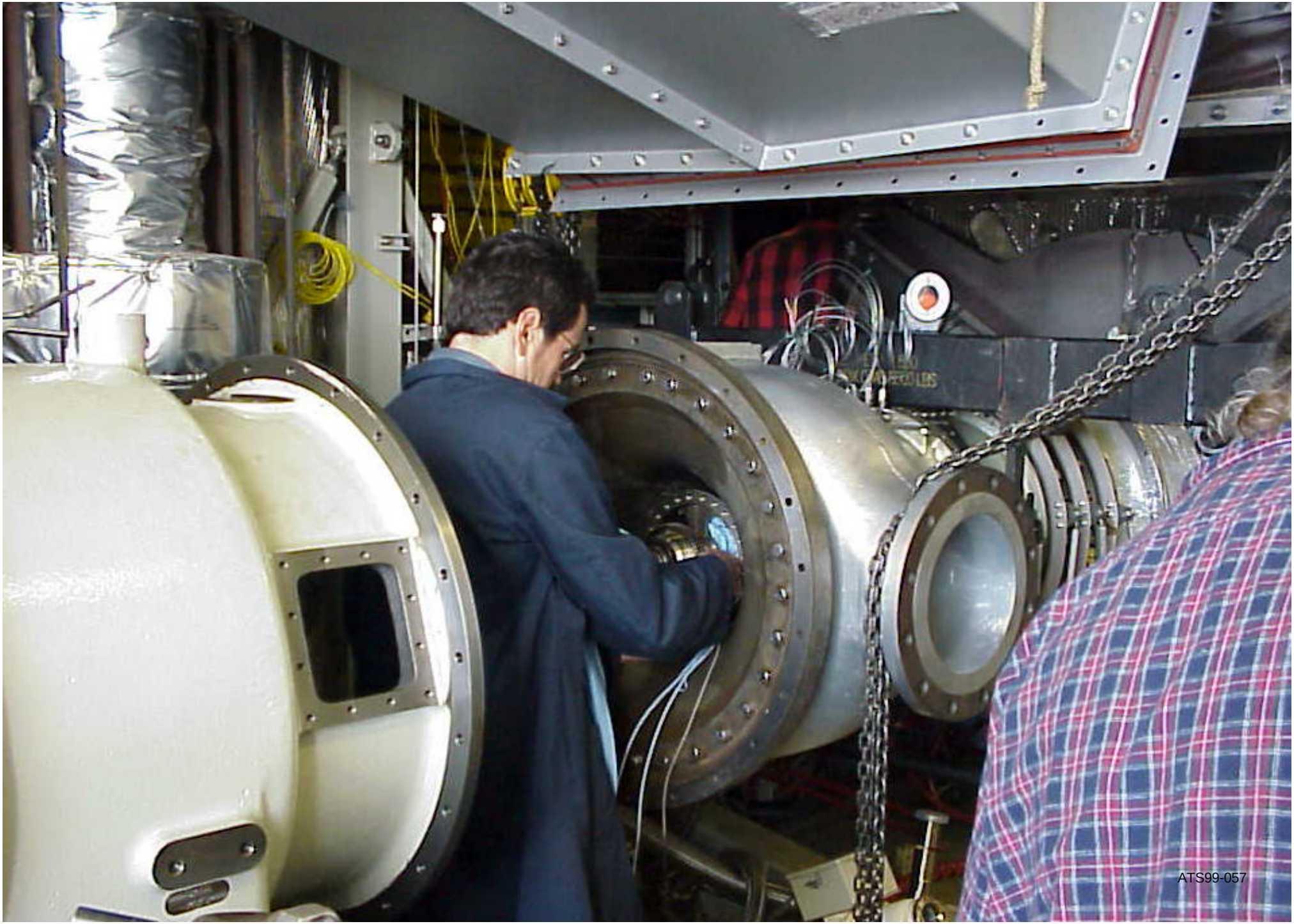
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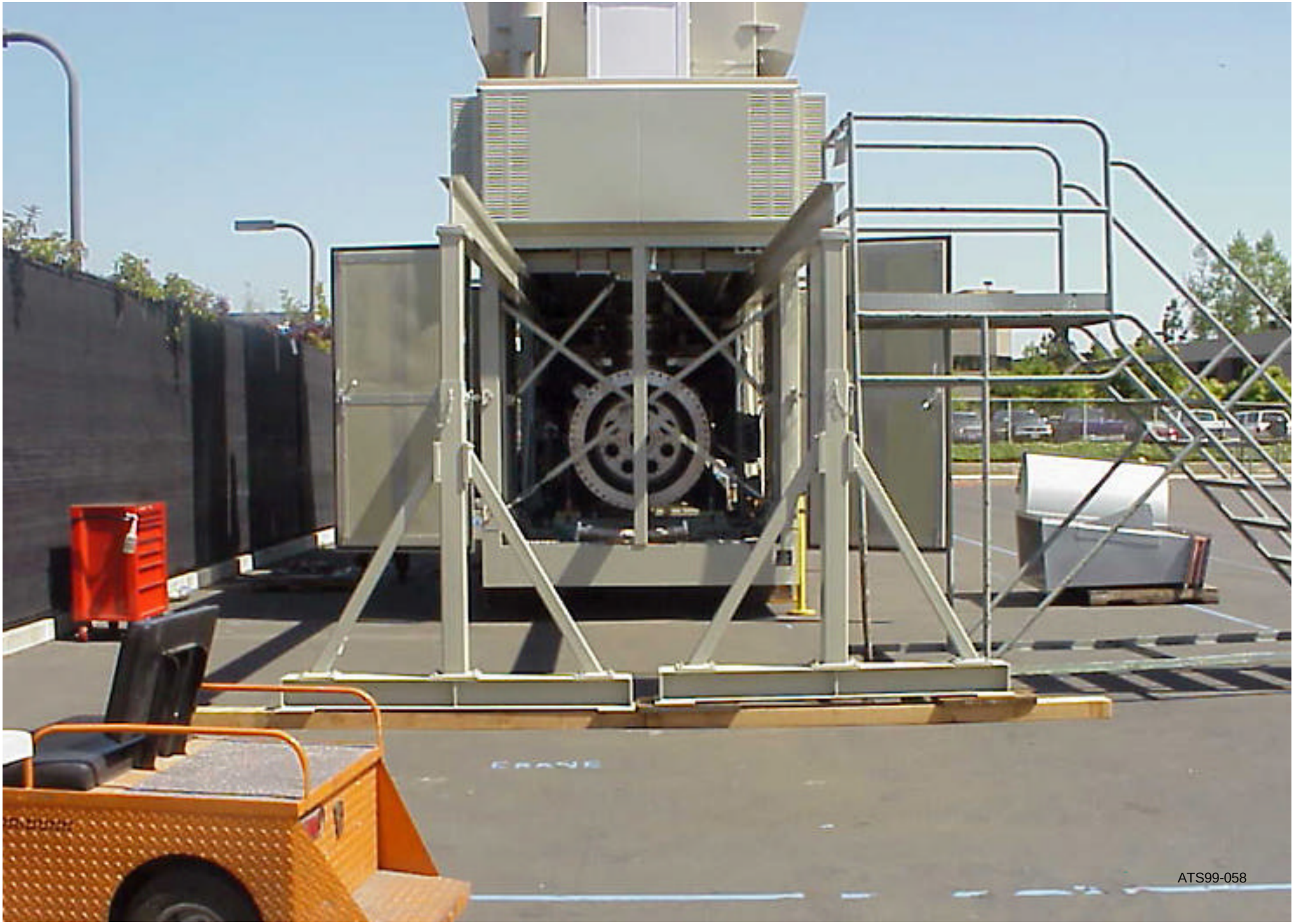
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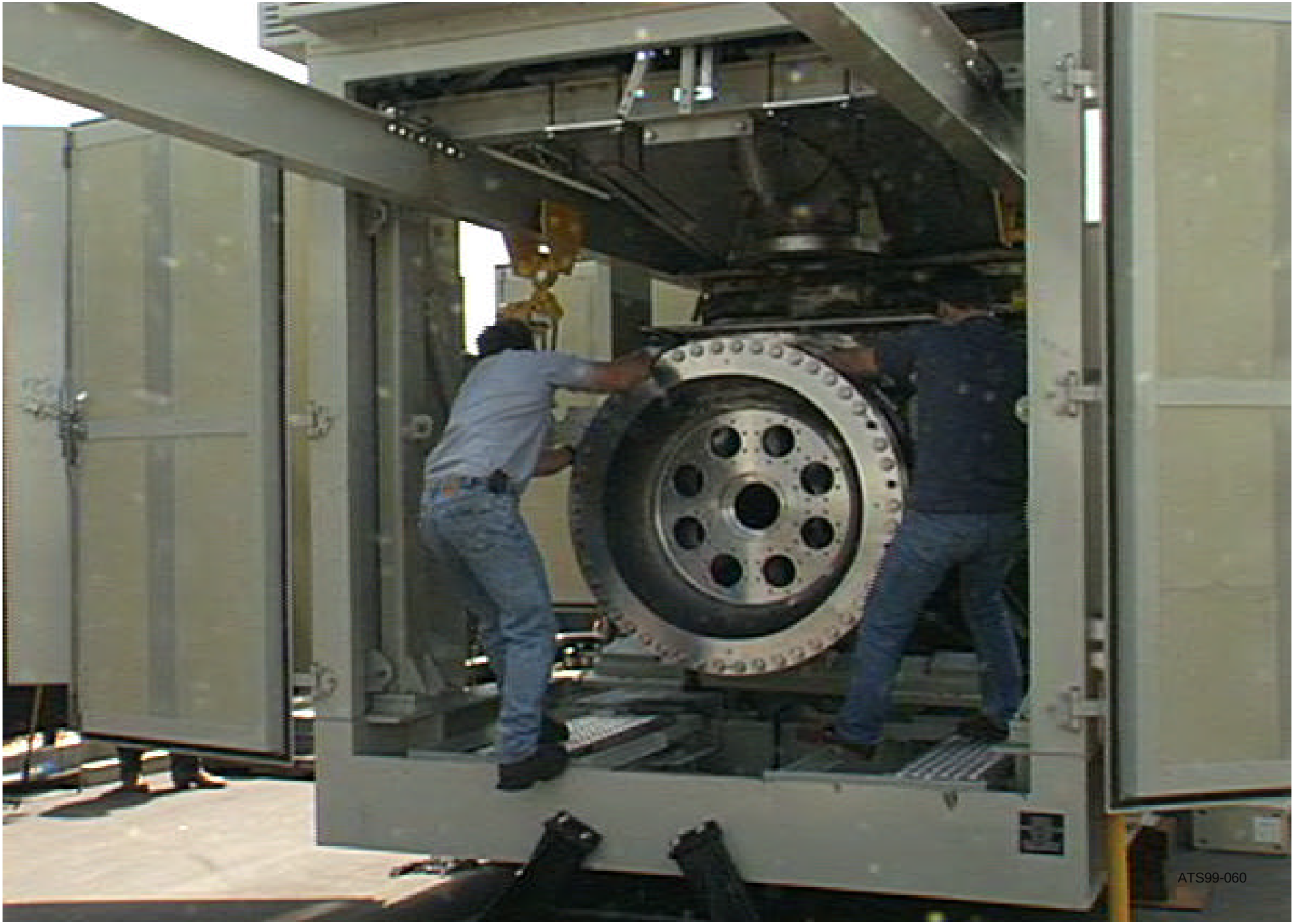
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