Low Frequency High Amplitude Temperature Oscillations in Loop Heat Pipe Operation

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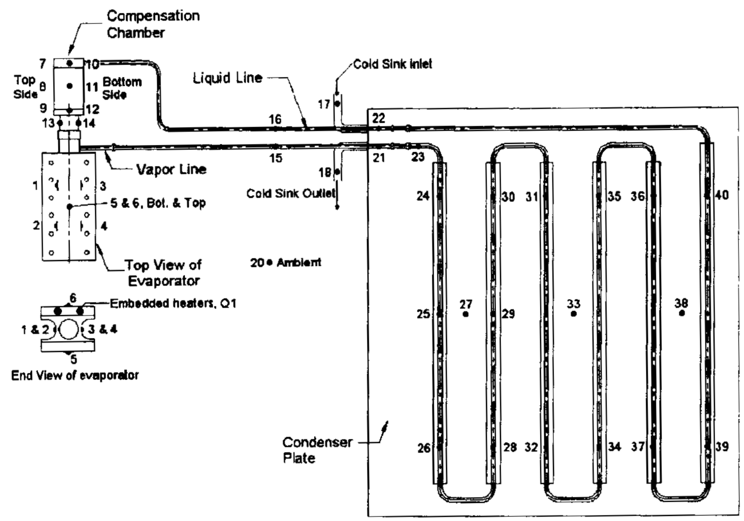
Outline

- Introduction/Background
- Objectives
- Proposed Theory
- Test Loop and Test Results
- Effects of Various Parameters
- Summary
- Conclusion

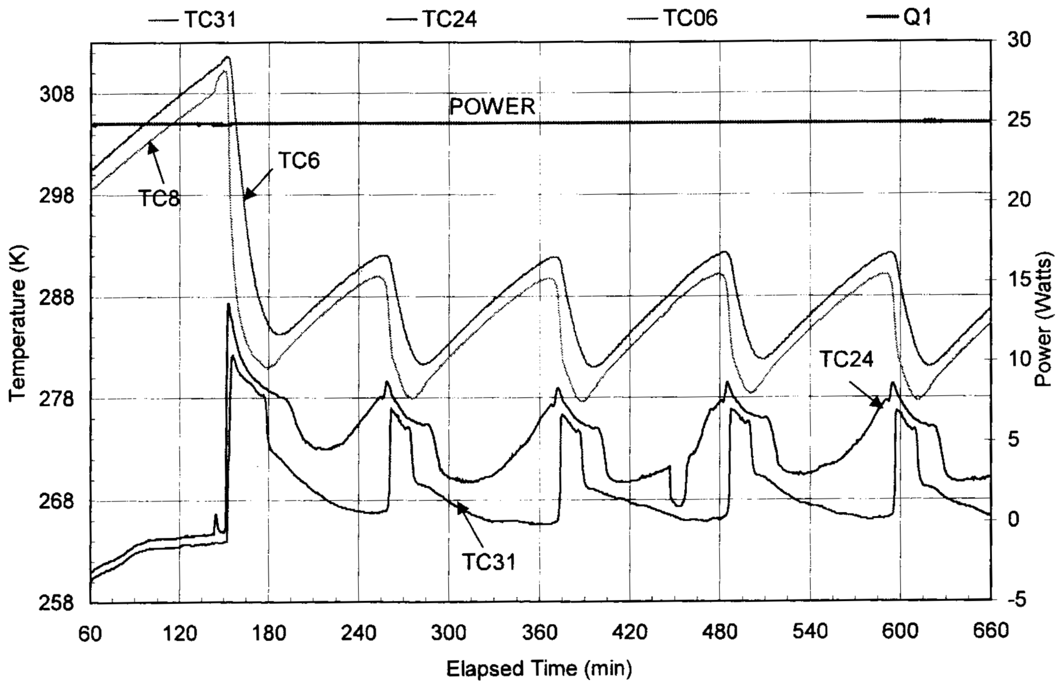
Background

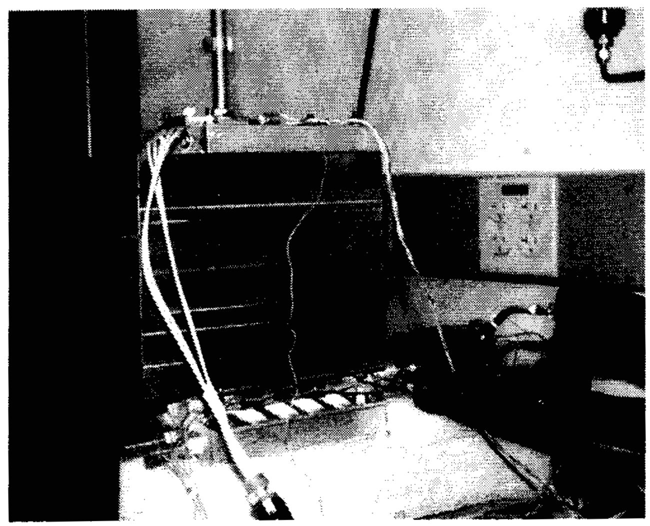
Temperature Oscillation in TES LHP EDU (25W/263K)

- **Large amplitude temperature oscillations were observed in JPL LHP tests in 2000.**
  - **Constant power, constant sink**
  - **No satisfactory explanation.**



12/8/1999 25W start, 263K sink





Three Types of LHP Temperature Oscillations

- Ultra High Frequency Temperature Oscillations
  - Periods less than 1 second
  - Related to two-phase flow characteristics.
  - No published experimental data
  - Not important in spacecraft thermal control
  - Pressure oscillations are more of a concern
- High Frequency, Low Amplitude Temperature Oscillations
  - Periods on the order of seconds to minutes
  - Amplitudes on the order of one Kelvin
  - Caused by vapor front movement near condenser inlet or exit
- Low Frequency, High Amplitude Temperature Oscillations
  - Periods on the order of hours
  - Amplitudes on the order of tens of Kelvin
  - Several possible causes

Low Frequency High Amplitude LHP Temperature Oscillations

- Constant Applied Power/Oscillating Sink Temperature
  - Observed in flight or simulated thermal vacuum tests.
  - Results are expected.
- LHPs with a Single Evaporator and Two Parallel Condensers
  - One sink is colder than saturation temperature, the other is warmer.
  - The flow regulator with warm sink dries out periodically.
  - Oscillations can be eliminated by placing the two flow regulators side by side.
- LHPs with Large Thermal Masses
  - Constant applied power/constant sink temperature
  - Topic of this presentation

