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Scale-Up of Hydrogen Transport Membranes for Carbon Capture Applications

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Doug Jack, Carl Evenson, John Faull, David Anderson,
Richard Mackay, Jason Stotter, Darcie Bailey

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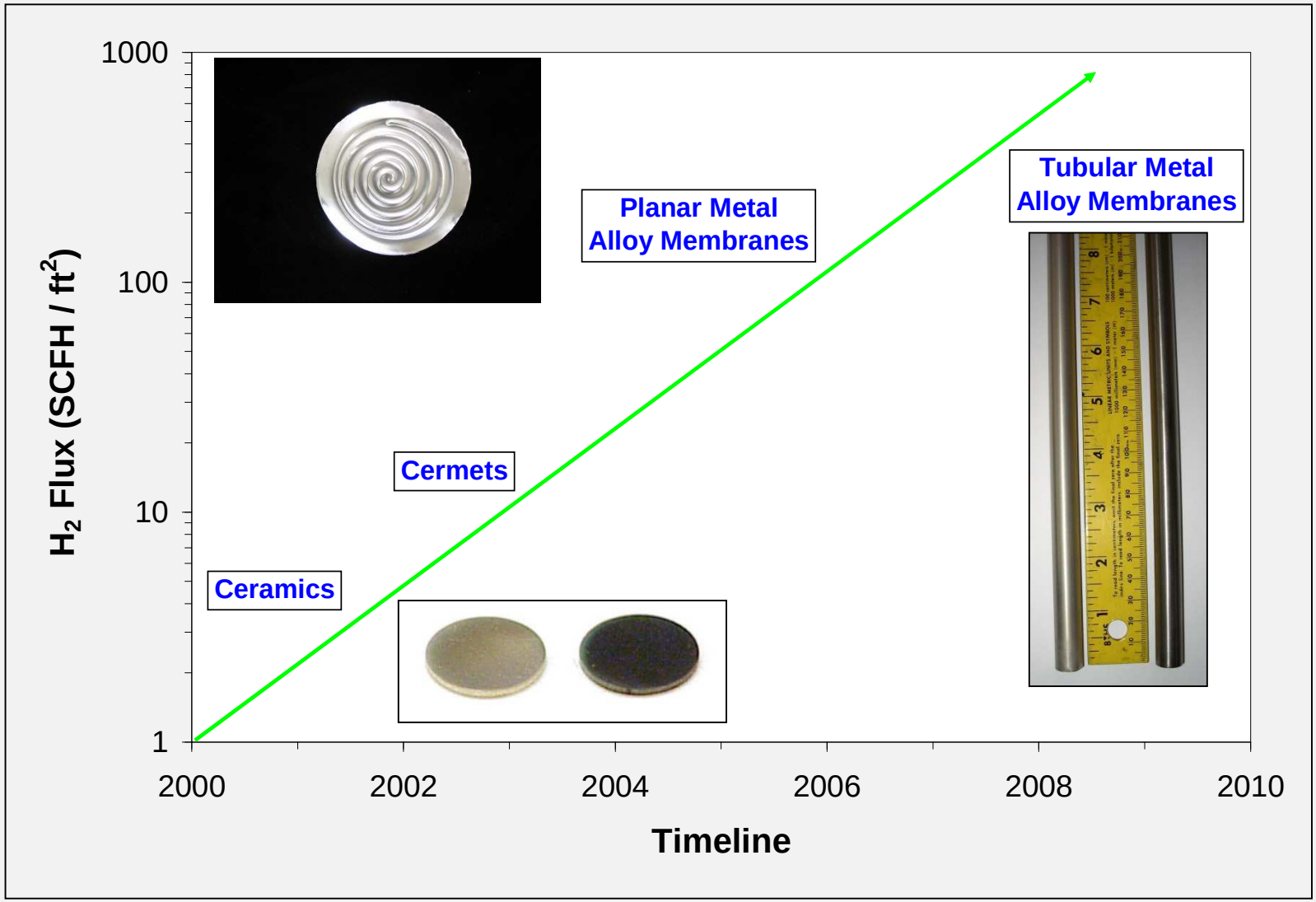
H_2 Membrane Background