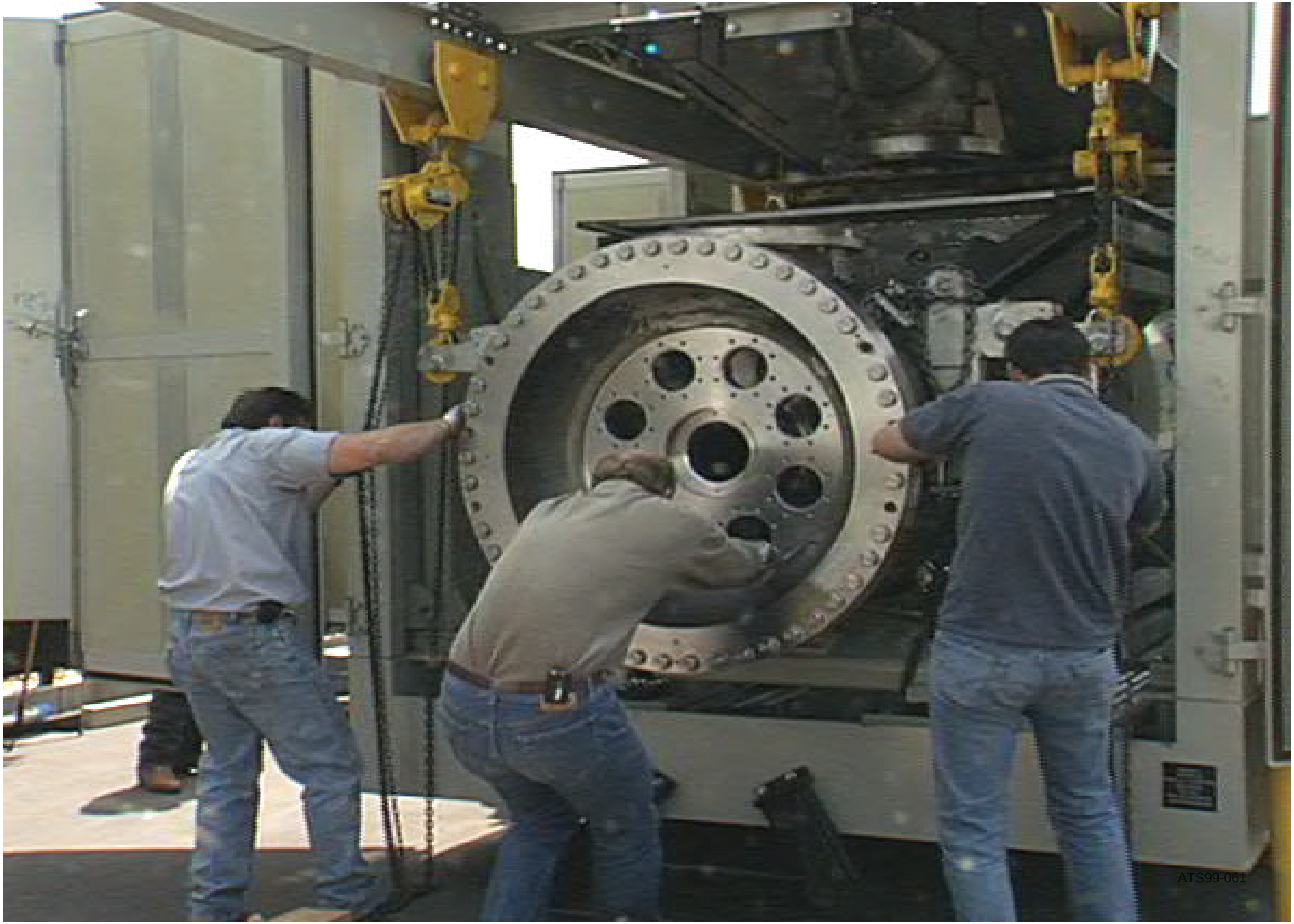
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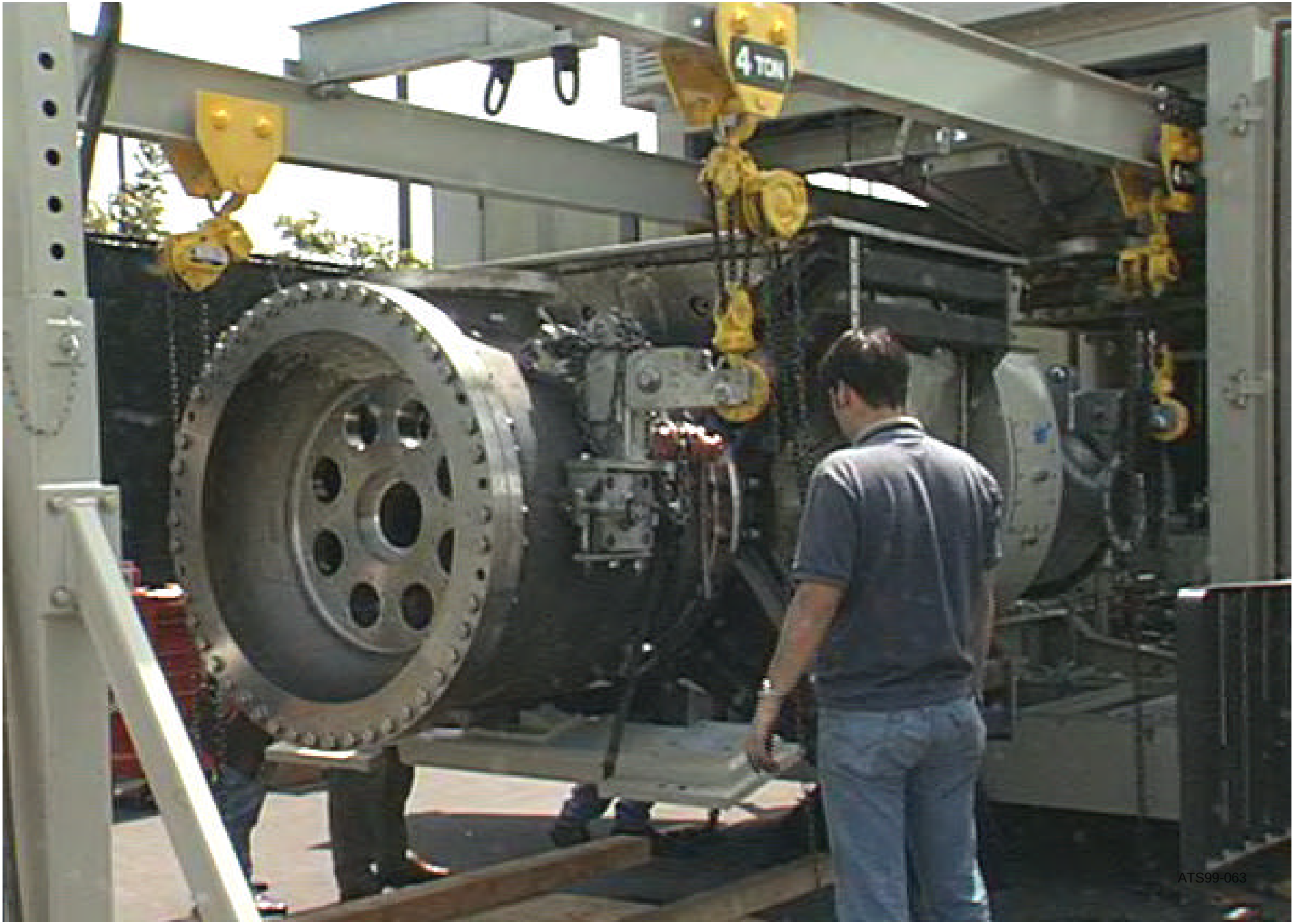
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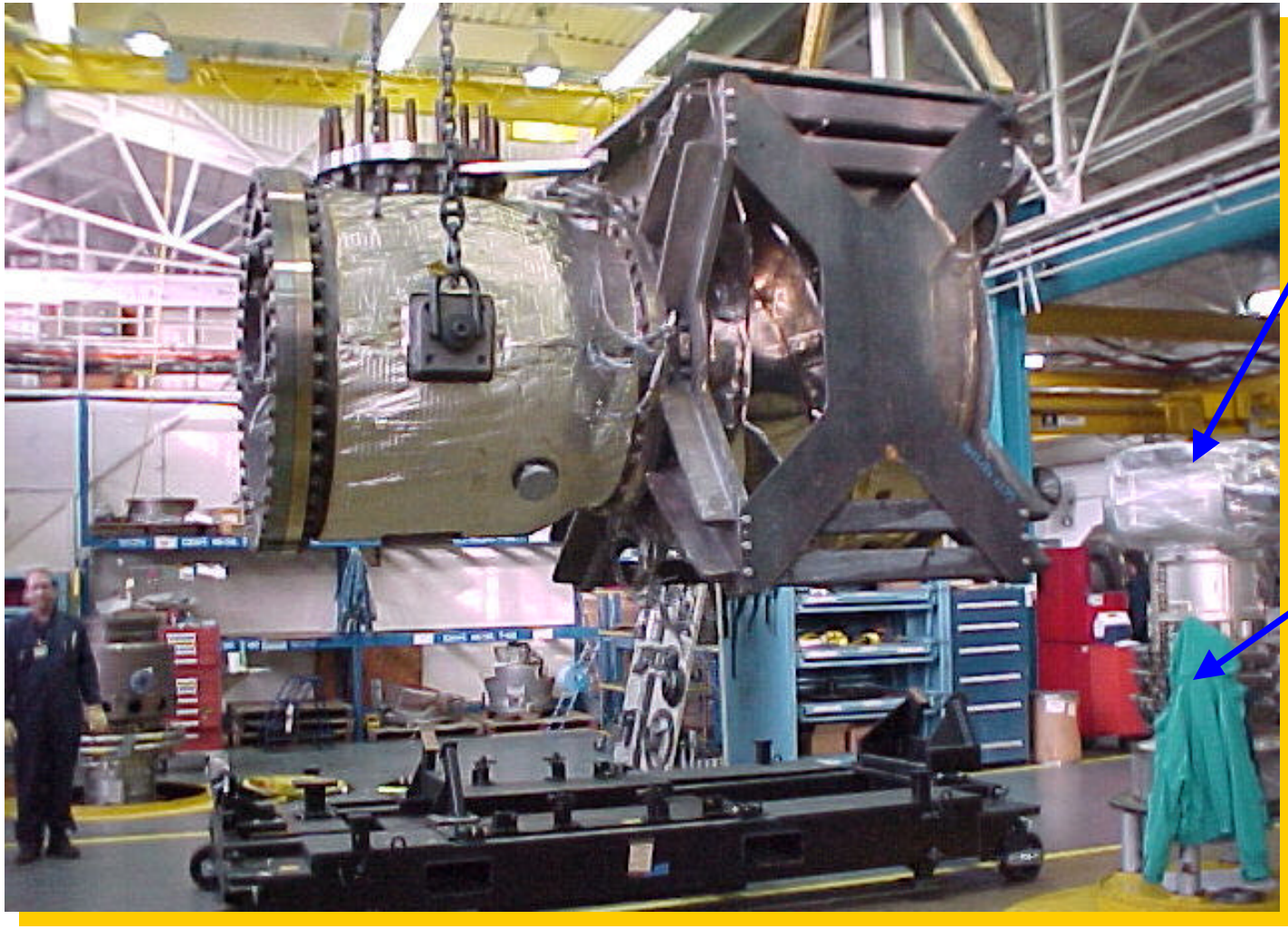
Engine #1 Modular Disassembly