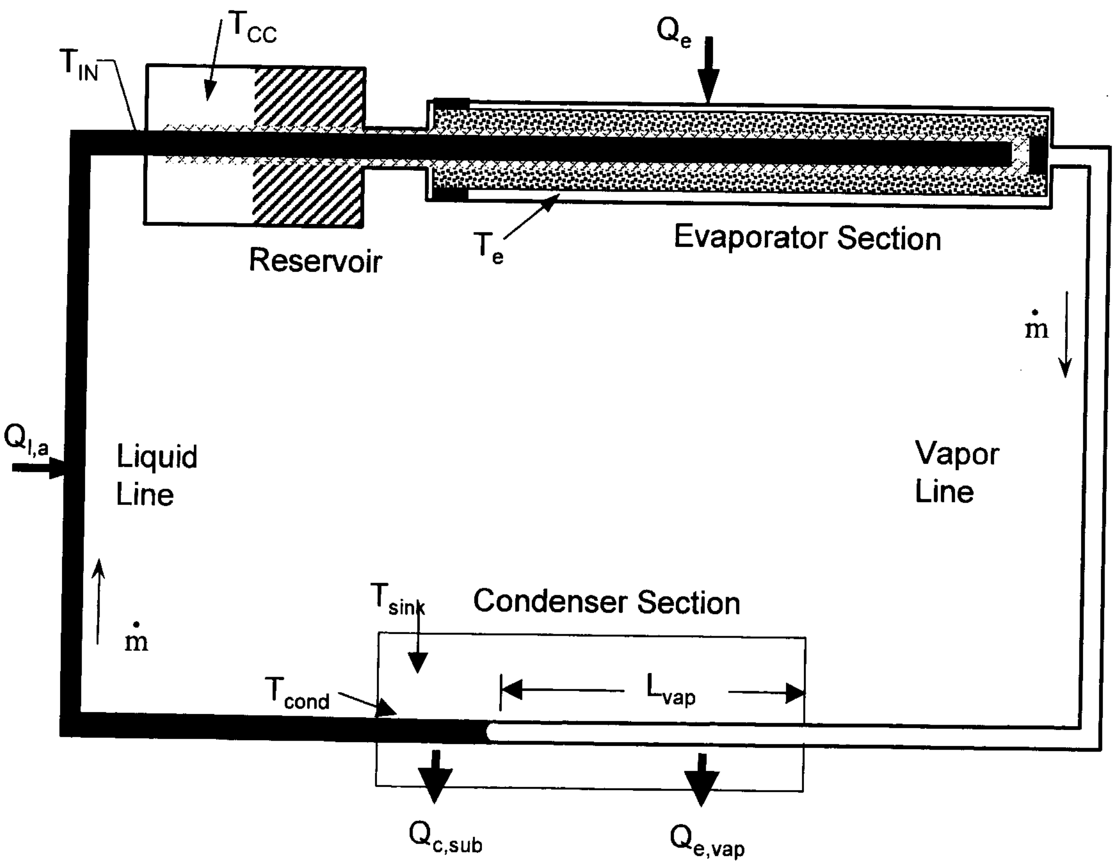
Objectives

- Investigate low frequency, high amplitude temperature oscillations.
  - LHP with a single evaporator and a single condenser
  - A large thermal mass attached to the evaporator
  - Constant applied power and constant sink temperature
- Propose a new theory for low frequency, high amplitude temperature oscillations.
  - Physical processes
  - Interactions among LHP components
  - Source of temperature oscillation
  - Factors affecting the amplitude and period of temperature oscillation
- Verify the theory with test results from TES LHP EDU testing.

Synopsis of the Proposed New Theory

- With a constant sink, an oscillating heat input to the evaporator will lead to a temperature oscillation.
- Under certain conditions, the large thermal mass attached to the evaporator can modulate a constant applied heat load into an oscillating heat input to the evaporator, causing the loop temperature to oscillate.
  - The thermal mass absorbs energy when the CC temperature is rising, and releases energy when the CC temperature is falling.
  - The net evaporator power oscillates between a maximum that is higher than the applied power, and a minimum that is lower than the applied power.
- In order to sustain a low frequency, high amplitude temperature oscillation, all of the following three conditions must prevail:
  - A large thermal mass is attached to the evaporator.
  - A small power is applied to the thermal mass.
  - The sink temperature is colder than the ambient temperature.
- Once it has started, the temperature oscillation can continue indefinitely until the operating condition changes.

Schematic of an LHP without Thermal Mass



$$Q_e = Q_{e,cc} + Q_{e,vap}$$

$$Q_{e,cc} = G\,(T_e - T_{cc})$$

$$Q_{e,vap} = \dot{m}\lambda$$

$$L_{vap} = Q_{e,vap}/[h\pi D(T_{cc} - T_{sink})]$$

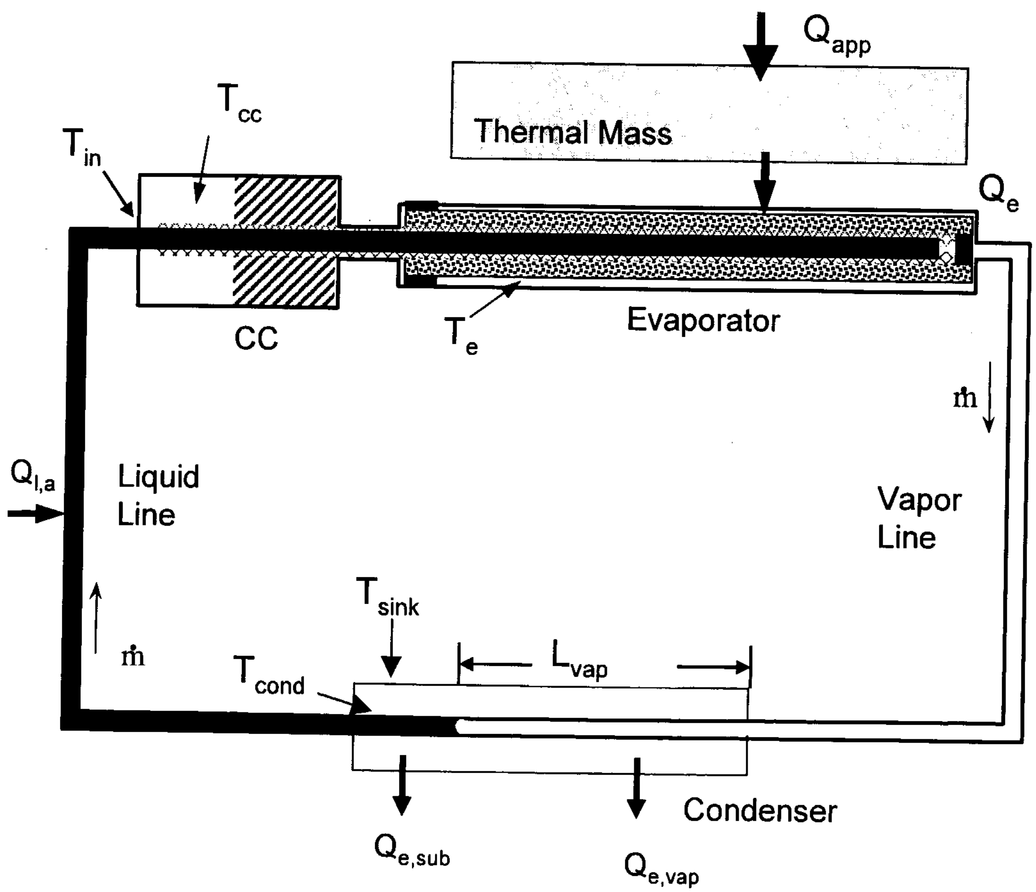
$$T_{in} - T_{cond} = Q_{l,a}/(\dot{m}\,C_p)$$