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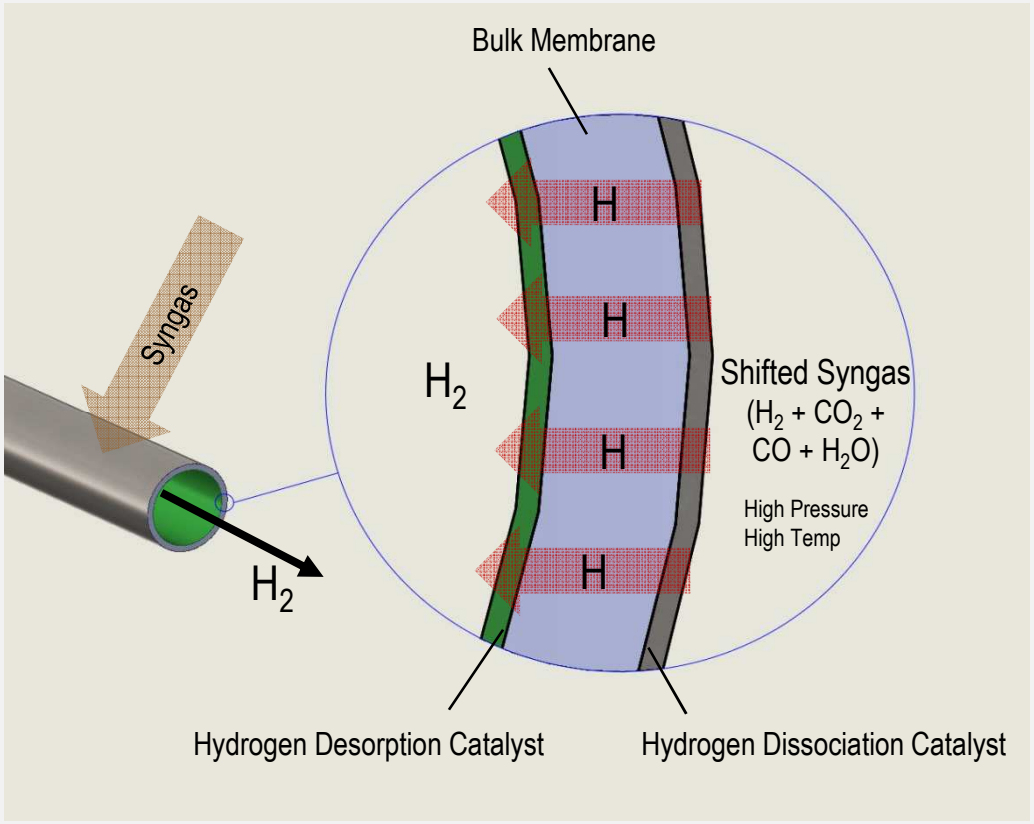
Dense Metal Membrane

- Sieverts' Law:

$$J = \frac{P}{d}\left({P_f}^{0.5} - {P_s}^{0.5}\right)$$

- where:
  - J = hydrogen flux (mol/m^2/s)
  - d = membrane thickness (m)
  - P = permeability (mol/m/s/Pa$^{0.5}$)
  - P_f = hydrogen partial pressure on the feed side of the membrane (Pa)
  - P_s = hydrogen partial pressure on the sweep side of the membrane (Pa)



