FAILURE MODES IN HEAT RECOVERY STEAM GENERATORS (HRSGS)

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- In this presentation we are going to discuss about the main HRSG failure mechanism influenced by cycle chemistry and thermal transient behaviors.
- These findings are from available literature up to date.
- According to our findings we can mainly divide these into 2 parts.

  - **Cycle chemistry influenced failure mechanisms**
    - FAC
    - UDC
  - **Thermal transients influenced failures**

Cycle chemistry influenced failure mechanisms

Flow-Accelerated Corrosion (FAC)

- Occurs when the protective oxide layer (magnetite) on carbon steel dissolves due to water flow or wet steam, causing metal loss and thinning.

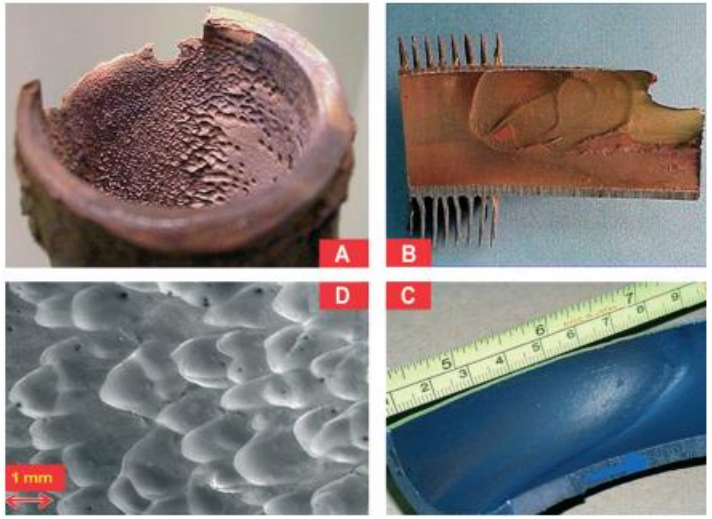
Where?

Single-Phase FAC:

- Economizer/preheater tubes at inlet headers.
- Vertical LP evaporator tubes near bends and outlet headers (HGP units).
- IP evaporator tubes in triple-pressure units at reduced pressure.

Two-Phase FAC:

- LP evaporator transition headers.
- Horizontal LP evaporator tubes at tight hairpin bends (VGP units).
- LP drum internals.
- Deaerators and LP heater shells in conventional plants.



Three examples of FAC in HRSG LP evaporator tubing.

A) shows single-phase FAC in a vertical tube (HGP),
B) shows an example of two-phase FAC in a vertical tube (HGP),
C) shows two-phase FAC in a tight hairpin bend of a horizontal tube (VGP), and
D) shows the surface of FAC damage on an HRSG LP evaporator taken with a scanning electron microscope showing the typical scalloped appearance always seen of FAC.
(Source: A and B are from Dooley et al. [27])

Flow-Accelerated Corrosion (FAC)

Role of Feedwater Chemistry in FAC Control

Reducing All-Volatile Treatment (AVT(R)):

- Uses ammonia and reducing agents.
- Oxygen Level: < 10 µg/kg : Maintain low oxygen levels
- ORP: –300 to –350 mV (optimal), can be as high as –80 to –100 mV.
- Risk: Increased susceptibility to FAC under less controlled ORP.

Oxidizing All-Volatile Treatment (AVT(O)):

- No reducing agents; relies on air in-leakage.
- Oxygen Level: < 10 µg/kg at condensate pump discharge.
- ORP: Around 0 mV, slightly positive or negative.
- Benefit: Reduces FAC risk by minimizing reducing conditions.

Oxygenated Treatment (OT):

- Adds oxygen and ammonia to feedwater.
- ORP: +100 to +150 mV.
- Benefit: Strong oxidation environment, highly effective in preventing FAC.

Under Deposit Corrosion (UDC)

- Localized corrosion develops beneath deposits on a metal. These corrosion products are mostly formed due to FAC in the low temperature parts of the system.

- There are 3 main UDC mechanisms.
  - Caustic Gouging
  - Acidic phosphate corrosion
  - Hydrogen Damage

(i) Caustic Gouging

How?