$$Q_{e,cc} = Q_{c,sub} - Q_{l,a}$$

$$Q_{e,cc} = \dot{m}\,C_p\,(T_{cc} - T_{in})$$

$$\Delta P = \lambda(T_e - T_{cc})/(T_{cc}\Delta v)$$

Schematic of an LHP with Thermal Mass



$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

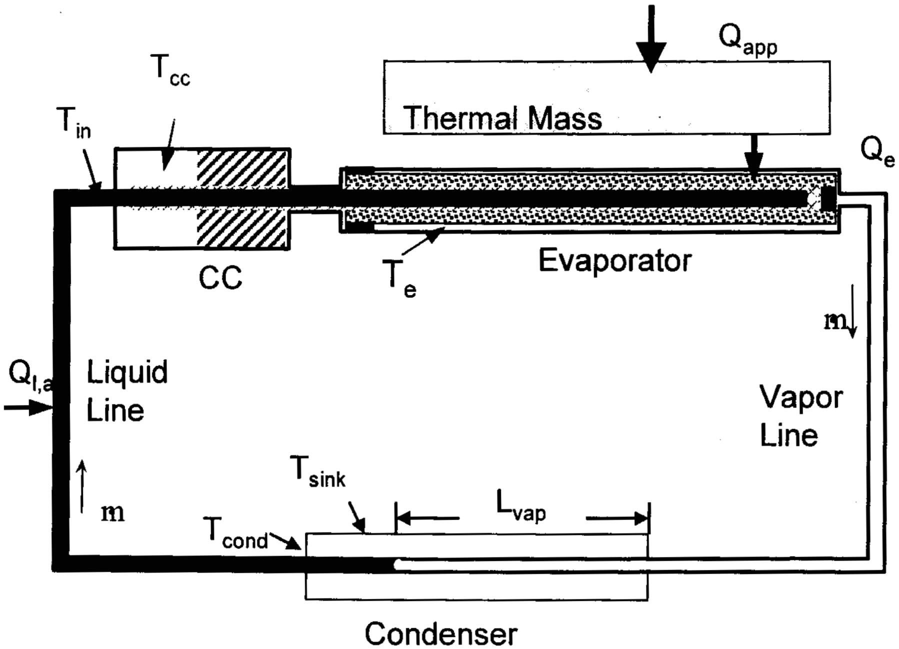
$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

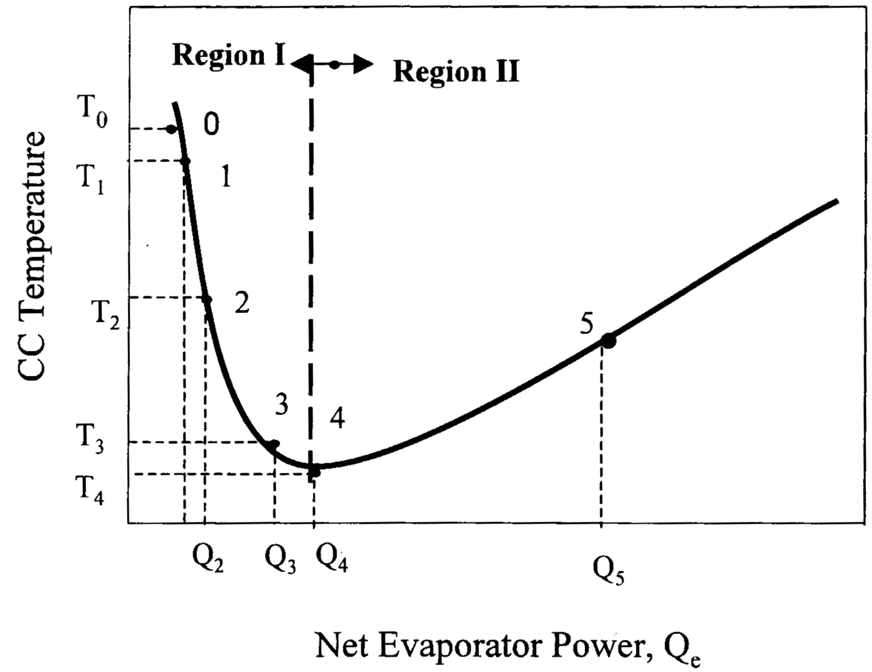
$$T_{tm} = fn(Q_{app}, Q_e, M_{tm}, C_{p,tm})$$

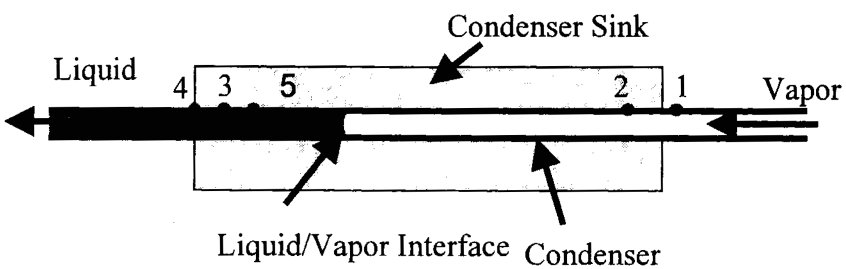
$$T_e = fn(T_{cc})$$

$$T_{cc} = fn(Q_e, T_{sink}, T_{amb})$$

Schematic of an LHP with Thermal Mass







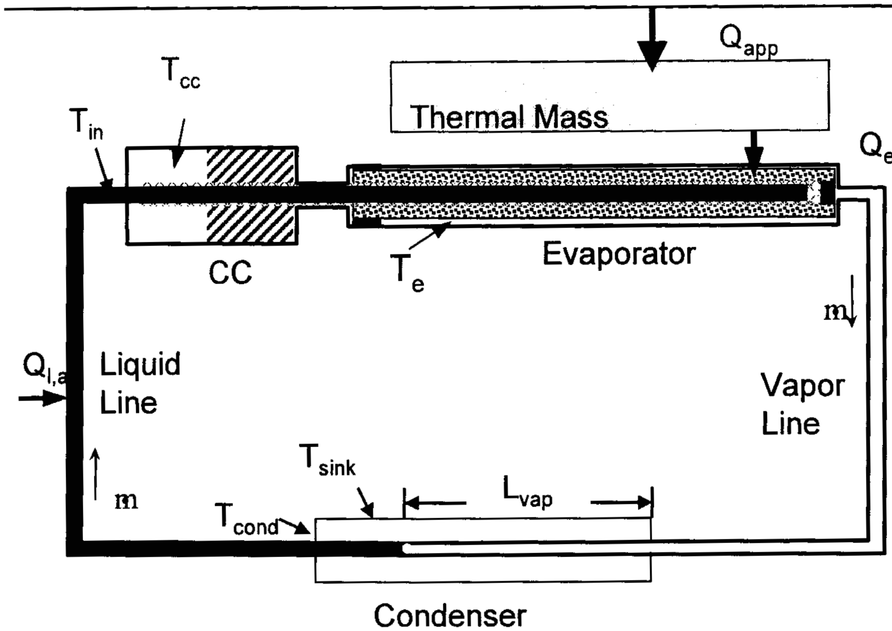
$$M_{cc} C_{p,cc} \frac{dT_{cc}}{dt} = Q_e - mC_p (T_{cc} - T_{in})$$