Dense, self-supporting membrane

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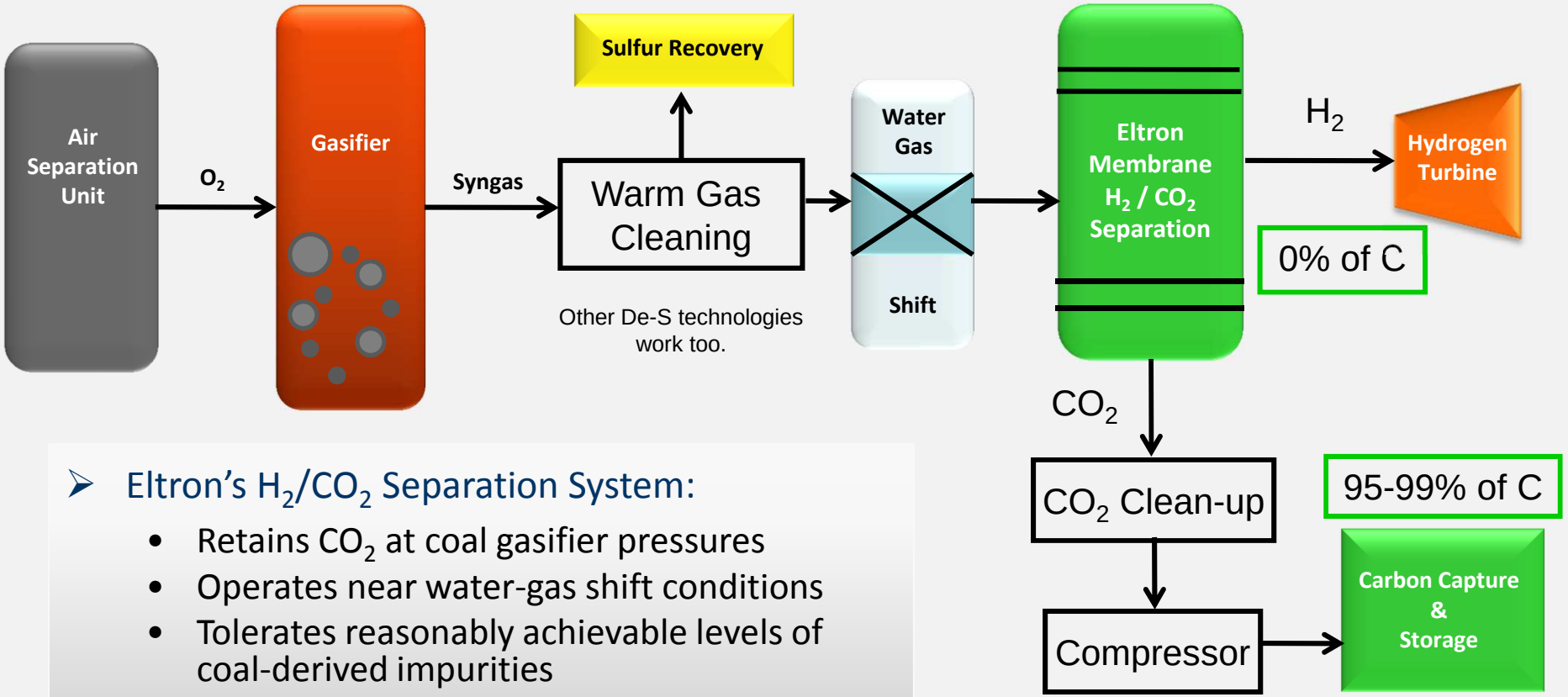
IGCC-CCS Process Overview



- Eltron's H_2/CO_2 Separation System:
  - Retains CO_2 at coal gasifier pressures
  - Operates near water-gas shift conditions
  - Tolerates reasonably achievable levels of coal-derived impurities
  - Delivers pure H_2 for use in fuel cells, gas turbines, and hydrocarbon processing
  - Is cost effective compared to standard technologies for carbon capture

Other Applications:
Polygen, chemicals, PDH, CTL, GTL, Integrated Membrane Rxrs.

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Scale-Up Path

	1	2	3
Bench-Scale	**Pilot - Subscale Engineering Prototype (SEP)**	**Pilot – Process Demonstration Unit (PDU)**	**Pre-Commercial Module (PCM)**
Eltron	Eastman Chemical Co.	Eastman Chemical or PCM site.	To Be Determined
Simulated Syngas	Gasified Coal	Gasified Coal	Gasified Coal / Petcoke
Planar disks, 6” - 2’ long membrane tubes	2 5’ tubes	~ 20 10’ tubes	~ 640 - 1600 10’ tubes
Up to 1 lb/day	Up to 12 lbs/day	~250 lbs/day	4-10 T/day

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1 SEP Scope

- Performance
  - Evaluate flux, life, impurity effects of coal syngas at pilot scale
  - Establish operating conditions
  - Develop safe operating procedures for start-up, shutdowns
- Mechanical Design
  - Assess strength of materials, embrittlement, construction and sealing techniques
  - Understand manufacturing costs and maintenance issues
- Engineering and Economic Analysis
  - Develop mass transport resistance model
  - Refine membrane module process model
  - Update techno-economic process model - Integrate results into flow sheets and compare process economics versus other technologies

