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Update: High-Temperature Electronics and Testing

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Outline

- Introduction
- High-Temperature Electronics at Sandia
- High-Temperature Testing Guidelines
- What Sandia Can Do

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Introduction - Why?

New high-temperature SiC & SOI electronics benefits both sides of the energy equation.

- **Oil and Gas Exploration**
  - **Deep-offshore GOM wells are hot, 200 – 300 Celsius. Costs >$100 Mil each!**
  - **On-shore natural gas wells are >17,000 ft.**
  - **Steam injection production is a growing market**
- **Geothermal Power Production**
- **Nuclear Power**

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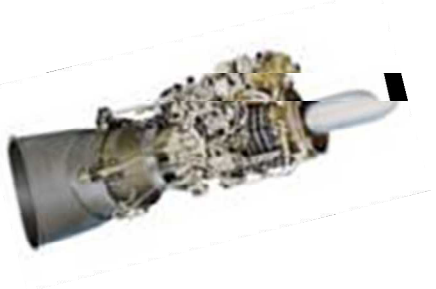
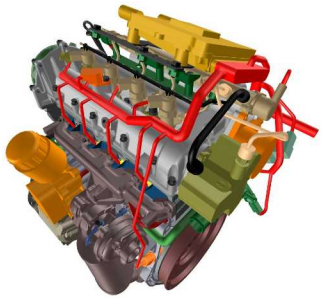
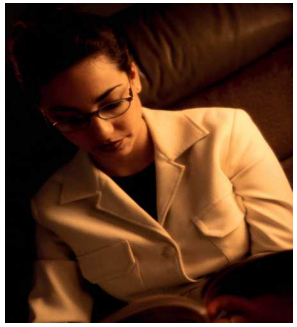
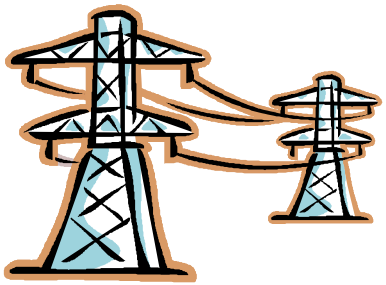
Introduction - Why?









- **Aircraft saves fuel**
  - **Fly by wire (Replace hydraulics and pneumatics with electrical)**
  - **Distributed controls on the engine**
  - **200 to 600 Celsius/44,000 hrs**
- **Automobiles saves fuel**
  - **Improved hybrids**
  - **Drive by wire**
  - **125 – 180 Celsius /10 years**
- **Power grid improvements**
  - **Modular controls**
  - **Reduced cooling fans**
  - **>150 Celsius – 20kV**

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Introduction – Common Goals for Using High-Temperature Electronics

- Increase temperature capability of electronics
  - passively cool electronics
- Save volume and space
  - Replace active cooling with passive cooling (Example – On an aircraft, to cool 1 kWatt of thermal energy, must add 25 pounds to the aircraft)
- Improve power system efficiency
  - Eliminate transients and improve current capabilities for electronic systems for T > 150 Celsius.
- Reduce thermal hot spots
- Increase power density
- Increase operating life and reliability

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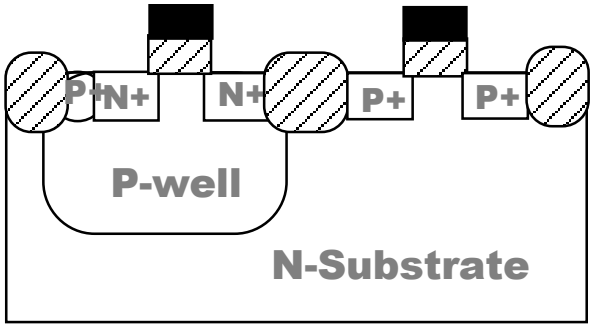
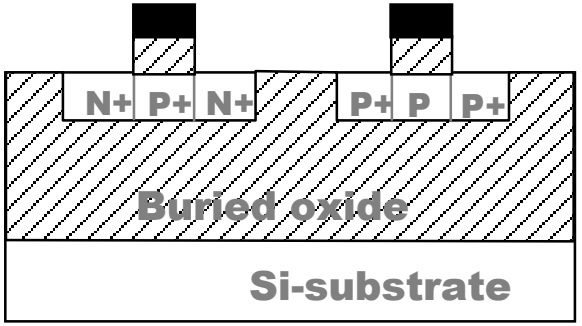
Introduction – What Are High Temperature Electronics? SOI Devices