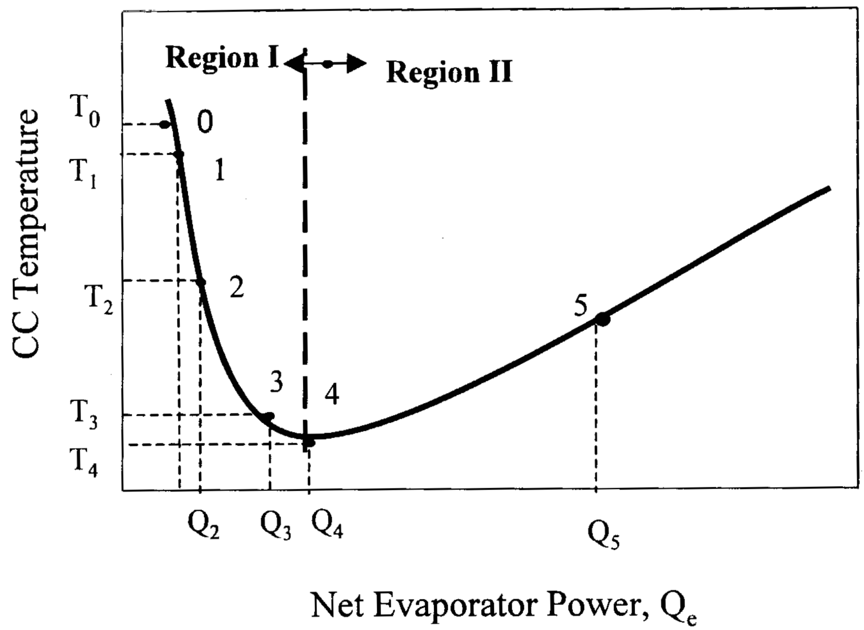
$$T_{cc} = fn(Q_e, M_{cc}, C_{p,cc}, T_{sink}, T_{amb})$$

$$T_e = fn(T_{cc})$$

$$L_{vap} = Q_{e,vap} / [h \pi D (T_{cc} - T_{sink})]$$

CC Temperature Decreasing





- **Initially, vapor line has liquid.**
- **Q_{app} applied to thermal mass. T_{tm} and T_e increase.**
- **Loop starts. Cold liquid feeds to CC. T_{cc} decreases.**
- **T_e decreases. Q_e increases. $Q_e > Q_{app}$, T_{tm} decreases.**
- **T_{cc} continues to decrease, Q_e continues to increase.**
- **T_{sink} is fixed. T_{cc} reaches a minimum.**
- **Q_e reaches a maximum. $Q_{e,max} > Q_{app}$.**
- **Q_e begins to decrease, T_{cc} begins to increase.**

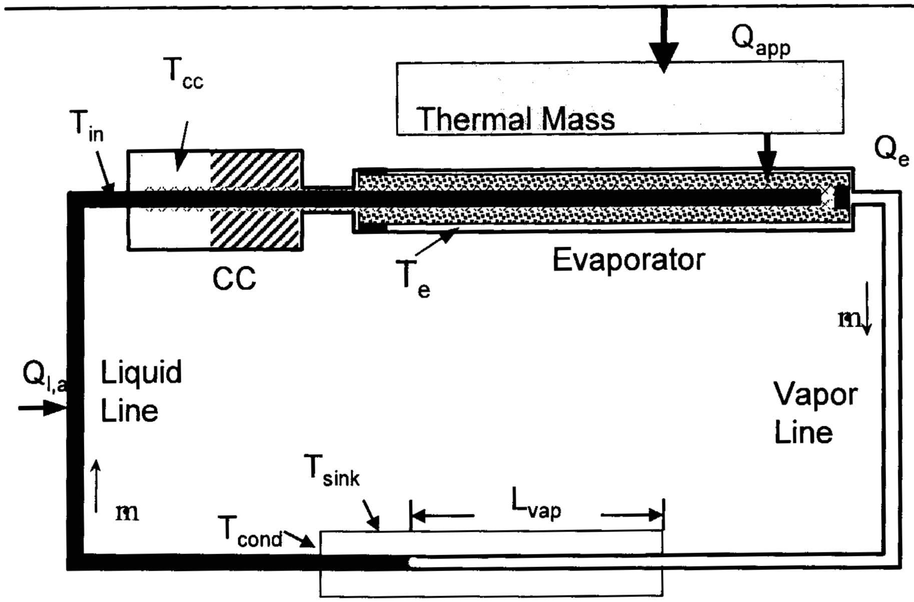
$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

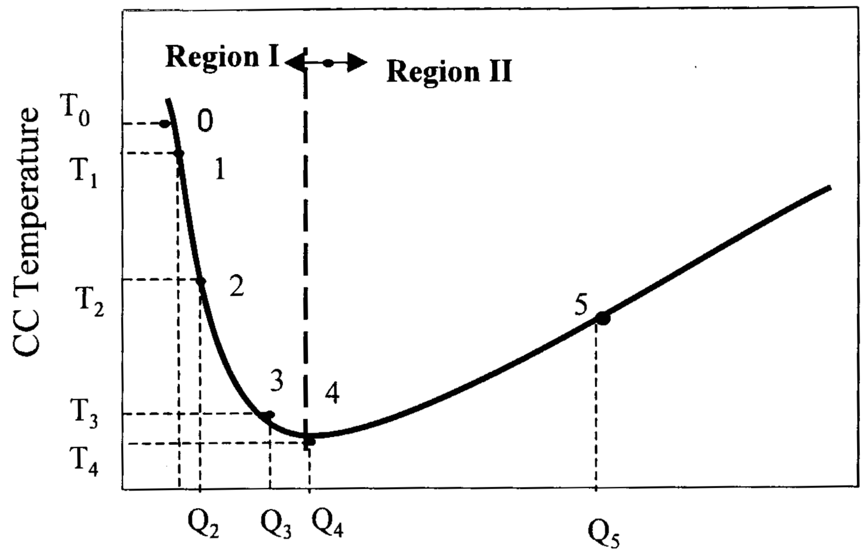
$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

$$Q_e = Q_{app} - M_{tm} C_{p,tm} \frac{dT_{tm}}{dt}$$

$$L_{vap} = Q_{e,vap} / [h \pi D (T_{cc} - T_{sink})]$$

CC Temperature Increasing





- T_{cc} continues to increase. Q_e continues to decrease. Q_e is still greater than Q_{app}. T_{tm} continues to decrease.
- $Q_e = Q_{app}$. T_{tm} begins to increase.
- $Q_e < Q_{app}$ because T_{tm} is too low to sustain $Q_e = Q_{app}$. T_{tm} continues to increase. Q_e continues to decrease.
- Q_e reaches a minimum $Q_{emin.}$ T_{tm} is so high that

  $G_{e,tm}(T_{tm} - T_e) > Q_{e,min}$
- Q_e begins to increase. T_{cc} begins to decrease.