- Caustic gouging is a type of Under Deposit Corrosion in boiler and HRSG tubes, caused by excessive deposits of corrosion products and concentrated sodium hydroxide.
- The concentrated sodium hydroxide dissolves (fluxes) the protective magnetite layer, Eq. (1), and/or the tube metal, Eq. (2). The products of these reactions are crystals of sodium ferroate and ferroite.

$$Fe_3O_4 + 4NaOH \rightarrow 2NaFeO_2 + Na_2FeO_2 + 2H_2O \qquad (1)$$

$$Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2 \qquad (2)$$

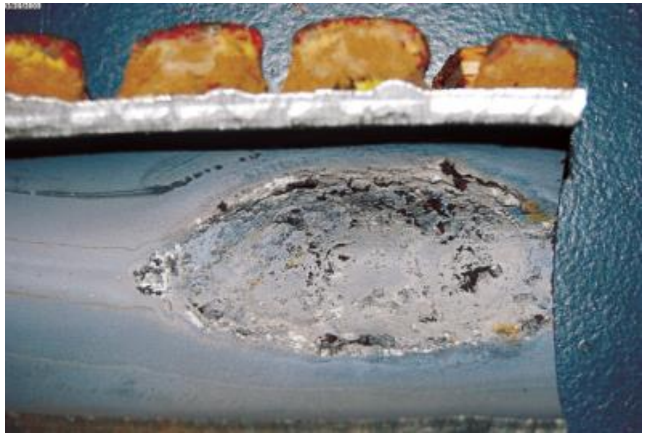
Where?

- HP Evaporators: Due to sodium hydroxide concentration under thick deposits.
- Tube Bends and Welds: Flow disruptions lead to deposit accumulation.
- LP and HP Evaporator Tubes: When there's internal flow disruptions.

(i) Caustic Gouging

Features of failure	• Gouged areas; thick, adherent deposits. • Ductile, thin-edged or pinhole failure. • Longitudinal cracks are the typical appearance in HP evaporators of HRSGs since any bulging is restricted by the fins.
Key microstructural features	• Material removal only, no microstructural changes in the tube material. • No protective magnetite layer.
Attack rate	• Rapid (up to 2 mm per year).

Heavy deposits and caustic gouging



Closeup view of gouge

(i) Caustic Gouging

Root causes?

- **Poor feedwater treatment:** Results in high levels of corrosion products (iron and copper oxides) which can deposit in HRSG tubes.
- **High concentration of sodium hydroxide** in boiler water due to:
  - Excessive sodium hydroxide under sodium hydroxide treatment.
  - Overuse of sodium hydroxide during all-volatile treatment (e.g.,startup or overcoming acidic contamination).
  - High sodium hydroxide levels used as a pH control under phosphate treatment.
- **Flow disruptions:** In the internal water flow inside HRSG HP evaporators, contributing to increased deposition of corrosion products.
- **Undetected/excessive deposits:** Due to inadequate tube sampling or delayed chemical cleaning.
- **Ineffective chemical cleaning:** Deposits remain in critical areas of HRSGs.
- **Ingress of sodium hydroxide:** Due to issues in makeup water treatment units or condensate polishers.

(ii) Acidic phosphate corrosion

How?

- In high temperatures and pressures (>100 bars) phosphate hideout can occur and it will cause a sudden decrease in phosphate concentration in the feed-water. Excess phosphate will be deposited as Sodium iron hydroxy phosphate – SIHP.
- SIHP is unstable at ambient water conditions, thus it re-dissolves when water is cooling (phosphate hideout return). This will decrease Na to phosphate ratio.
- Na to phosphate drops below 3, feed-water will become acidic.it will react with the oxide layer and create $NaFePO_4$ and Fe_2O_3.
- This reaction convert Magnetite layer into hematite rapidly and cause severe corrosion.