- Silicon-On-Insulator (SOI) isolates transistors on an insulating material providing:
  - Isolation reduces leakage currents by ~100 times!
  - Latchup immunity
  - 25% Faster Switching
  - Better isolation for analog and digital on the same die
- SOI is the same process as used for Radiation Hardened silicon



A: Cross-section of bulk CMOS inverter



B: Cross-section of a SOI CMOS inverter

In short, SOI is just a better way to build silicon electronic devices

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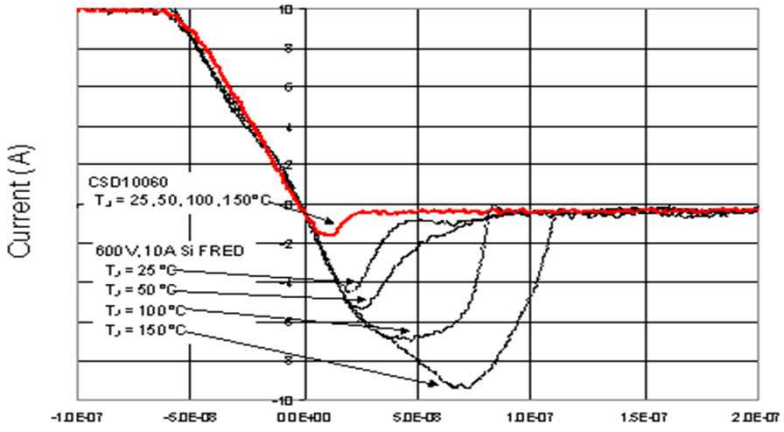
Introduction – What Are High Temperature Electronics? SiC Devices

- SiC has 7 times the voltage breakdown of Si
- SiC has ~3 times the thermal conductivity of Si
- SiC devices are 5 to 10 times smaller than Si
- The smaller SiC power transistor can be operated much faster allowing for smaller passives devices



Courtesy Anant Agarwal, Cree HiTEC 2006

Courtesy Suresh Soni, GTI 2006

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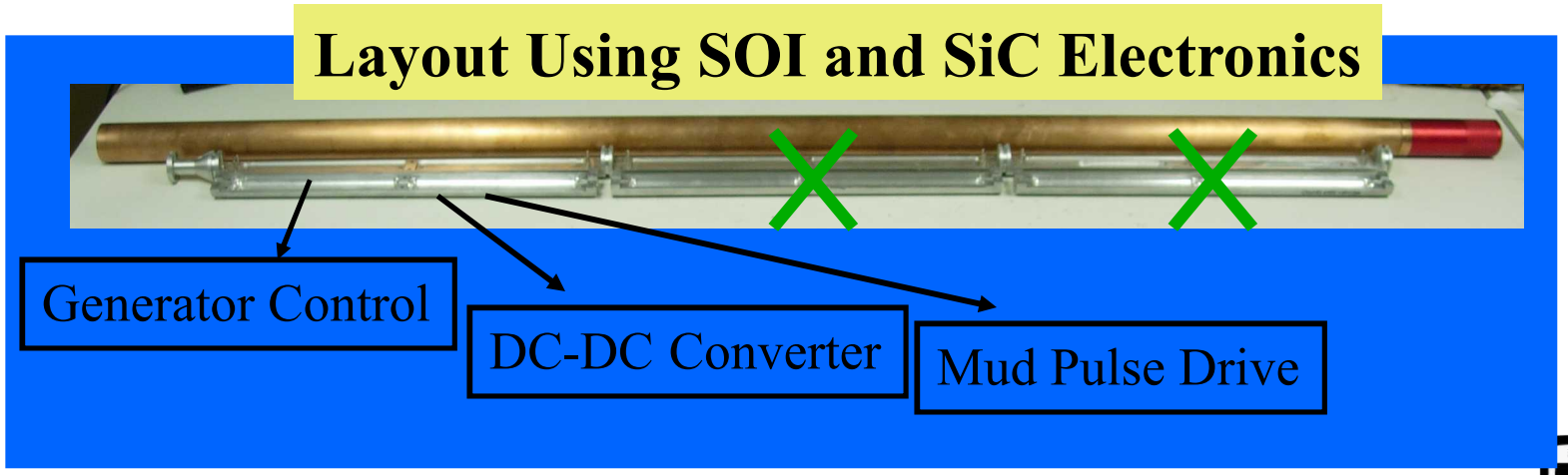
Introduction – Advantage of Using SOI and SiC Devices in Applications

- HPHT turbine regulator using HT SOI and SiC electronics
  - 1/3 the size of the conventional 200°C Si switcher
  - Operates up to 250°C+
  - Commercial systems reduce energy loss by 30-50%
- In 3-5 years this SiC technology will dominate the drilling industry power electronics!!!