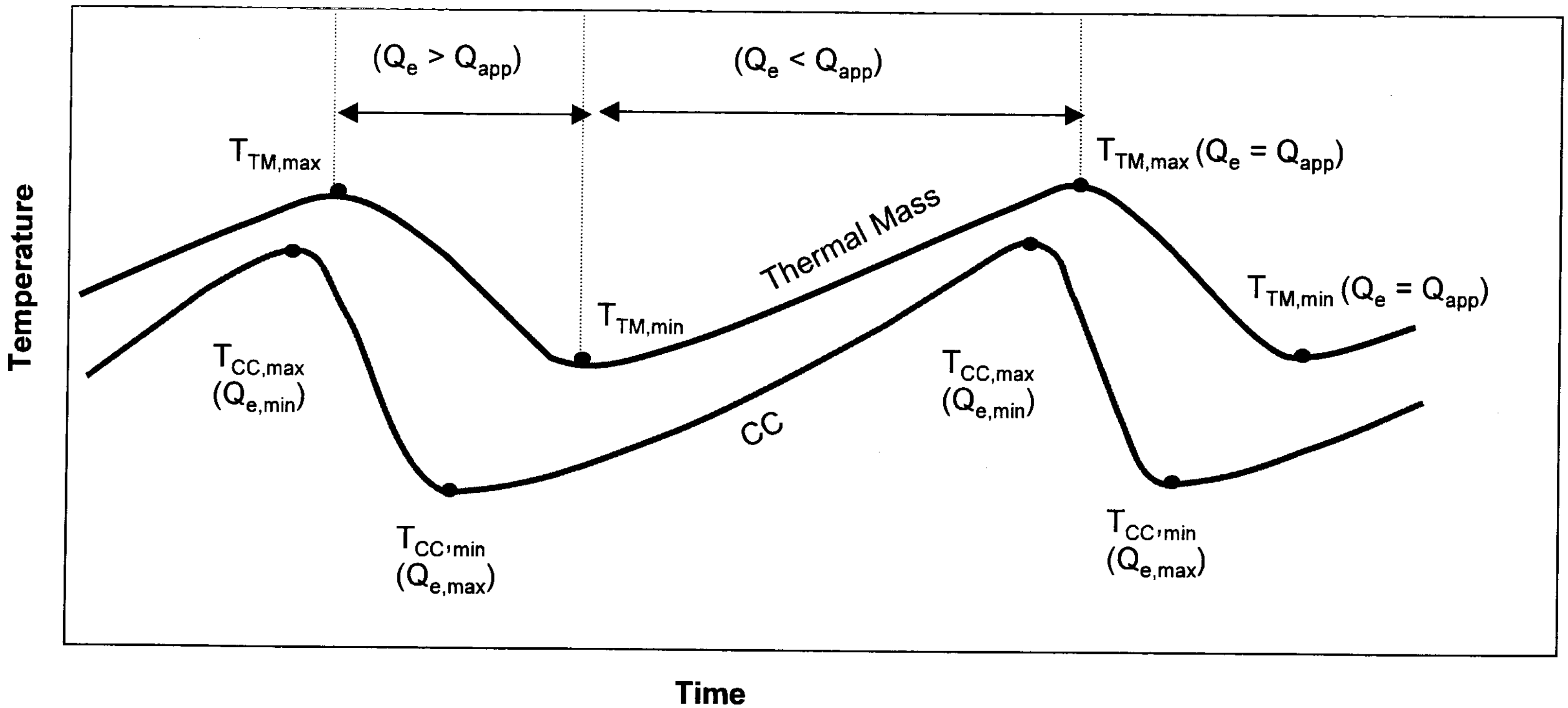
$$M_{tm}C_{p,tm}\frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

$$Q_e = Q_{app} - M_{tm}C_{p,tm}\frac{dT_{tm}}{dt}$$

$$L_{vap} = Q_{e,vap}/[h\pi D(T_{cc} - T_{sink})]$$

CC and Thermal Mass Temperatures
(Theoretical)



$$T_{cc} = fn(Q_e, T_{sink}, T_{amb})$$

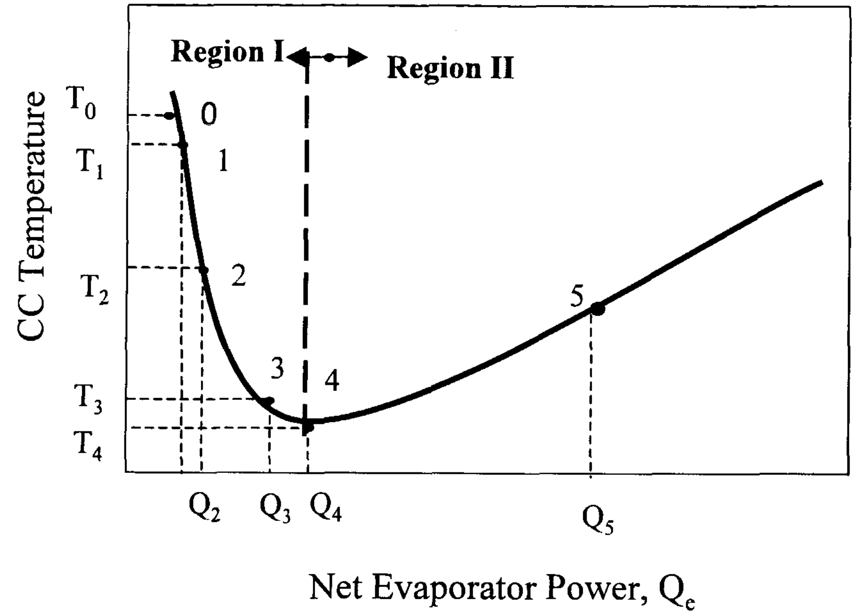
$$T_e = fn(T_{cc})$$

$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

Review of Necessary Conditions

- The three necessary conditions to sustain a high amplitude temperature oscillation:
  - A large thermal mass is attached to the evaporator.
  - A small power is applied to the thermal mass.
  - The sink temperature is colder than the ambient temperature.
- If any of the conditions is not met, the thermal mass temperature will never decrease. Q_e will gradually increase until $Q_e = Q_{app}$ at the steady state.
  - The LHP will operate steadily in region I.
- If $Q_{app} > Q_4$, the transient will be short and LHP will operate steadily in Region II.



$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

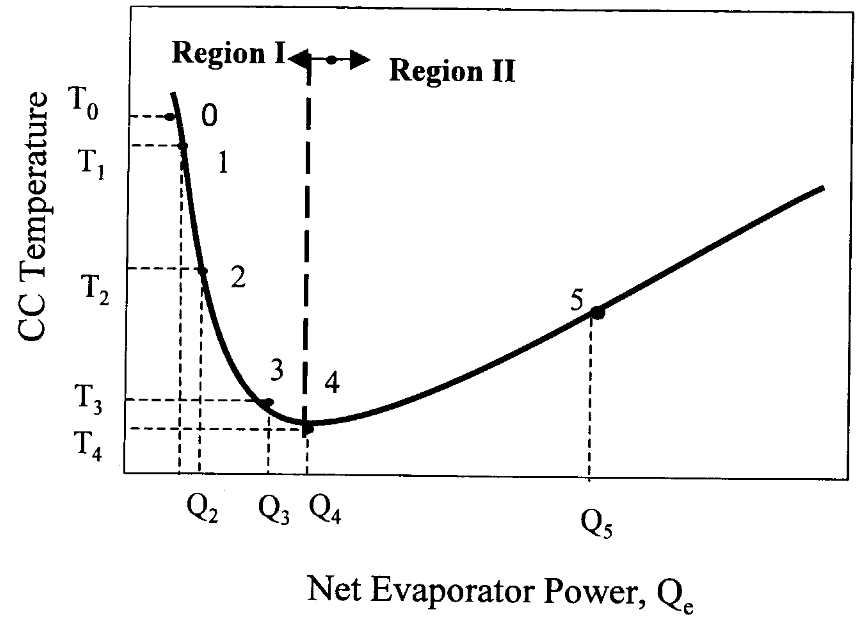
$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

$$Q_e = Q_{app} - M_{tm} C_{p,tm} \frac{dT_{tm}}{dt}$$

$$L_{vap} = Q_{e,vap} / [h \pi D (T_{cc} - T_{sink})]$$

Two Important Corollaries

- A high amplitude temperature oscillation is possible only in Region I, it can never occur in Region II.
    - Part of the mechanism that drives the temperature oscillation is that the net evaporator power decreases and the CC temperature increases simultaneously after Q_e reaches a maximum and T_{cc} reaches a minimum.
- $Q_{e,max}$ can never exceed Q_4 during a high amplitude temperature oscillation.