Combustor and Turbine Modules



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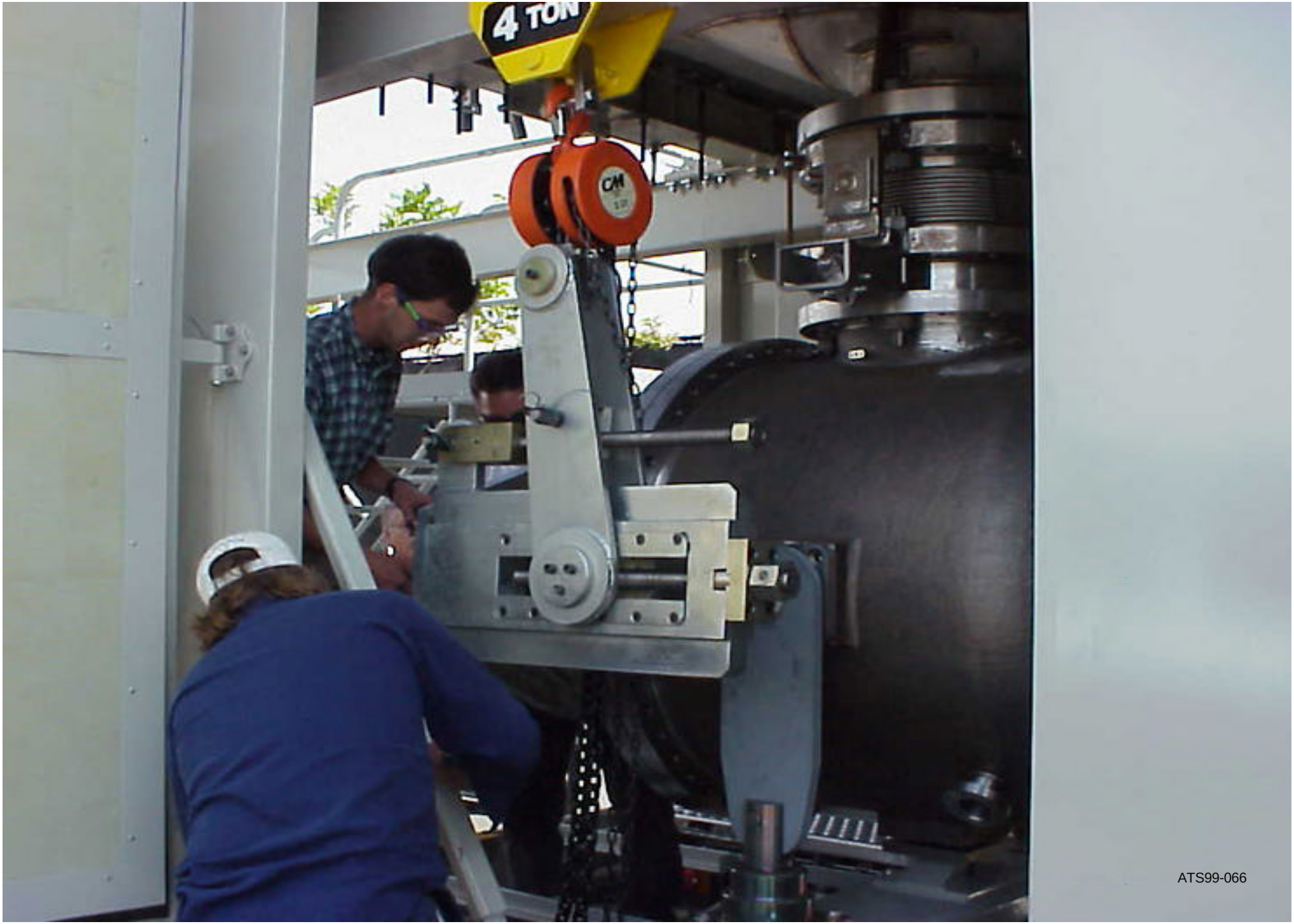