High-Temperature Electronics at Sandia - Our Suppliers are the Industry Leaders

- **Below is a short list of the companies Geothermal Research Department is currently working with**

Quartzdyne Inc.

Presidio Components, Inc.

Paine Electronics

Multilayer Prototypes, Inc

Kulite Semiconductor Products

Honeywell SSCS

Weed Instrument Company

Cissoid

Electrochemical Systems

Kemlon Products

Semisouth Laboratories

Endevco Corp

Rockwell Scientific/ GTI

Regal Plastic Supply Co.

Biotronics

Honeywell Richmond

Solid State Devices Inc.

General Atomics

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High-Temperature Electronics at Sandia – Geothermal Research Progress

- Sandia has a complete DAQ 250°C (482°F) tool able to stay in the well indefinitely.
  - Long-term demonstration testing with over 17,000 hrs at 193°C
    - Complete 48 channel µP tool tested to 250°C
    - Currently planning a long-term 225°C demonstration
  - Currently testing a 275-300°C tool in Bakersfield, Ca.
    - Simple two-data-channel tool
    - Planning a long-term 8 week test with a major oil company
  - DWD for downhole bit monitoring while drilling at 225°C
- We can quickly modify our tool to use almost any electronic component or sensor

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High-Temperature Electronics at Sandia – Evaluating New High-Temperature Components

- HT PC Board Material

- 300°C Quartz Crystal
- 300°C SOI Clock Chip

- EEPROM 64K X 16

- 400°C SiC MEM Pressure Sensor (for aircraft engines)

- 250°C SiC JFET Normally On
- 200°C SiC JFET ~Normally Off

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High-Temperature Electronics at Sandia - New Components Coming to Geothermal Research by January 2007

- **8 bit PWM SOI (Automotive)**
- **2K EEPROM SOI (Automotive)**
- **8-Channel, 12-Bit SOI A/D**
- **350°C SOI MEM Pressure Sensor**
- **275°C 8/16 bit SOS HC11 µP with ROM (Late Jan)**

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High-Temperature Electronics at Sandia – Proving Reliability of High-Temperature Electronics and Systems - Long-Term SOI Tool Demonstration

Objective: Demonstrate a microprocessor, multi-channel data collection set of SOI electronics

The Coso well was chosen at 193°C. This is the hottest location within the well. We have 750+ days in the well, along with 750 hours at 200°C inside a test oven.

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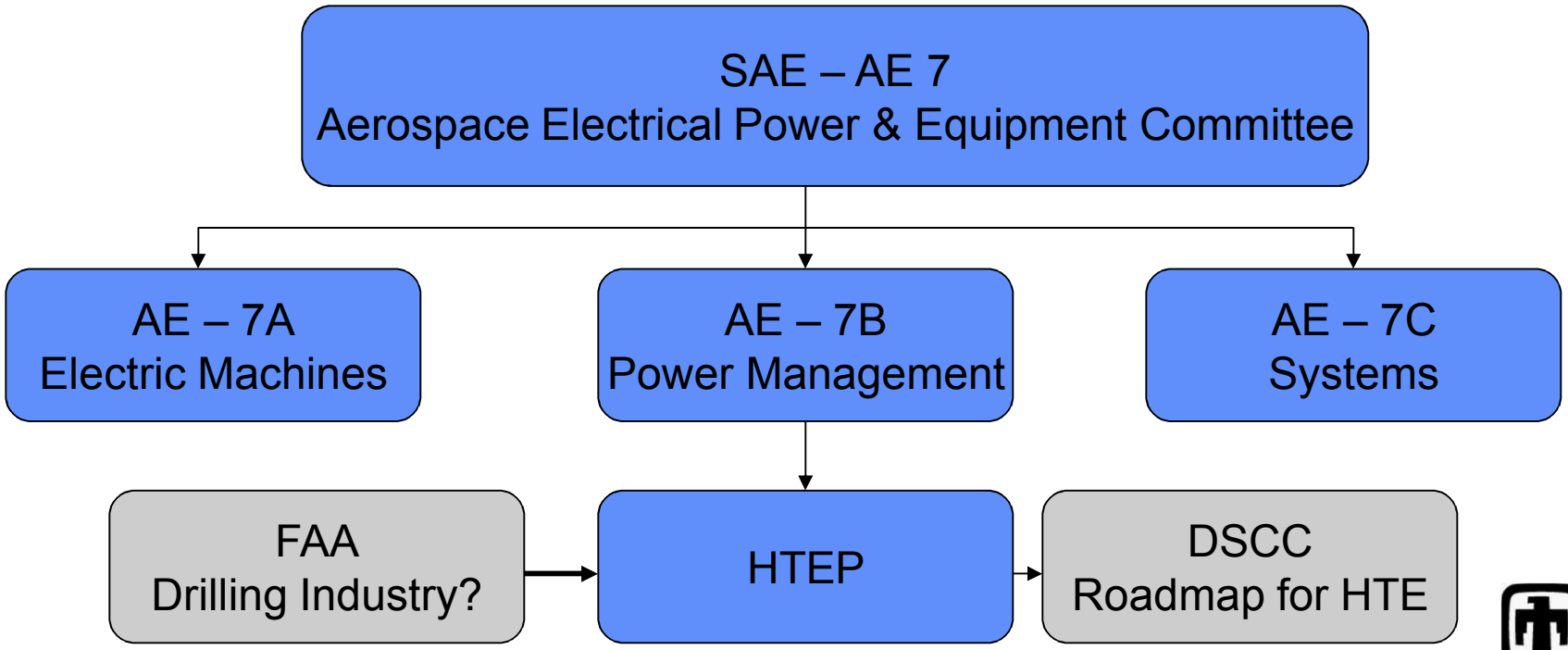
Current Issues with High-Temperature Electronics