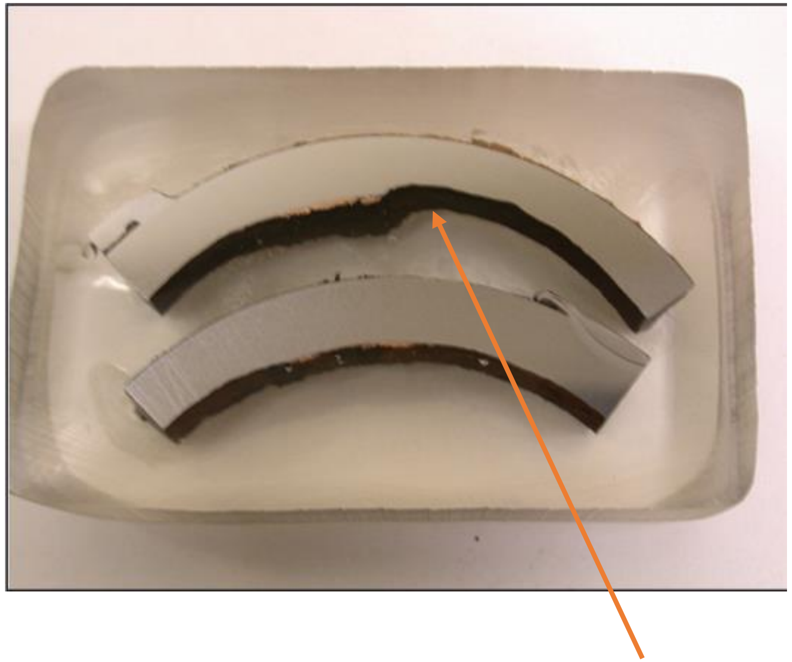
$$Fe_3O_4 + 3Na^+ + 3H_2PO_4^- + H_2 \longleftrightarrow 3NaFePO_4 + 4H_2O \quad (1)$$

It is the consumption of hydrogen by Reaction (1) that drives the conversion of magnetite to hematite:

$$Fe_3O_4 + 2Fe_3O_4 + H_2O \longleftrightarrow 3Fe_2O_3 + H_2 \quad (2)$$

From PPChem, 2010

(ii) Acidic phosphate corrosion



Acidic phosphate corrosion gouge

Where?

- HP evaporator tubes and headers.

Root causes

- Formation of deposits
- Phosphate hideout
- Phosphate hideout return
- Flow disruptions

Identification

- Tube thinning can be identified using ultrasonic testing.

(iii) Hydrogen Damage

- Condensation of chlorides under the deposits create local acidic environment. This will generate atomic hydrogen and defuse into perlite structure.
- These atomic hydrogen will react with cementite in pearlite structure and micro-cracks will be generated. This will lower the strength of the carbon steel and lead premature ruptures in the pipes.
- Chloride irons can enter the cycle through minor condenser leakages.

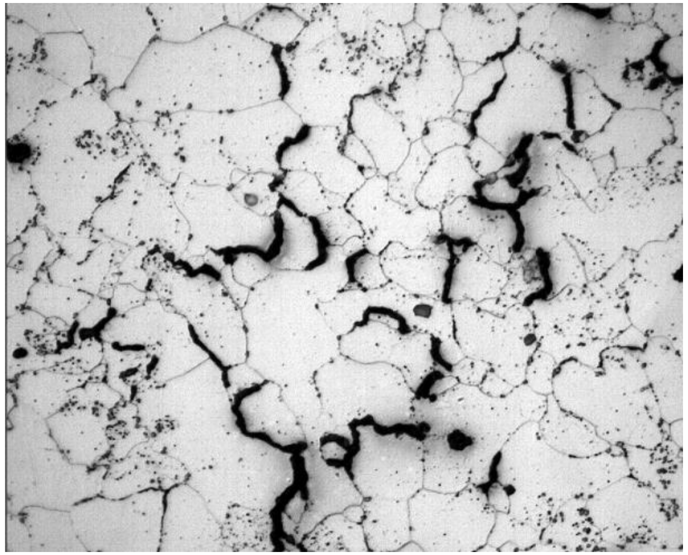
$$Fe_3C + 4H \rightarrow 3Fe + CH_4 \qquad (1)$$

Where?

- HP evaporator tubes

Identification

- Some times tube thinning does not occur. Harder to identify using NDE methods.



Micro-fractures in pearlite structure

Thermal transients influenced failures

What are thermal transients?

- They are the repeated heating and cooling cycles happens during plant’s startup, shutdown and load changes.

How they cause failures?

- This thermal transients cause thermal stresses in the components due to restricted expansions and temperature gradients.
- Transients cause irreversible fatigue damage in components during each thermal cycle.
- After a number of repeated cycles, small cracks will form in the stress concentrations and eventually they lead to **thermal fatigue failures** and **corrosion fatigue failures**.