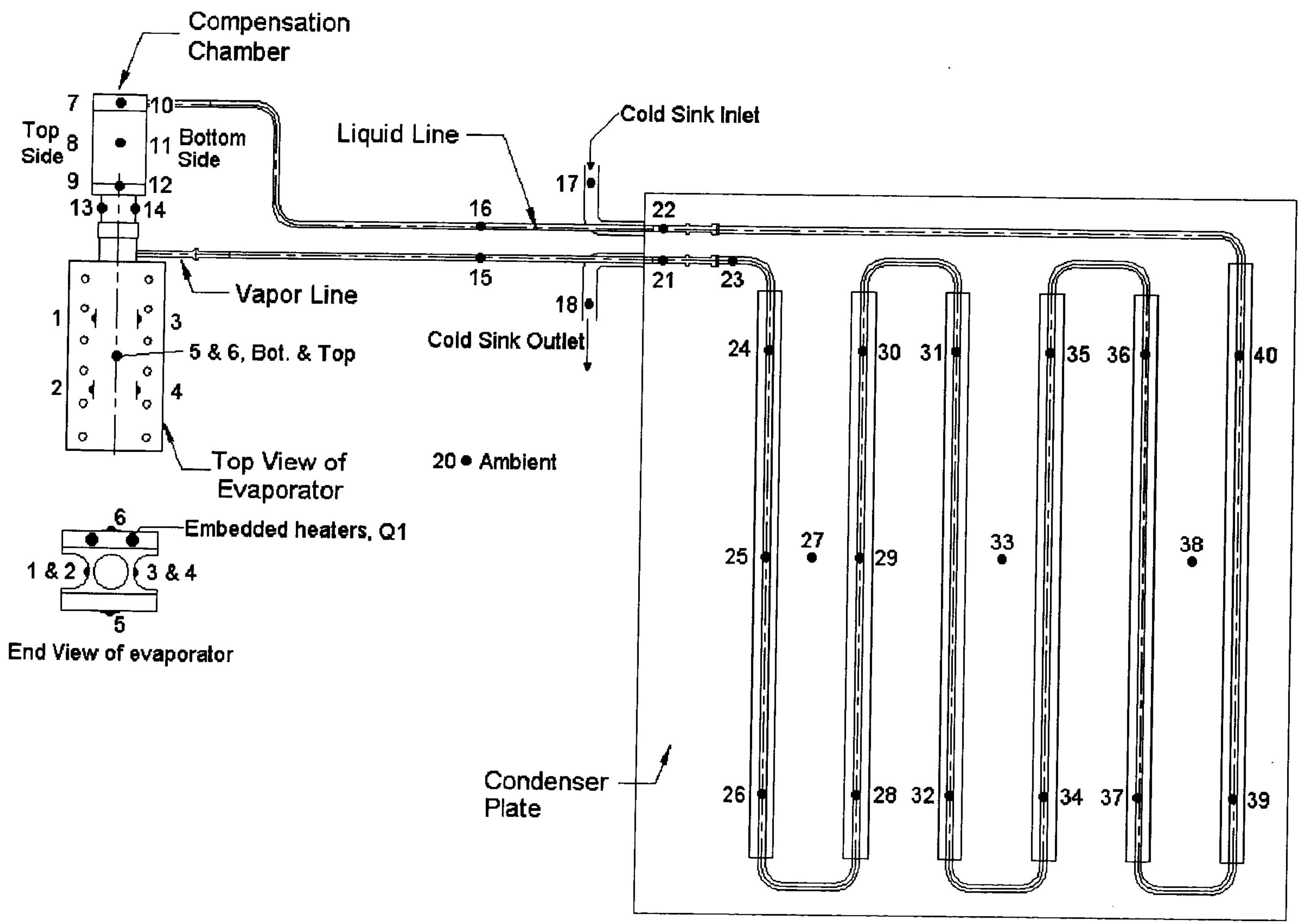
$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

$$Q_e = Q_{app} - M_{tm} C_{p,tm} \frac{dT_{tm}}{dt}$$

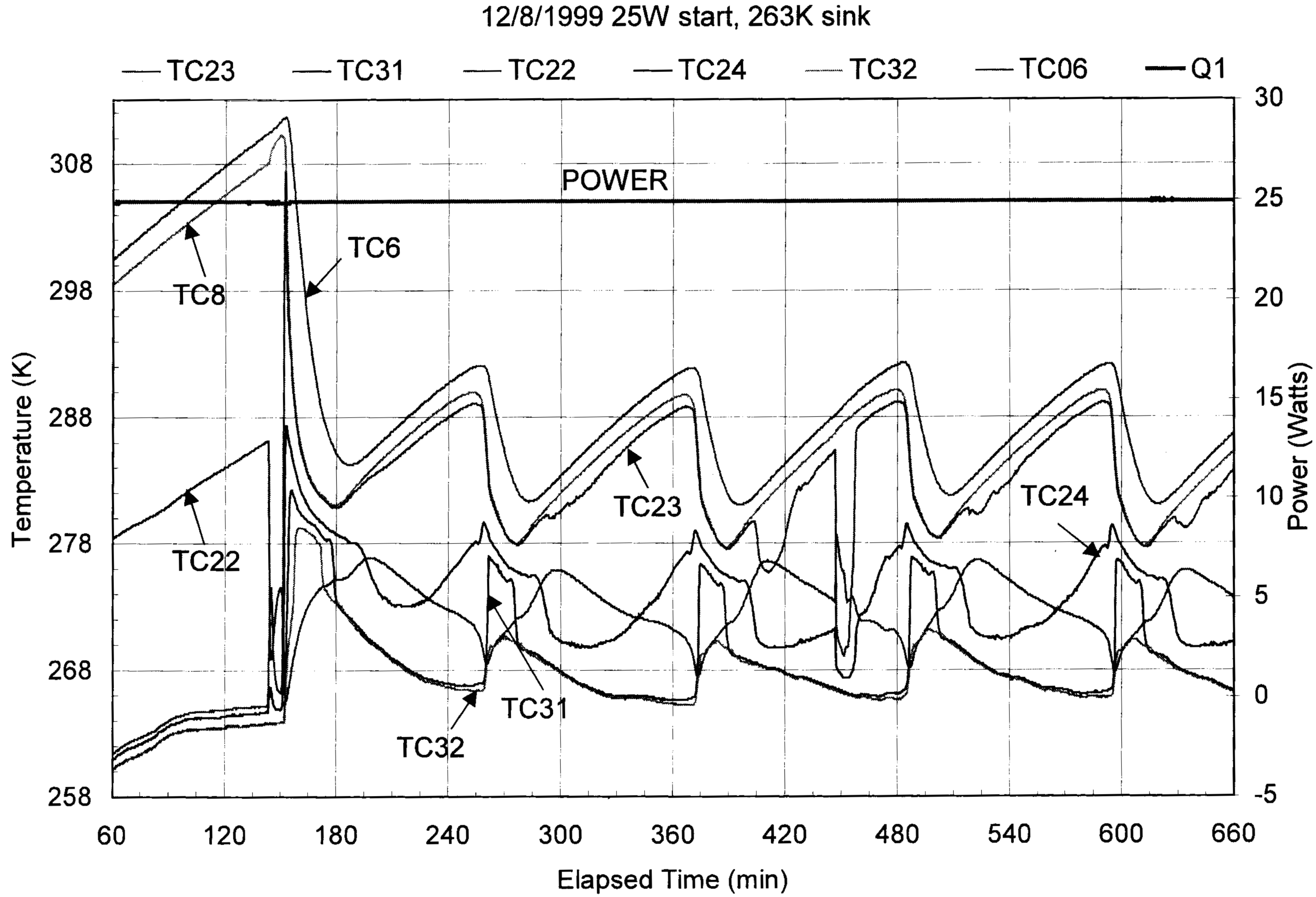
$$L_{vap} = Q_{e,vap}/[h\pi D(T_{cc} - T_{sink})]$$