- **Capacitors**
  - **Lack of high-voltage, high-capacitance capacitors due to limitations of X7R ceramic**
- **Solders/ Interconnects**
  - **Lack of high-temperature solders (other than 95.5-2.0-2.5 Pb-Sn-Ag)**
- **Packaging (Standard FR4 PCB limited to 175°C)**
  - **What is the best approach – MCM (Al_2O_3, AlN substrates) or high-temperature polymer packaging (polyimide)?**

High-Temperature Test Guidelines – Who Is Proposing the Guidelines

- **Defense Supply Center Columbus (DSCC) maintains the military standards for components (MIL-PRF). However, components that are qualified are very expensive.**
- **High-Temperature Electronics Panel (HTEP) of SAE – AE7 Committee Is Proposing High-Temperature Test guidelines, which will help to establish reliability of high-temperature components and to make them affordable.**



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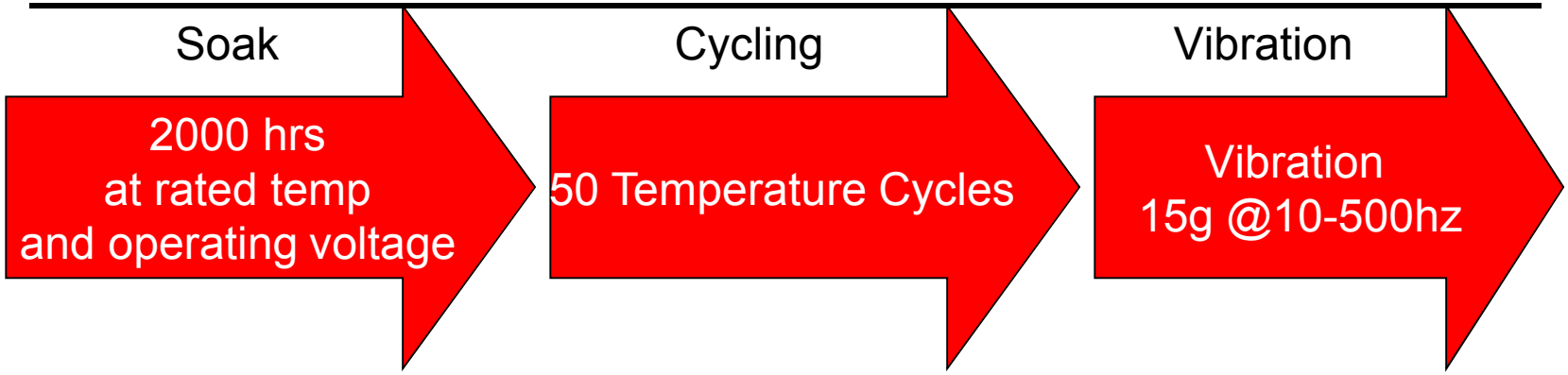
High-Temperature Test Guidelines – Why Have Guidelines

- Aid component manufacturers in identification of components as high-temperature and reliable
- Aid design engineers and system engineers in minimizing qualification testing and development time by using qualified high-temperature electronic components (along with standardized test data from the manufacturer).
- Aid end-users of high-temperature systems in identifying products that are built with high-temperature, reliable components and sensors.

Suggested Minimum Testing for HT Components and Sensors

(Proposed Guidelines Being Developed by High-Temperature Electronics Panel (HTEP) of Society of Aerospace Engineers (SAE) – AE7 Committee)



Test device is calibrated to manufacturers operating specification

A failed device is any device falling more than 5% outside of the manufacturers specification. A complete set of test data, test devices and procedures must be reported in open publication.