How to identify?

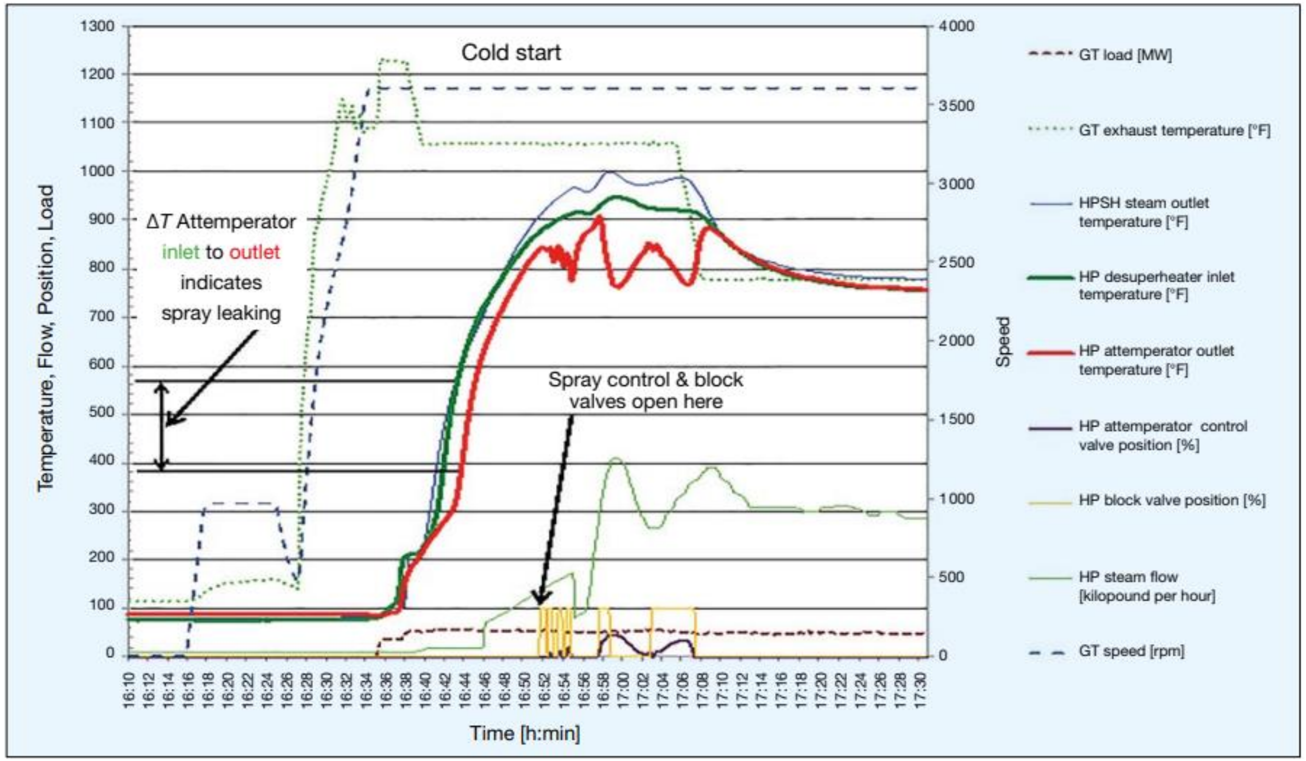
- Through plant’s distributed control system(DCS) trends.

Commonly identified causes for damaging thermal transients

- Attemperator spray water leakages.
- Attemperator overspray.
- Ineffective HP SH draining during startup.
- High pressure ramp rates in HP and LP drums.
- HP bypass control valve erosion.
- Forced cooling

Attemperator spray water leakages

- When the HP SH outlet has zero or low steam flow and attemperator water leakage is present in the system. Spray water will accumulate at the bottom of the pipes.
- Small leakages cause no problem. But better to be aware of this.
- Possible failures:
  - Cracks in girth welds
  - Hogging of the pipe due to top and bottom temperature difference of the pipe.



Main cause:

- Master control/Martyr block valve logic

Identified by looking at the ΔT between attemperator inlet and outlet during early startup.