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SEP Pilot Testing

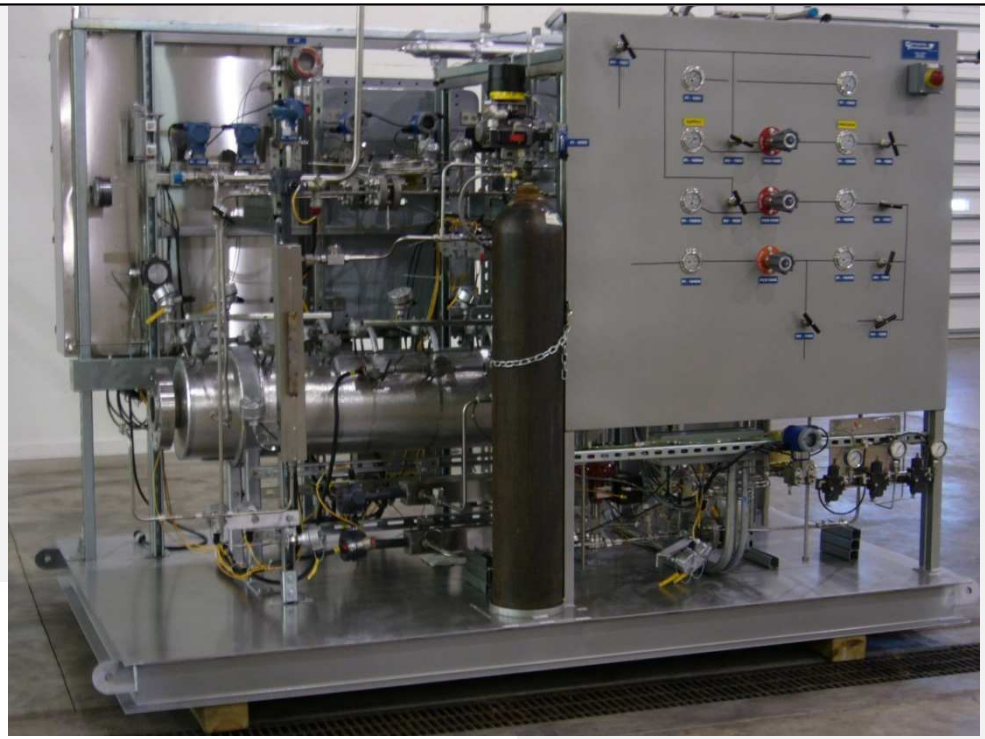
Raw Syngas

ZnO

WGS

HTM Skid

Installed and operated at Eastman Chemical in Kingsport, TN



Skid built by:

Continental Technologies

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SEP Pilot Results

- SEP unit successfully operated
  - Start-up, shut-down, control strategies developed
  - Membranes tested at feed pressures up to 850 psig
  - Membranes tested under sweep & no-sweep conditions
  - Two different substrate manufacturers and sealing mechanisms demonstrated
  - One set of tubes operated over a range of 16 different conditions for ~250 h
  - Stability of flux under coal-derived syngas equivalent to stability in lab
  - Max hydrogen production of ~3 lbs/day
- Observed flux and corresponding hydrogen recovery was lower than expected.
  - Mass transfer limitations
  - Catalyst deposition scale-up procedures not optimized

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2 Process Development Unit

- Operation 2012
- Target 250 lbs/day
- 1st scale-up step with a tube bundle
  - Designed using CFD
  - Optimized seal design
- Scope
  - Collect performance, cycling, and lifetime data
  - Demonstrate 10’ long membrane tubes
  - Evaluate process dynamics