Test device is tested against manufacturers operating specification

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Suggested Minimum Testing for HT Components and Sensors (cont.)

- Destructive Physical Analysis (DPA) and Visual-Mechanical Examination per MIL-STD-1580
  - Verify workmanship, construction and materials in making the component or the sensor
  - Show that component is free of unsuitable materials for high-temperature (e.g., 100% Sn) and is defect free.
  - Prevent counterfeiting of qualified, high-temperature, high-reliability components
- Solderability
  - Ensure that reliable interconnects can between components and packaging.

What Sandia National Labs Can Do

- There is room for Sandia in HT component development
  - John Witham, 1732 for HT Capacitors
  - Karen Waldrip, 2521 for GaN crystal growth
- There is room for Sandia in component and system-level packaging development
  - The success of future systems is 100% dependent on packaging and interconnects
    - Most applications will use the same devices in die form
    - Robust packaging and reliable interconnects are the key to high-temperature electronic systems.
  - Paul Vianco, 1824 for Solders and die attach
  - Blake Jakaboski, 17152 for HT packaging

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What Sandia Can Do – Departments 1732 (Frequency Devices) and 1734 (Component Information & Models)

- Component Testing (Electrical, Thermal, Mechanical, Radiation) → 1732, 1734
- High Performance Electrical Modeling and Simulation (HPEMS – Xyce, Chile SPICE, etc.) → 1734
- Component Modeling (Library of >1800 component models, Model Verification, Model Extraction, Advanced Model Development, etc.) → 1734
- Failure Analysis (Electrical Failure Analysis Laboratory, Scanning Electron Microscope Laboratories, Focused Ion Beam System, Optical Microscopy Laboratory, Scanning Probe Microscope Laboratory) → Sandia Site Wide
- Reliability and Risk Assessments of Components → 1732, 1734

What Sandia Can Do – Departments 1732 (Frequency Devices) and 1734 (Component Information & Models) (cont.)

- Weapons Reserve COTS Insertion Process (WRCIP – Parts Selection, Procure and Accept, Reliability and Qualification) → 1732, 1734
- Development, use and implementation of commercial and Sandia-developed sensors to provide functional sensor sub-systems → 1732
- Design and development of clocks, oscillators and sensors for national security applications → 1732
- Design, develop and test custom capacitors for national security applications → 1732

What Sandia National Labs Can Do (cont.)

- Geothermal Research Can Do:
  - Provide third party test data on components and sensors
  - Simulate real world applications within the drilling industry by building complete HT – HR drilling tools
  - Provide a list of Sandia suppliers to anyone on request
  - Encourage new DOE programs in HT components, sensors and systems.

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Conclusions

- High temperature electronics and sensors have potential applications in geothermal, petroleum, aerospace, military and automotive industries after reliability is proven.
- High-temperature testing guidelines are needed to provide a formalized guideline for component manufacturers on high-temperature components and to establish the reliability of high-temperature components for end users.
- High-temperature electronics and components would benefit the energy industry and the national security of the United States.
- Thank you for your time and for your consideration.

Definitions

- SOI – Silicon on Insulator
- SOS – Silicon on Sapphire
- SiC – Silicon Carbide
- µP – microprocessor
- EEPROM – electrical erasable programmable read only memory
- MEM – micro-electro-mechanical
- JFET- Junction Gate Field Effect Transistor
- A/D – Analog to Digital
- PWM – Pulse Width Modulator
- ROM – Read Only Memory
- AlN – Aluminum Nitride
- Al_2O_3 – Aluminum Oxide
- X7R – Electronic Industry Association (EIA) designation of capacitance change of ±15% from -55°C to +125°C unbiased.

COTS Testing, Evaluation and Qualification Resources

- CALCE – Center for Advanced Life Cycle Engineering (http://www.calce.umd.edu/)
- DSCC – Defense Supply Center Columbus (http://www.dscc.dla.mil/)
- NASA Electronic Parts and Packaging Program (NEPP) (http://nepp.nasa.gov/)
- Sandia National Laboratories Microsystems Science, Technology & Components (http://www.sandia.gov/mstc/index.html)
- Honeywell Solid State Electronics Center (SSEC) (http://www.ssec.honeywell.com/hightemp/)
- NASA Silicon Carbide Electronics (http://www.grc.nasa.gov/WWW/SiC/index.html)
- Sandia National Laboratories Microsystems Science, Technology & Components – Electronic Components (http://www.sandia.gov/mstc/products/elect-comp/index.html)

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