From PPChem, 2019

Attemperator overspray

- When steam flow rate and temperature is not sufficient enough to evaporate the sprayed amount of water. The water droplets will accelerate and hit the pipe inner surface and can cause erosion.
- Identification
  - If the temperature downstream the attemperator drops to sat. temp it indicates an overspray

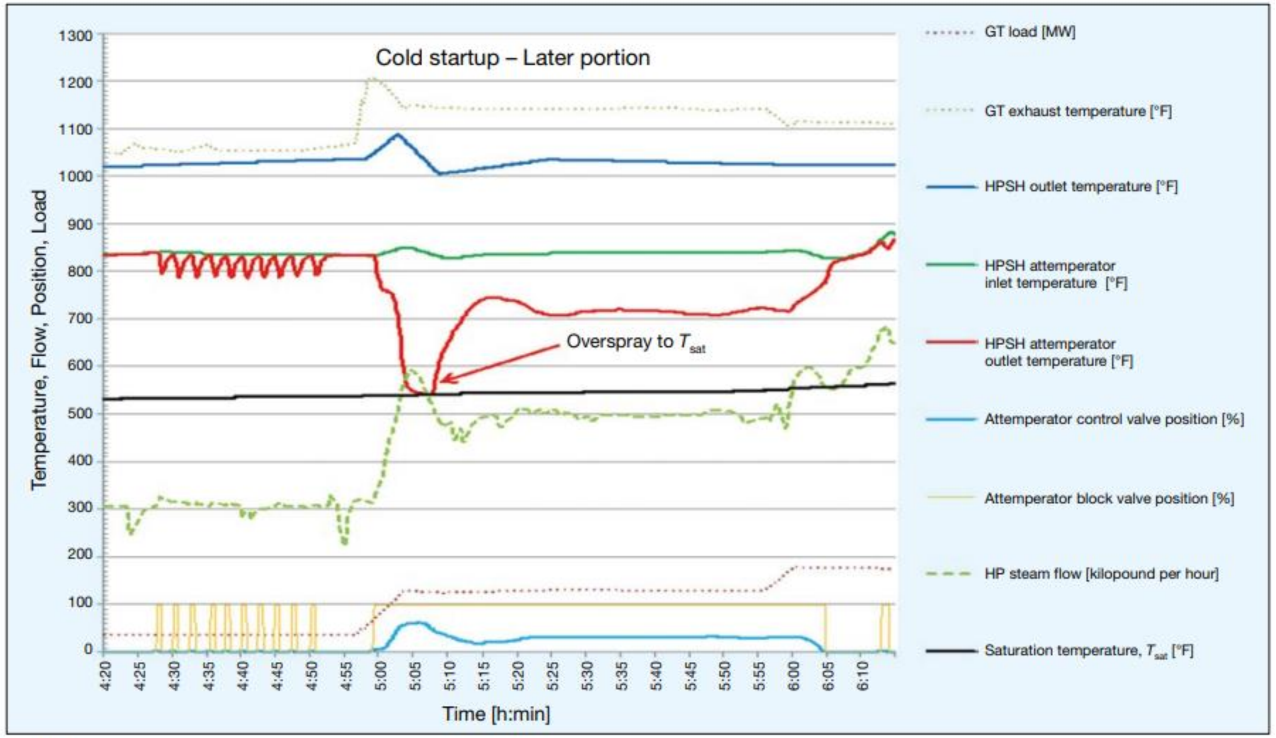


Figure 8:
Steam temperature at a thermocouple downstream of attemperator outlet (red line) dropping to T_{sat} (black line) indicates overspray.

Root causes:

- Issues in attemperator control system.
- Manual operation of the spray valve.
- Lack of attemperator protective logic

Ineffective HP SH draining during startup

- Migration of undrained condensate throught pipes cause damage to steam pipes, headers and tubes.
- Large amount of condensate will generated inside the SH tubes during CC purge, prior to the start up. It has to be drained properly before initiate the steamflow.
- Identification
  - Cannot identify directly. Condensate migration can be identified by looking at HP outlet temperature.