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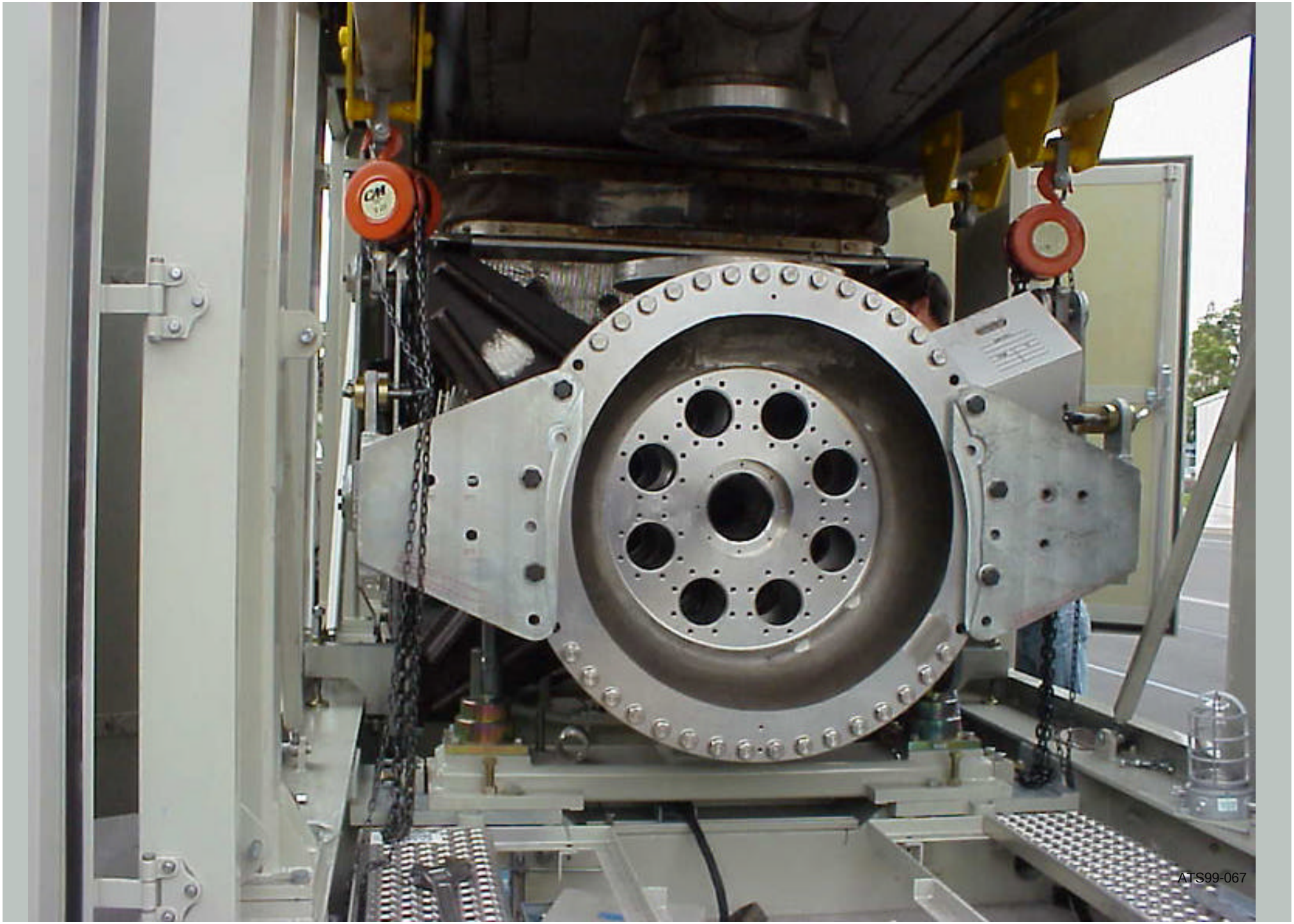
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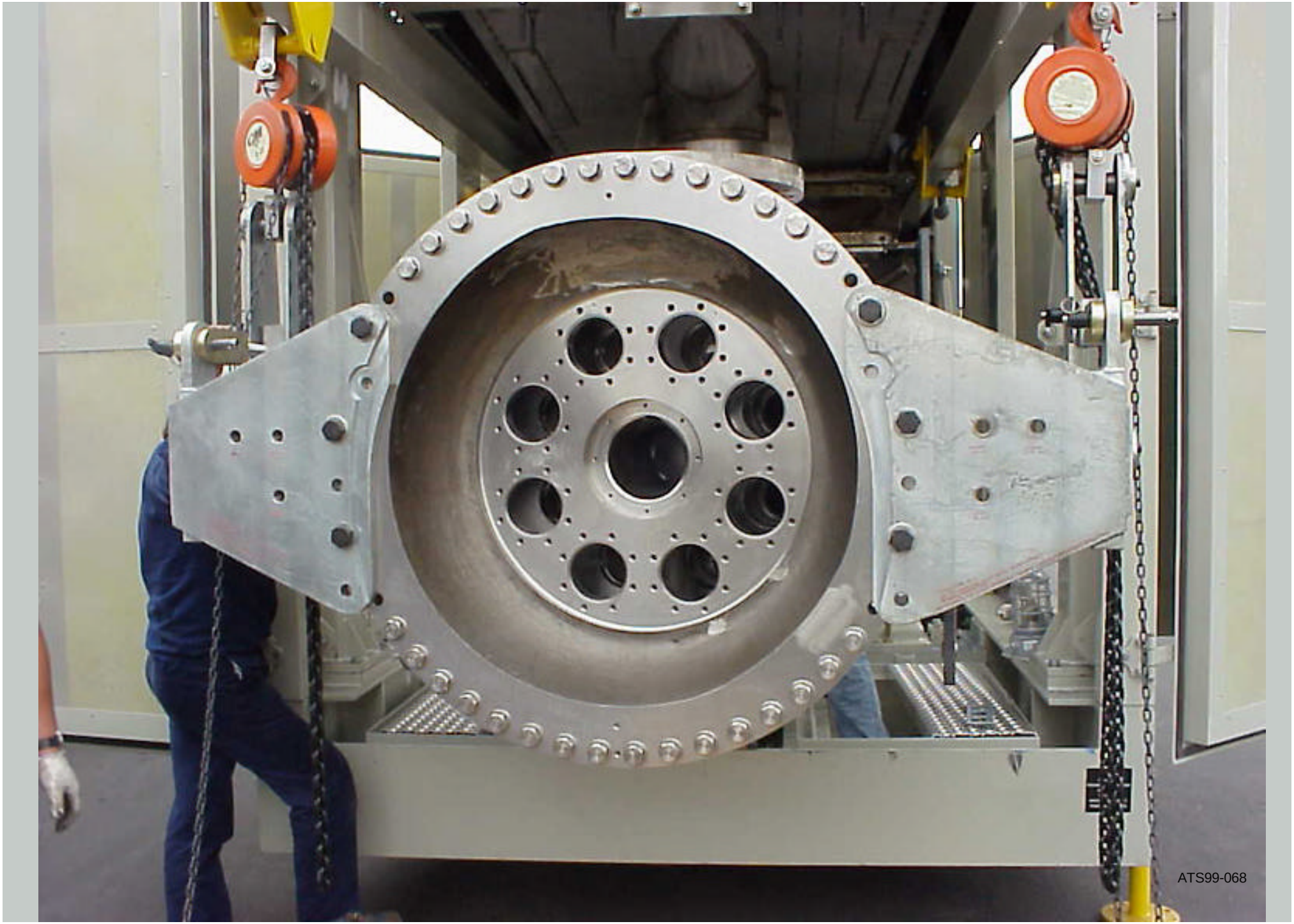
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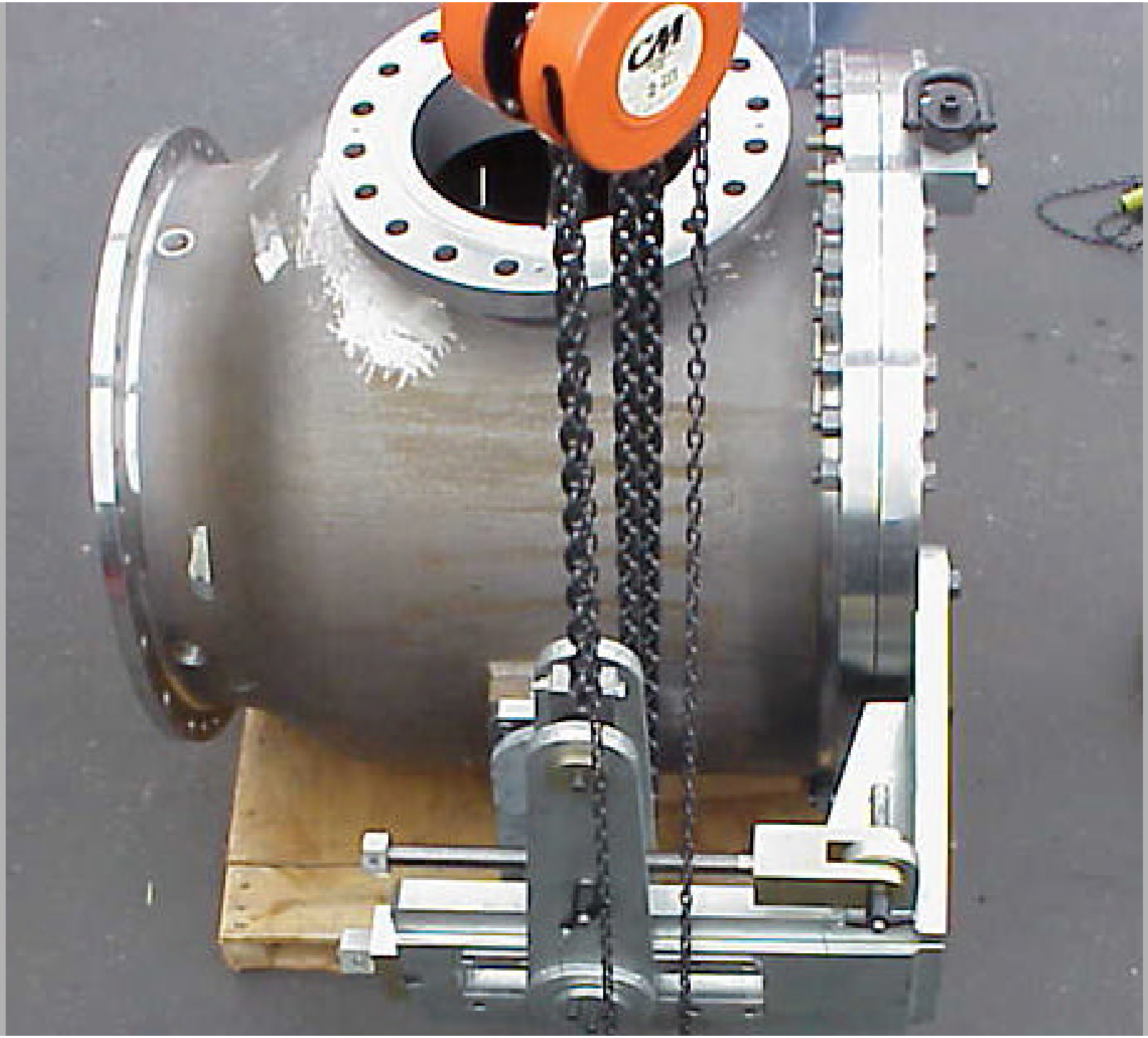