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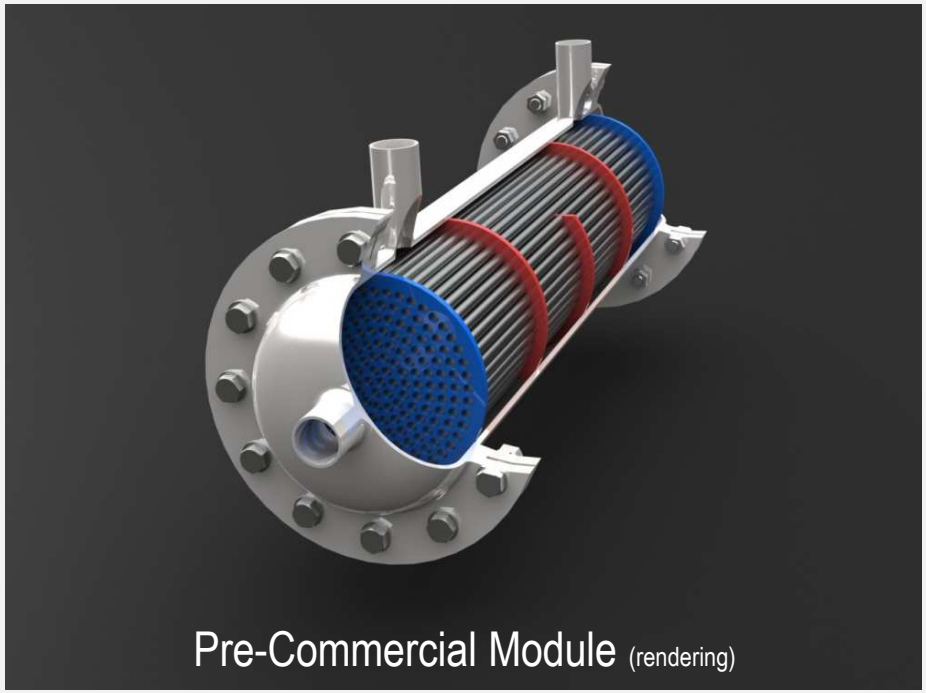
3 Pre-Commercial Module (PCM)

- ARRA Project - DOE $71.4 MM
- October 2011 – June 2015
- Scope
  - Accelerate PDU testing
  - Design, build & operate 4-10 ton/day demonstration reactor on live syngas
- Goal
  - Scale-up of HTM system for energy efficient carbon capture and H_2 separation from industrial sources
- Status
  - Pre-FEED completed by Eltron and URS



Pre-Commercial Module (rendering)

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Techno-Economic Modeling

- Provide guidance to development program
  - Focus on critical parameters
  - Shorten development time
- Establish commercial viability of process
  - IGCC Plants
  - Polygen applications
- Optimize value of technology
- Evaluate applications beyond IGCC plants
  - Refinery streams
  - Chemicals production

Techno-Economic Modeling

Assumptions

- Plant Capacity = 275 MW
- 95% H_2 Recovery
- Required Carbon Capture = 90%
- Required Sulfur Removal 99%
- Required NOx Removal ≤ 0.05 lb/MMBTU NOx
- Cost of Electricity - DOE financial model v3.0

No value assigned to CO_2 emissions avoided

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Techno-Economic Summary

	Case 1	Case 2	Case 3	Case 4
Pre-Combustion Gas Cleaning & CO2 Capture Method	2-Stage Selexol	Cold Gas (Amine) Cleaning & Eltron Membrane	Warm Gas Cleaning & Eltron Membrane	Warm Gas Cleaning & Eltron Membrane
Gasifier Cooling Method	Quench	Radiant-Convective	Radiant-Convective	Quench
Thermal Efficiency	27.4%	32.0%	33.6%	31.6%
% CO2 Captured	90%	90%	95%	95%
Cost of Electricity ($/MWh)	115.5	114.5	106.0	100.4

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Summary

- Eltron is in the process of scaling-up our membrane system.
- First scale-up step:
  - Stable performance under coal-derived syngas.
  - Operation over a range of conditions.
  - Two substrate suppliers and two different sealing techniques utilized.
  - Low than expected flux rates observed.
    - Eltron is executing a plan to resolve this issue.
    - More run time on real syngas needed to direct development program and obtain scale-up data.
- Next Steps:
  - Continued SEP operations in parallel with PDU design.
  - Finalize PCM site selection and kick-off FEED.
- Techno-economic modeling continues to show commercial viability.

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Thank You!

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