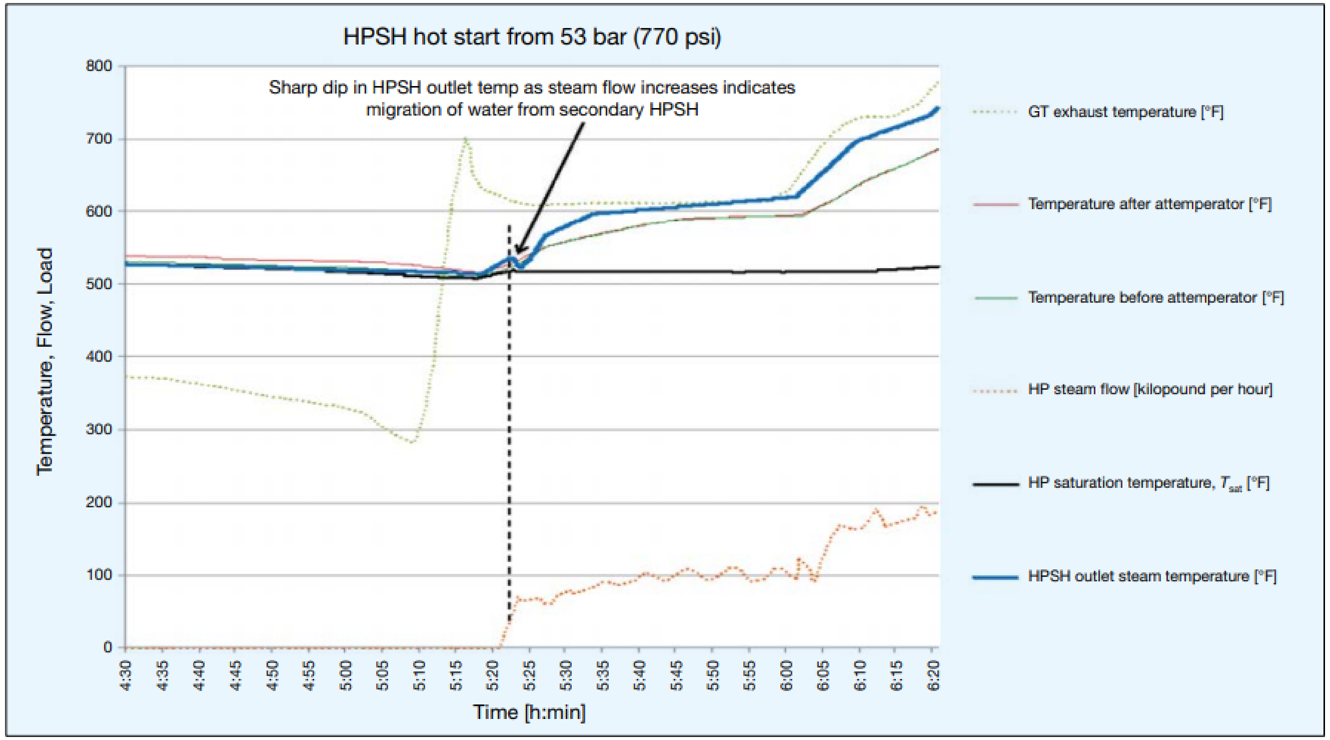


Figure 10:
Sharp dips in steam temperature when steam flow increases indicates migration of undrained water.

Causes:
- Small drain valves
- Small slope of the drain pipes
- Blowdown tank location
- Control valve operation

- NEM has mentioned that in our plant this draining procedure happens automatically during start up.
- They have also mentioned drains have sized for the cold most HRSG start up.

HP drum damages due to high pressure ramp rates

- If the drum pressure ramp rate exceeds the maximum ramp rate given by the manufacturers it will cause cracks in the magnetite layer. This can lead to corrosion fatigue failures.
- Depressurizing ramp rate is lower than the pressurizing ramp rates
- NEM has noted depressurizing ramp rates as,
  - HP drum ramp rate = -3 bar/min
  - LP drum ramp rate = -0.15 bar/min
- Where?
  - Drum to shell down-comer welds
  - Drum nozzles
- Identification
  - These can be identified by looking at the DCS plots/trends related to drum pressures.

Forced cooling

- Some manufactures cool down HRSGs rapidly before conduct maintenance work.
- This include venting steam through the HP drum vent, HP bypass system.
- This cause overly aggressive ramp rates in HP drum.
- Identification:
    - Can be identified through DSC trends.

HP bypass pressure control valve erosion

- Erosion in bypass valves due to passing wet steam through PCV.

References

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THANK YOU!