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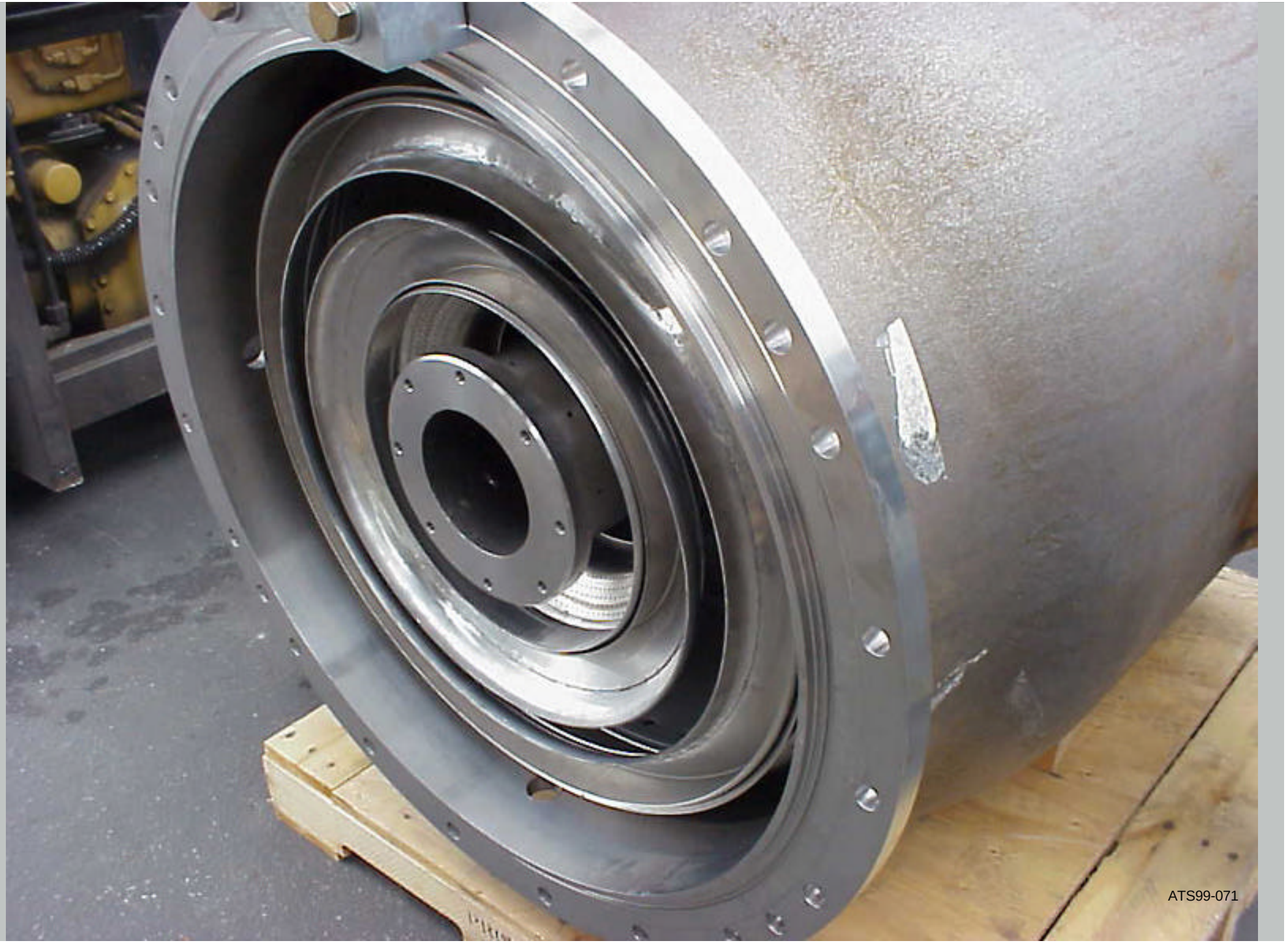
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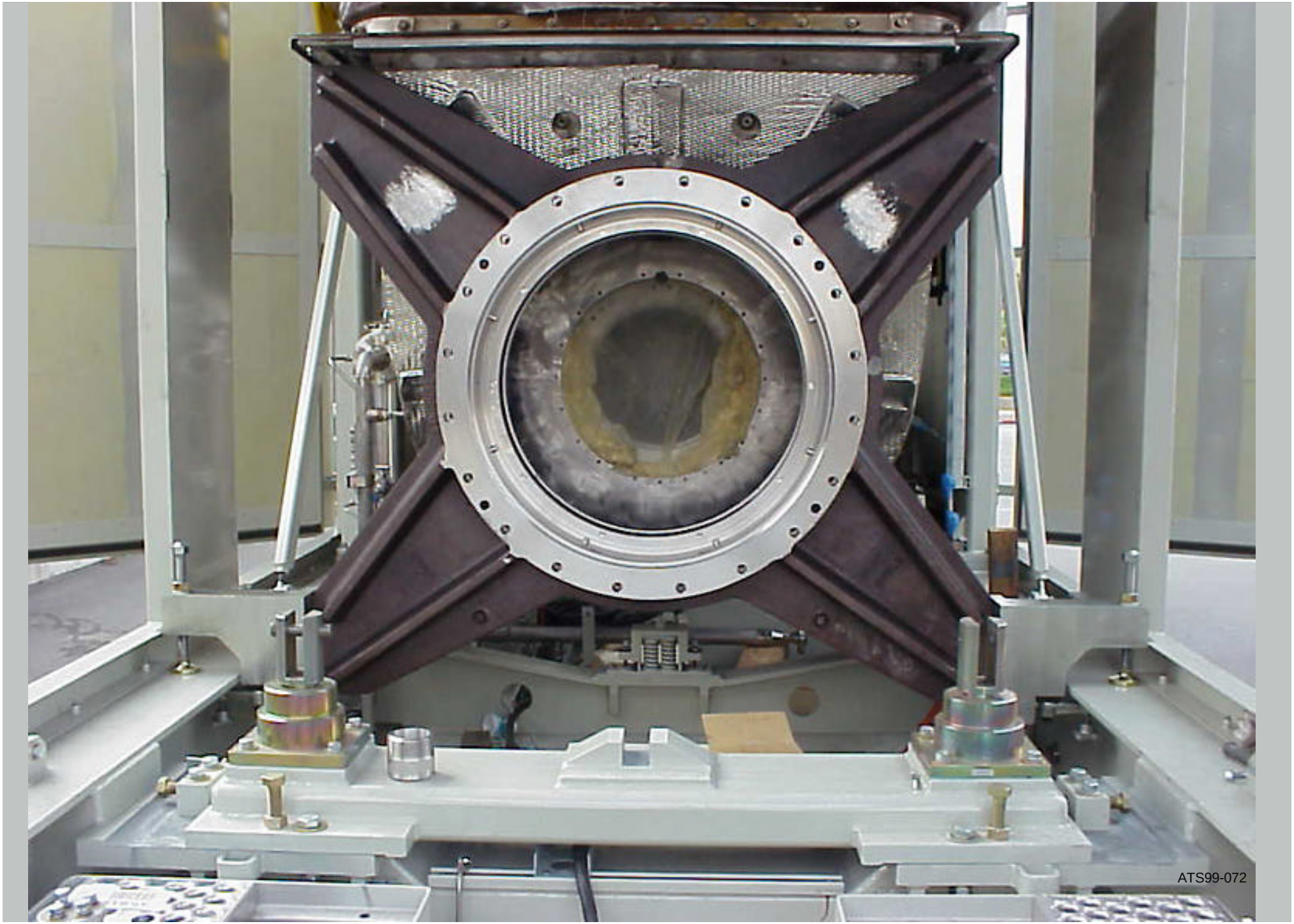
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Commercialization

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Opportunity in Current Energy Market

- **ENERGY USERS – Requirement for Competitive and Reliable Electricity**
- **ENERGY PROVIDERS – Need to Optimize Profits on Energy Sales, Whether Gas or Electricity, While Delivering Competitive and Reliable Energy**

PSC runs short of power

By Roger Fillen

Biggest customers asked to conserve

NORTH AMERICA

Ice storm keeps millions in the dark

Hydro-Quebec, Montreal, Que (Canada) designs its 735-kV towers to withstand 43 mm of ice—what technical experts consider protection against a once-in-a-century ice storm. But it wasn't enough to harbor transmission and distribution lines from January's devastation, which delivered as

cloudy, though, as Germany and the rest of Europe begin utility restructuring.

■ Spain is currently considering a measure similar to Germany's Electricity Feed law, but already provides premium payments to wind developers of about 8¢US/kWh. Wind development is heavily concentrated in the provinces of Galicia, Navarre, and Aragon, where provincial governments are strongly supportive.

■ Denmark installed over 200 MW in 1997, but its wind industry's impact spread

1. **January's ice storm** crippled parts of Canada

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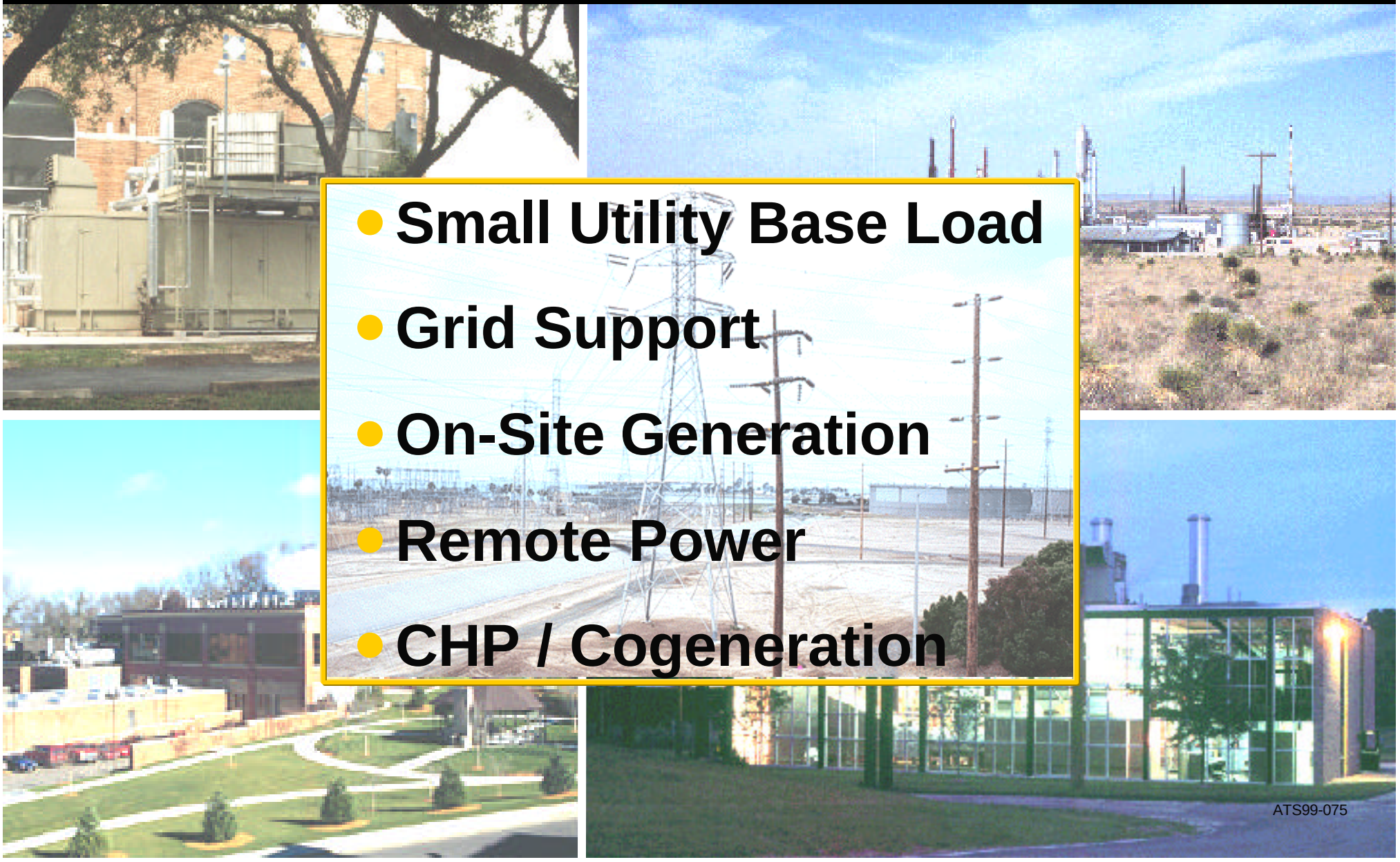
Broad Appeal in Diverse Applications