Schematic of TES LHP EDU

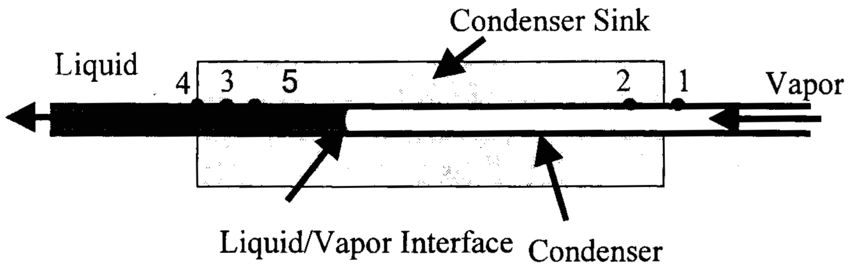


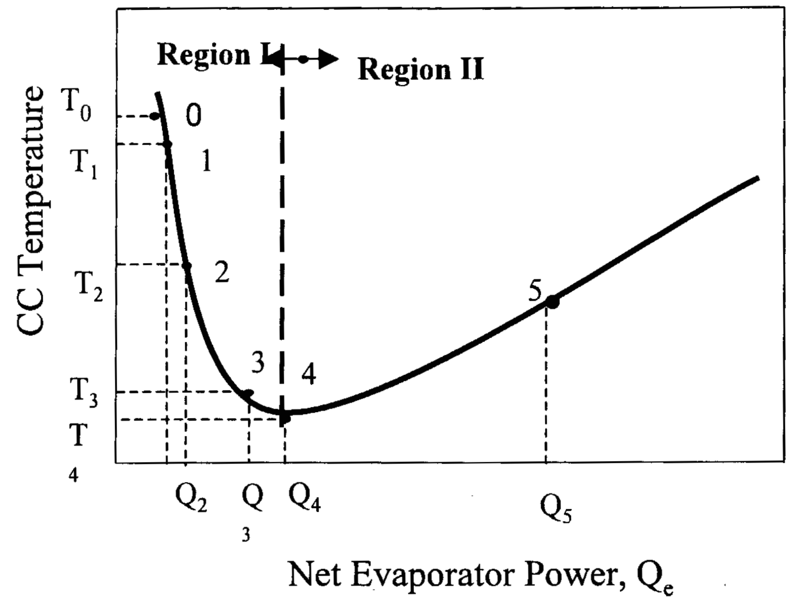
LHP Temp Osci
JTK - 9/15/03

Temperature Oscillation in TES LHP EDU
(25W/263K)



Vapor Front Movement and Temperature Oscillation





- **The range of the vapor front movement can be correlated to the amplitude of the temperature oscillation.**
  - **The larger the Q_e oscillation, the larger the CC temperature oscillation.**
  - **The larger the Q_e oscillation, the larger the range of L_{vap}.**
  - **The range of L_{vap} is nearly proportional to the amplitude of CC temperature oscillation.**
  - **Vapor front can never pass condenser exit.**

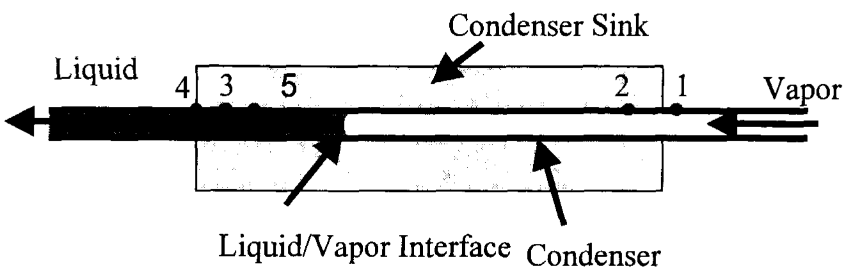
$$M_{tm} C_{p,tm} \frac{dT_{tm}}{dt} = Q_{app} - Q_e$$