- Small Utility Base Load
- Grid Support
- On-Site Generation
- Remote Power
- CHP / Cogeneration

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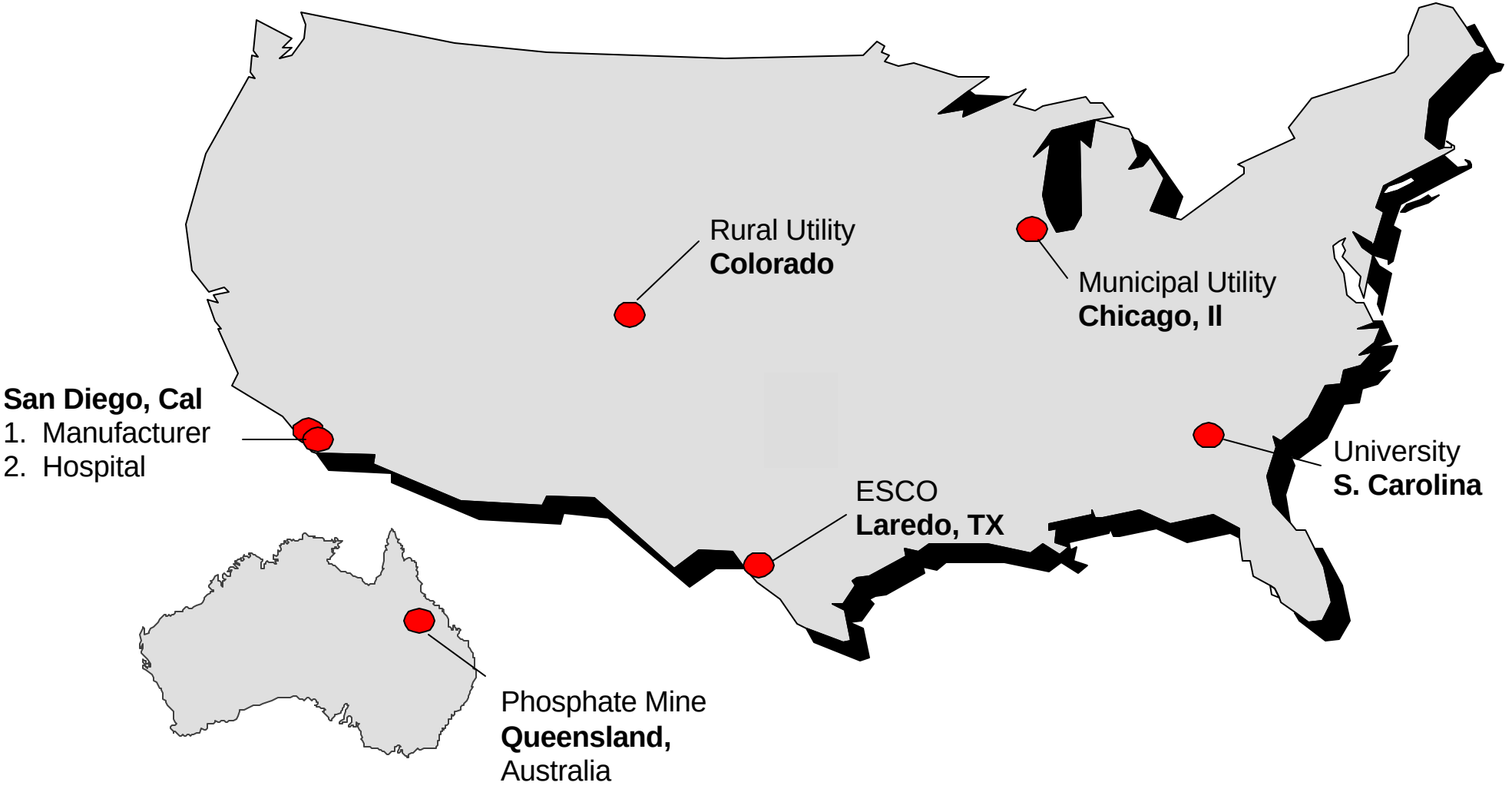
Initial Customer Installations



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Manufacturer
San Diego, California

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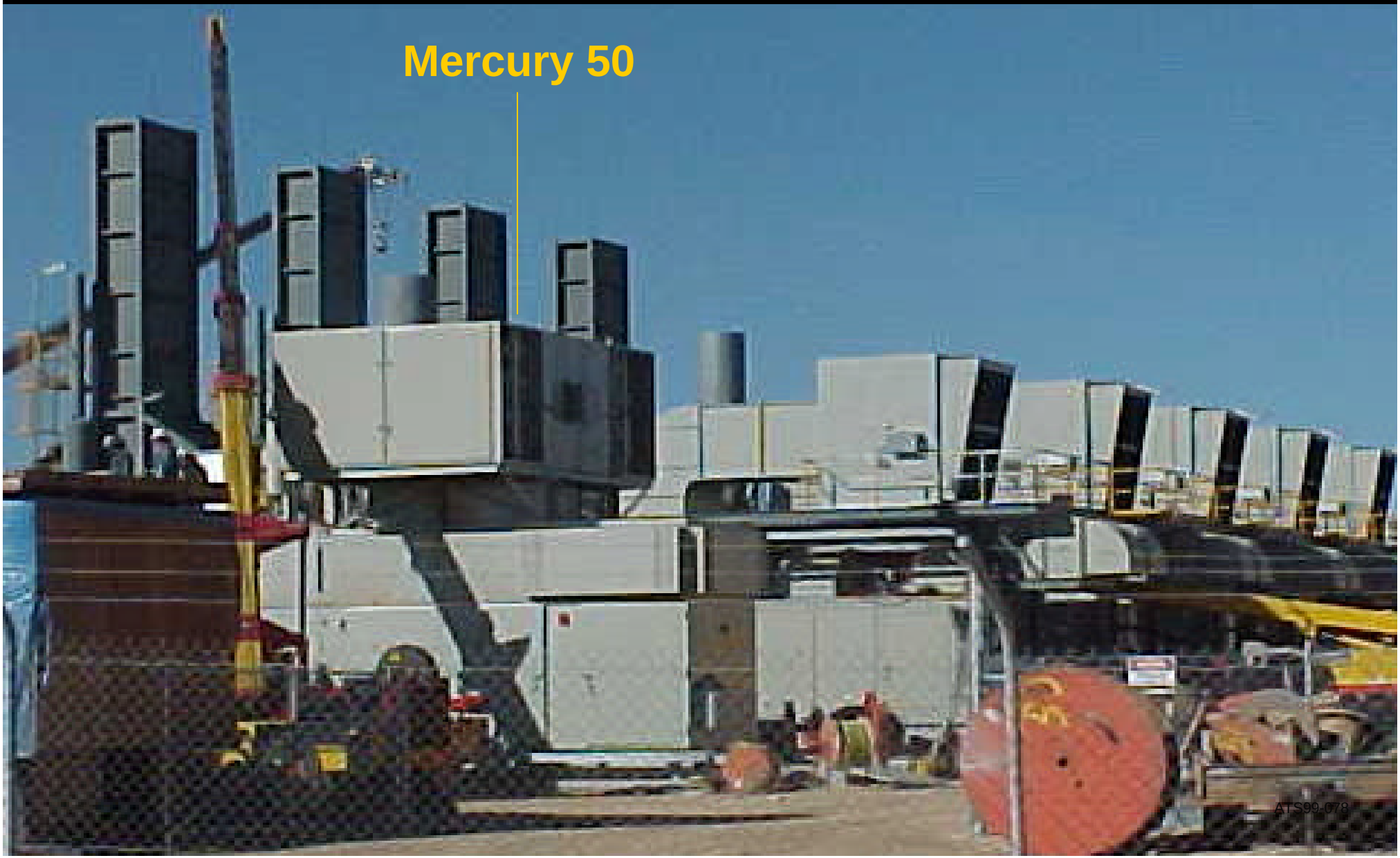
Phosphate Mine
Queensland, Australia

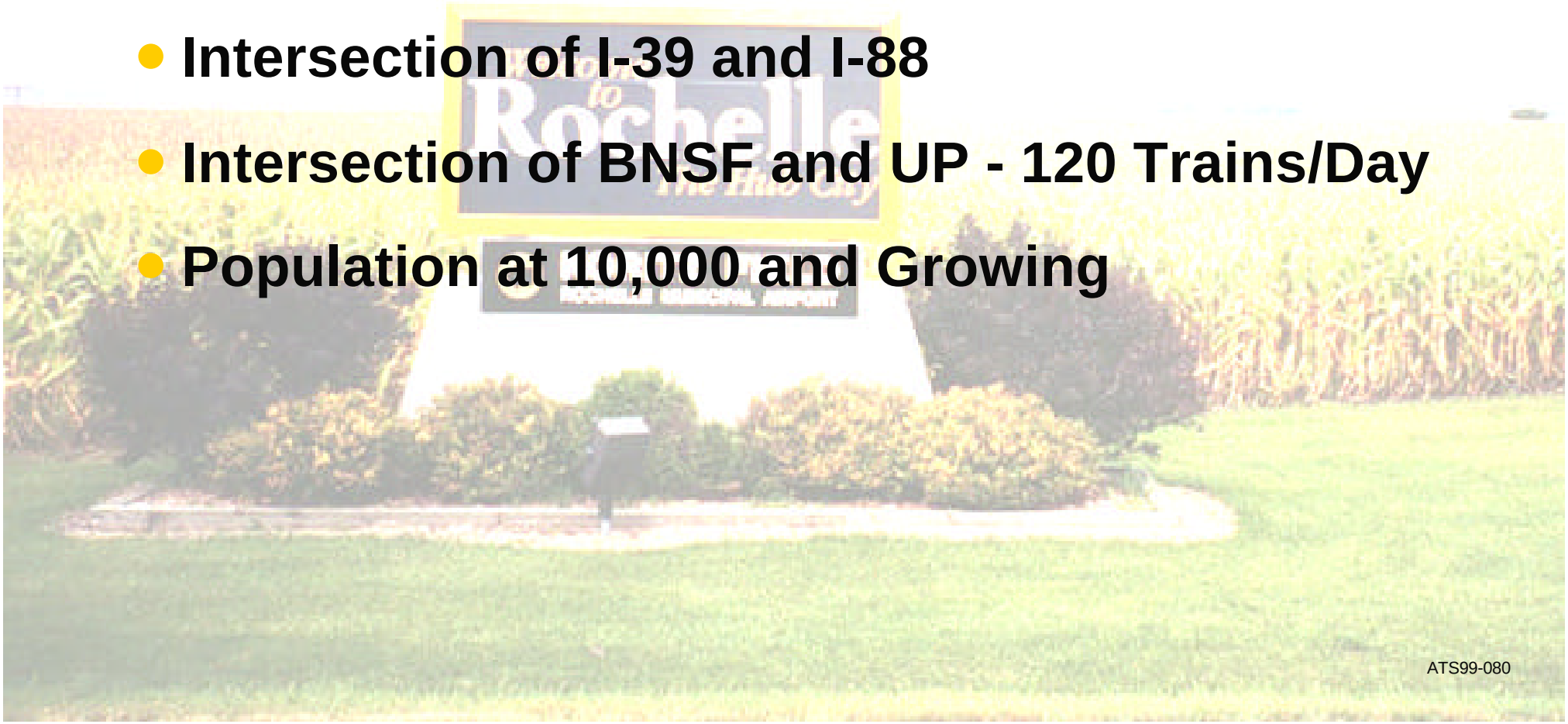


Ray Schwartz

Rochelle Municipal Utilities

City of Rochelle, Illinois

- Located in North Central Illinois
- Intersection of I-39 and I-88
- Intersection of BNSF and UP - 120 Trains/Day
- Population at 10,000 and Growing



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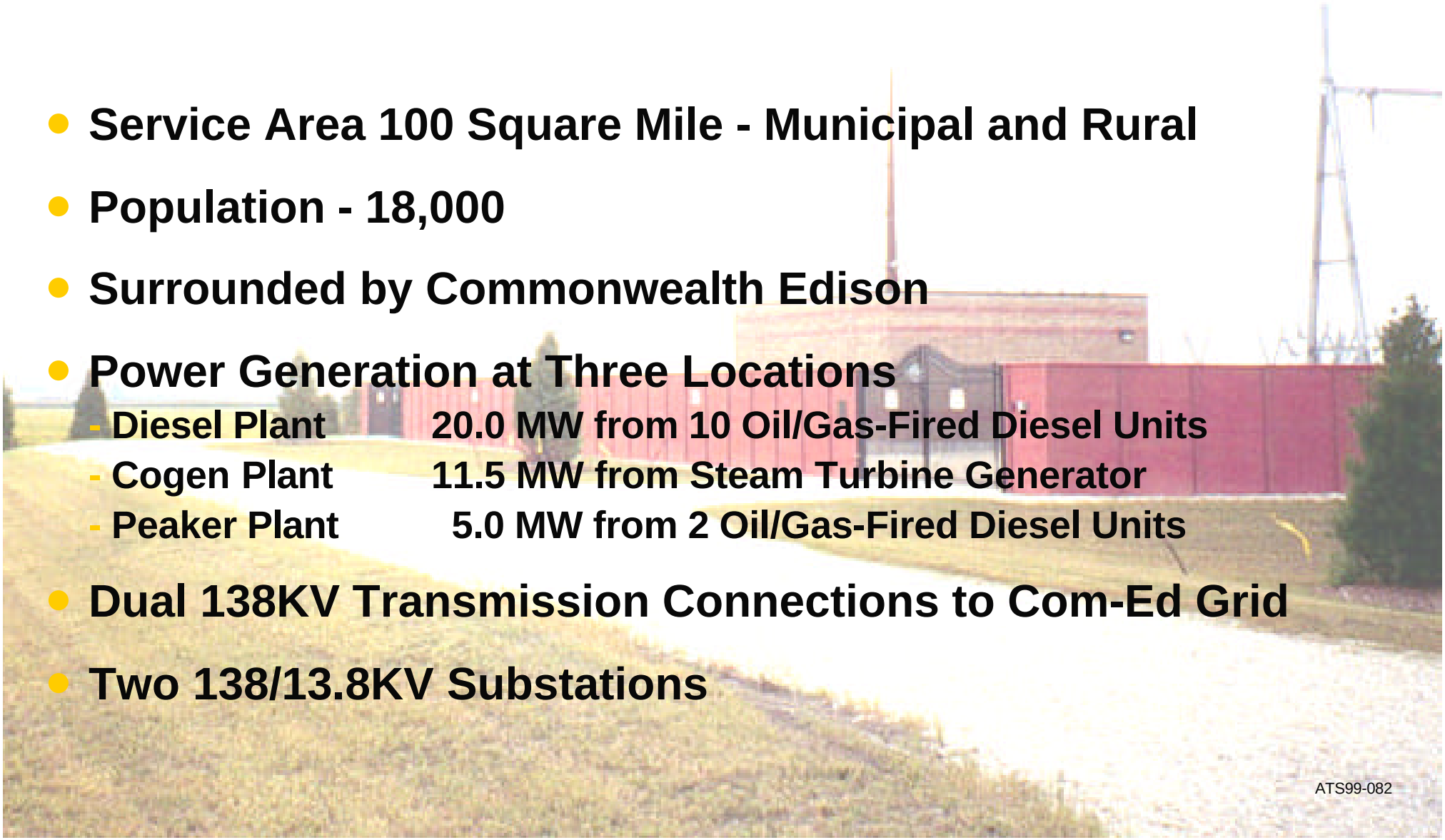
Rochelle Industrial Base

Growth from 19 to 38 Industries in 6 Years

- **Food Processing and Distribution Center**
  - Rochelle Foods (Hormel) — Food Processing
  - Kraft Foods — Food Processing
  - Erie Foods International — Food Processing
  - Del Monte Corp — Canned Food Distribution Center
  - Total Logistics Control — Frozen Food Distribution Center
  - Americold — Frozen Food Distribution Center
- **Other Industries**
  - Eaton Corporation — Electrical Parts
  - Silgan Container Corp — Can Manufacturing

ATS99-081

Physical Profile



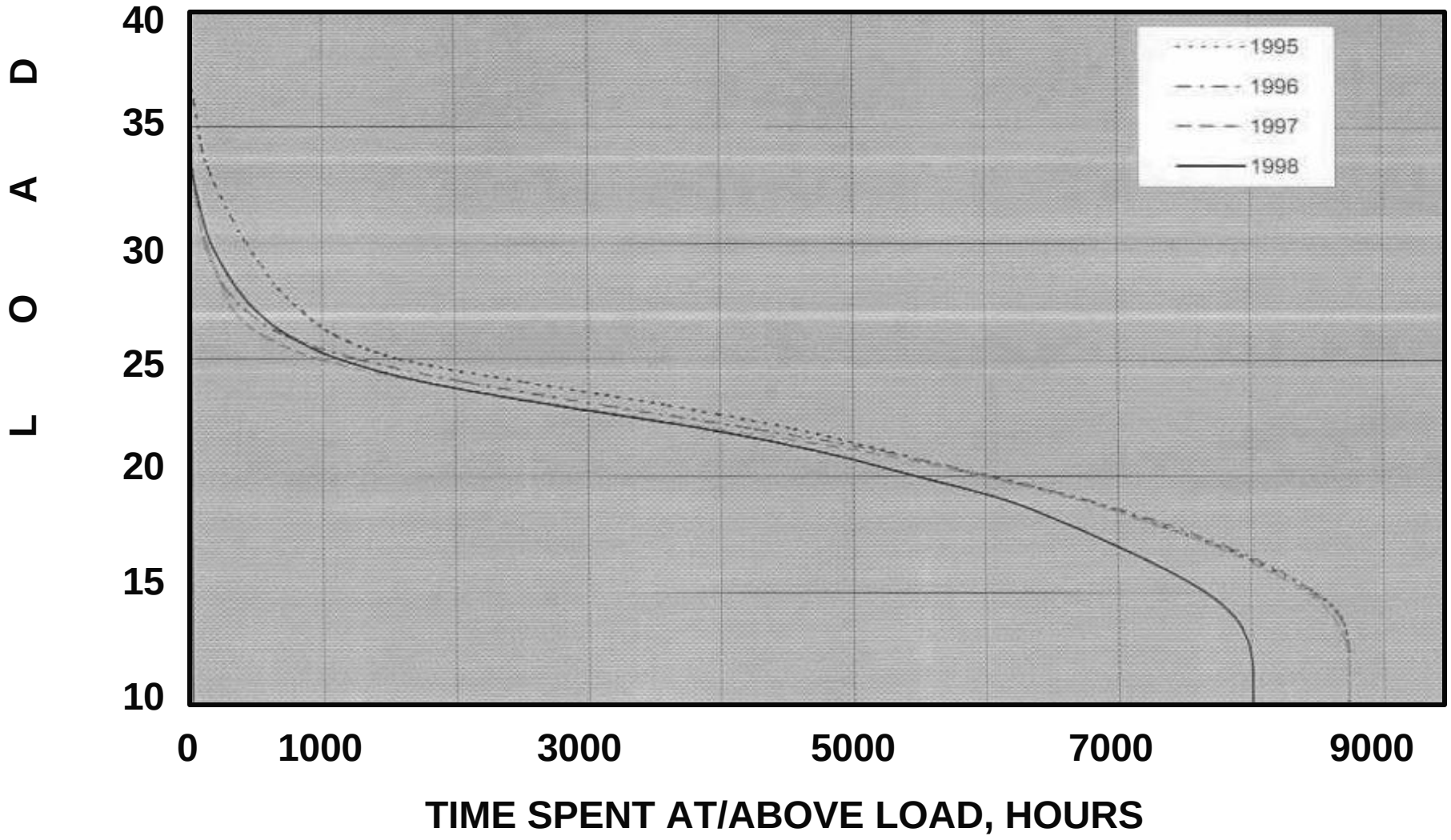
- Service Area 100 Square Mile - Municipal and Rural
- Population - 18,000
- Surrounded by Commonwealth Edison
- Power Generation at Three Locations
  - Diesel Plant 20.0 MW from 10 Oil/Gas-Fired Diesel Units
  - Cogen Plant 11.5 MW from Steam Turbine Generator
  - Peaker Plant 5.0 MW from 2 Oil/Gas-Fired Diesel Units
- Dual 138KV Transmission Connections to Com-Ed Grid
- Two 138/13.8KV Substations

ATS99-082

Power Supply

- Purchase 95 to 98% of Power Wholesale
  - Several Varying Blocks of Firm/Interruptible Power
  - Hourly Interruptible Power for Load Following
- Generation Assets - Current Function
  - Economic Dispatch (Market Hourly vs In-House Cost)
  - Firm Up Interruptible Power
  - Sales to Wholesale Market
  - Emergency Back-up
- Total Output 1998: 180,000,000 kW-hr

Annual Load Duration Curves



ATS99-084

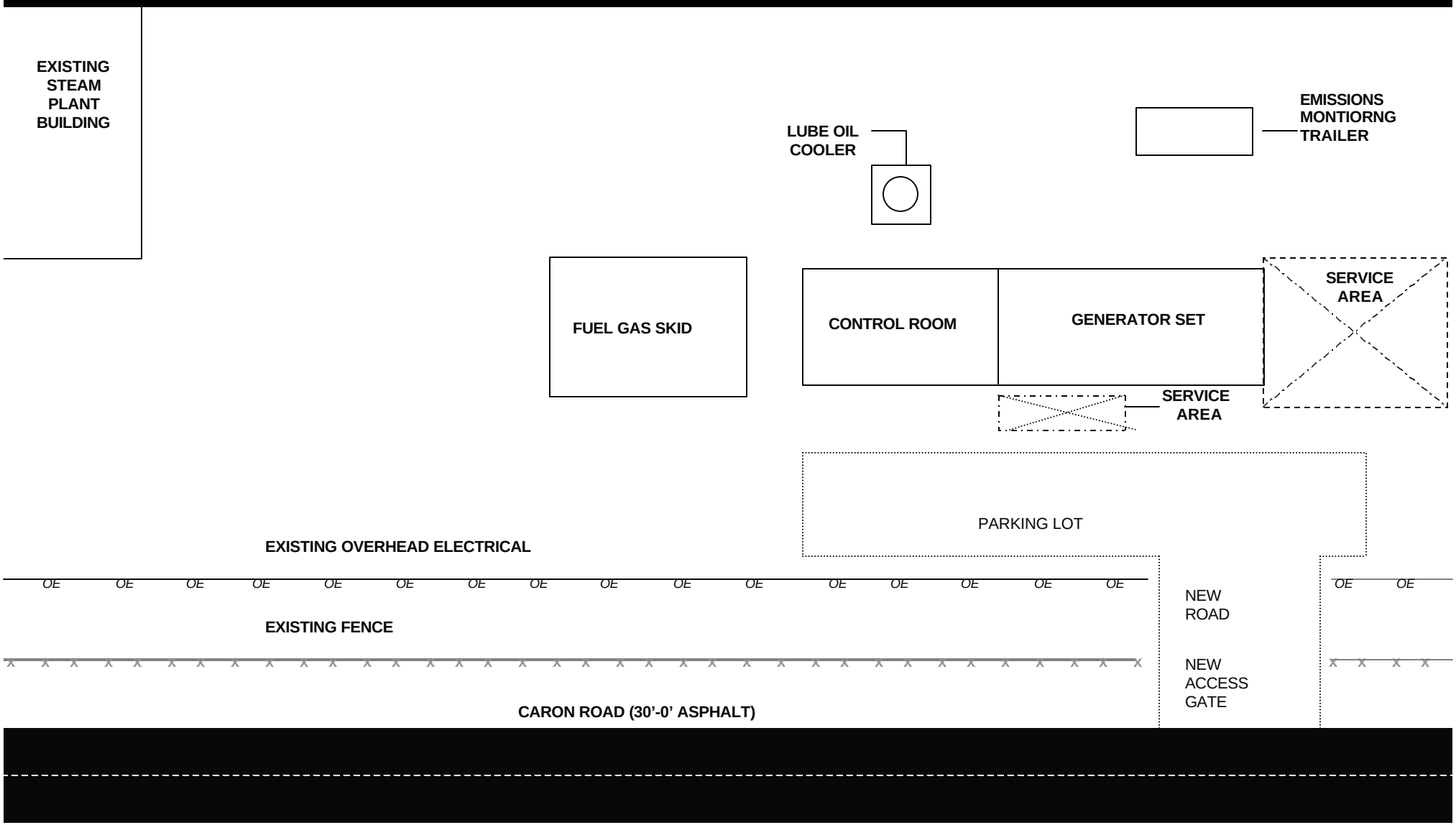
Why Distributed Generation?

- Places Capacity Nearer Load
- Reduces Impact of Transmission Curtailments
- Age of In-House Generation Assets
- Cost of Service

Why the Mercury 50?

- **Operational Flexibility**
  - Base Loading for Hedge Against Supply Interruptions
  - Intermediate Loading for Economic Dispatch
  - Peak Loading for Load Following and Economic Dispatch
- **Multiple Location Potential**
  - Commercial / Industrial Sites
  - Existing Cogen Plant
  - Existing Diesel Plant
  - Sub-Stations
- **Low Environmental Impact**
- **Competitive Operating Costs**

Mercury 50 / Rochelle Site Layout



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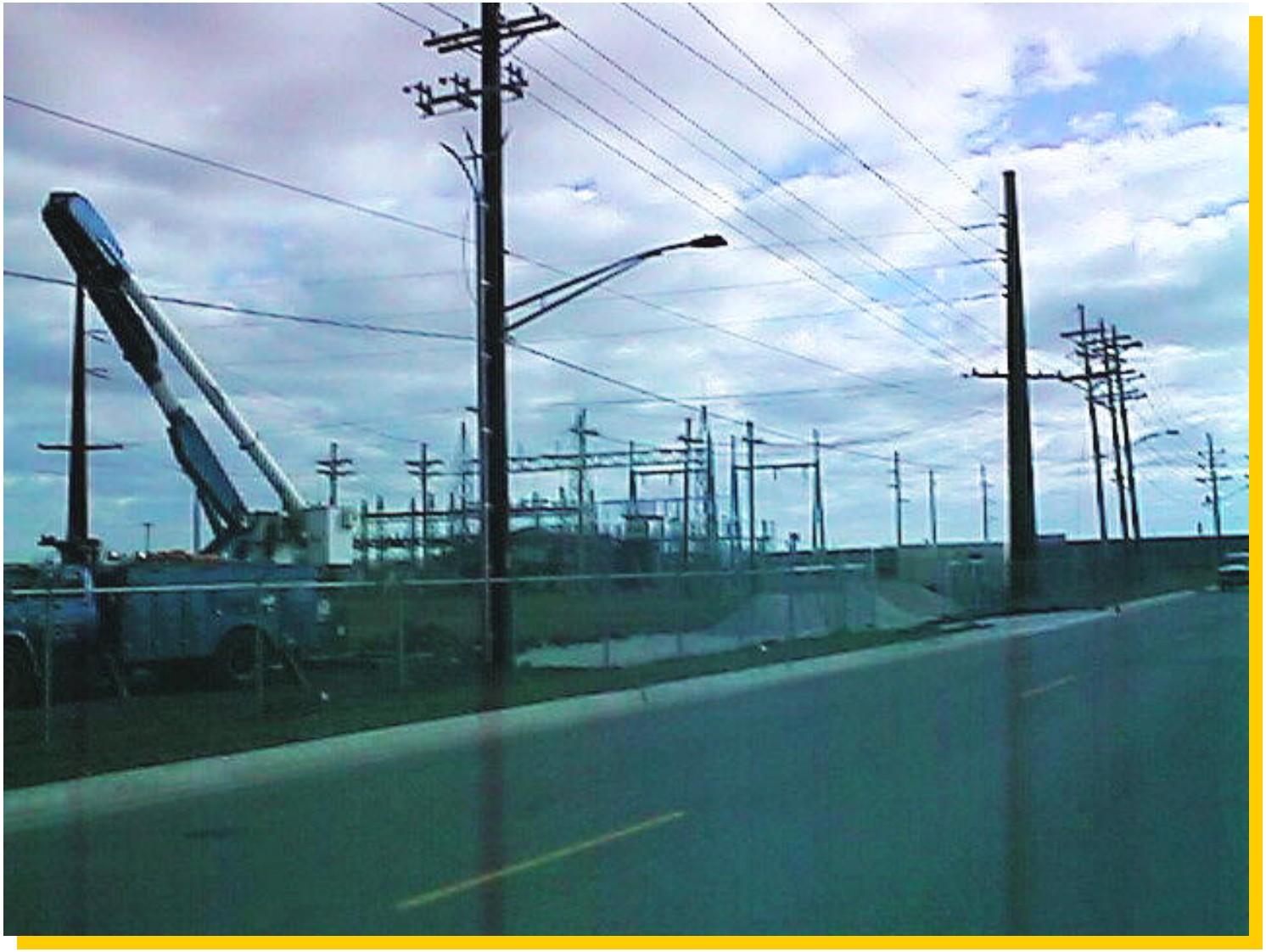
Mercury 50 / Rochelle Site Photo

ATS99-088

Mercury 50 / Rochelle Site Photo



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Mercury 50 / Rochelle Interface

- Direct Connection to 13.8KV System
- Unmanned Site
- Remote Start/Stop
- Fiber Optic Connection to SCADA

Rochelle Future

- Continued Steady Growth
- Intermodal Facility Strong Possibility
- Distributed Generation Role
  - Essential Element of Generation Fleet
  - Replacement for Existing Central Plant
  - Siting on Customer Premises Anticipated
  - Cogeneration Applications
  - Enhance Rochelle's Competitive Edge

Solar Turbines
A Caterpillar Company

Summary

Mercury 50 on Track for Full-Production Release in 2000

- Initial Development Activities Are Complete
- Exceeded Original ATS Program Goals
  - Only Durability Remains to Be Proven
- Field Evaluation Units Being Built and Shipped
- Continue Further Refinements to Achieve Stretch Goals
- Generated Significant Market Interest in ATS Product

Clear Commitment to Commercialize


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