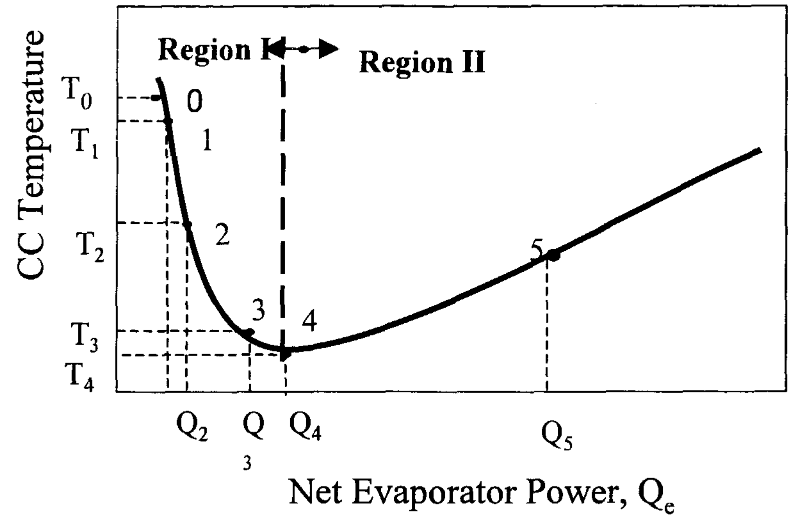
$$Q_e = G_{e,tm}(T_{tm} - T_e)$$

$$T_{cc} = fn(Q_e, T_{sink}, T_{amb})$$

$$L_{vap} = Q_{e,vap}/[h\pi D(T_{cc} - T_{sink})]$$

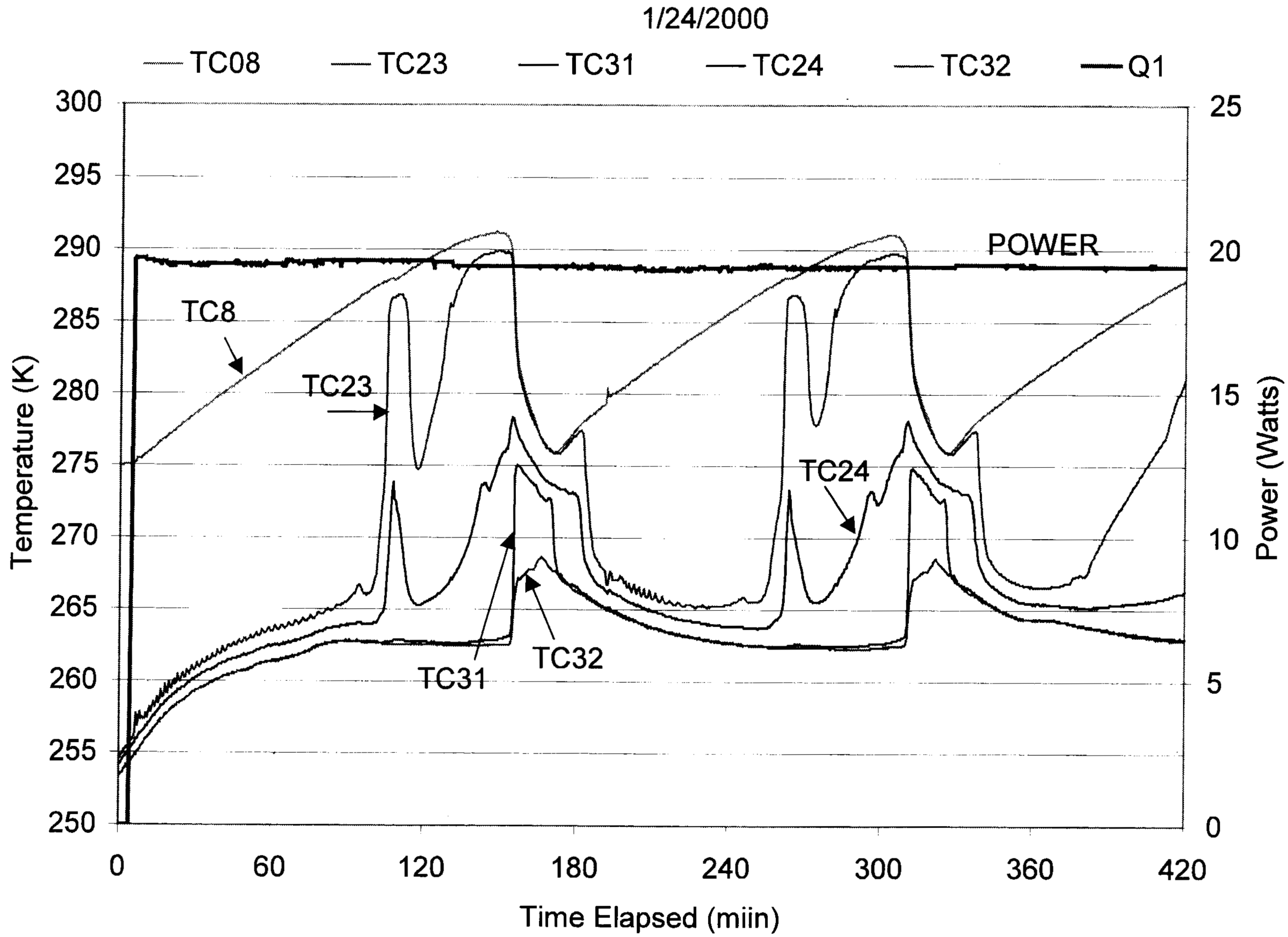
Vapor Front Location and Temperature Oscillation



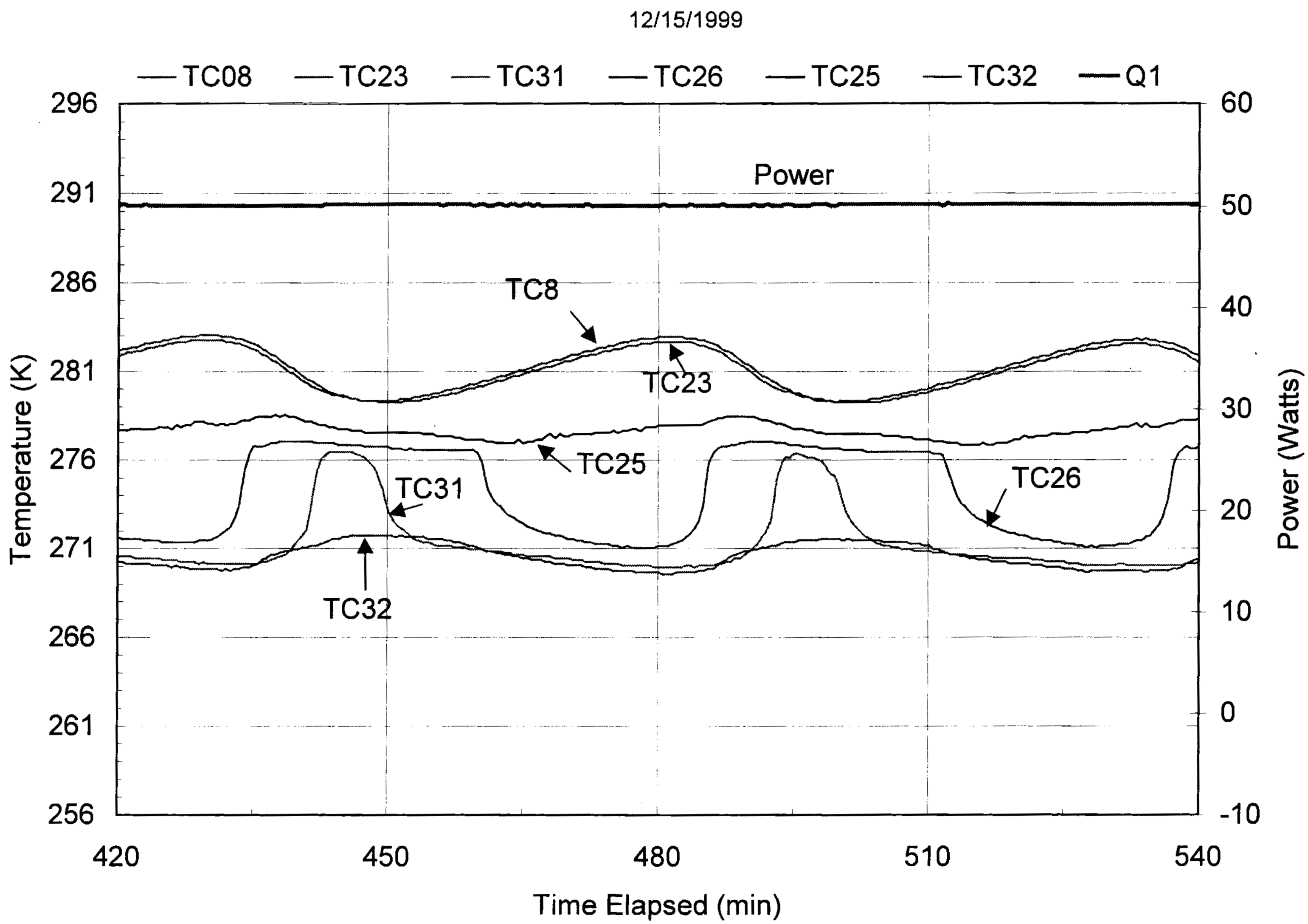


- With a very small applied power and/or a very cold sink, vapor may condense in the vapor line at the peak of the CC temperature ($Q_e = Q_{e,min}$).
  - The vapor line works as a condenser.
  - The liquid in the vapor line provides an "initial push" for a rapid CC temperature drop when T_{cc} begins to decrease.
- The smaller the applied power and/or the colder the sink, the higher the peak CC temperature.
- If the vapor front stays inside the condenser, the range of L will be small, leading to a small temperature oscillation.

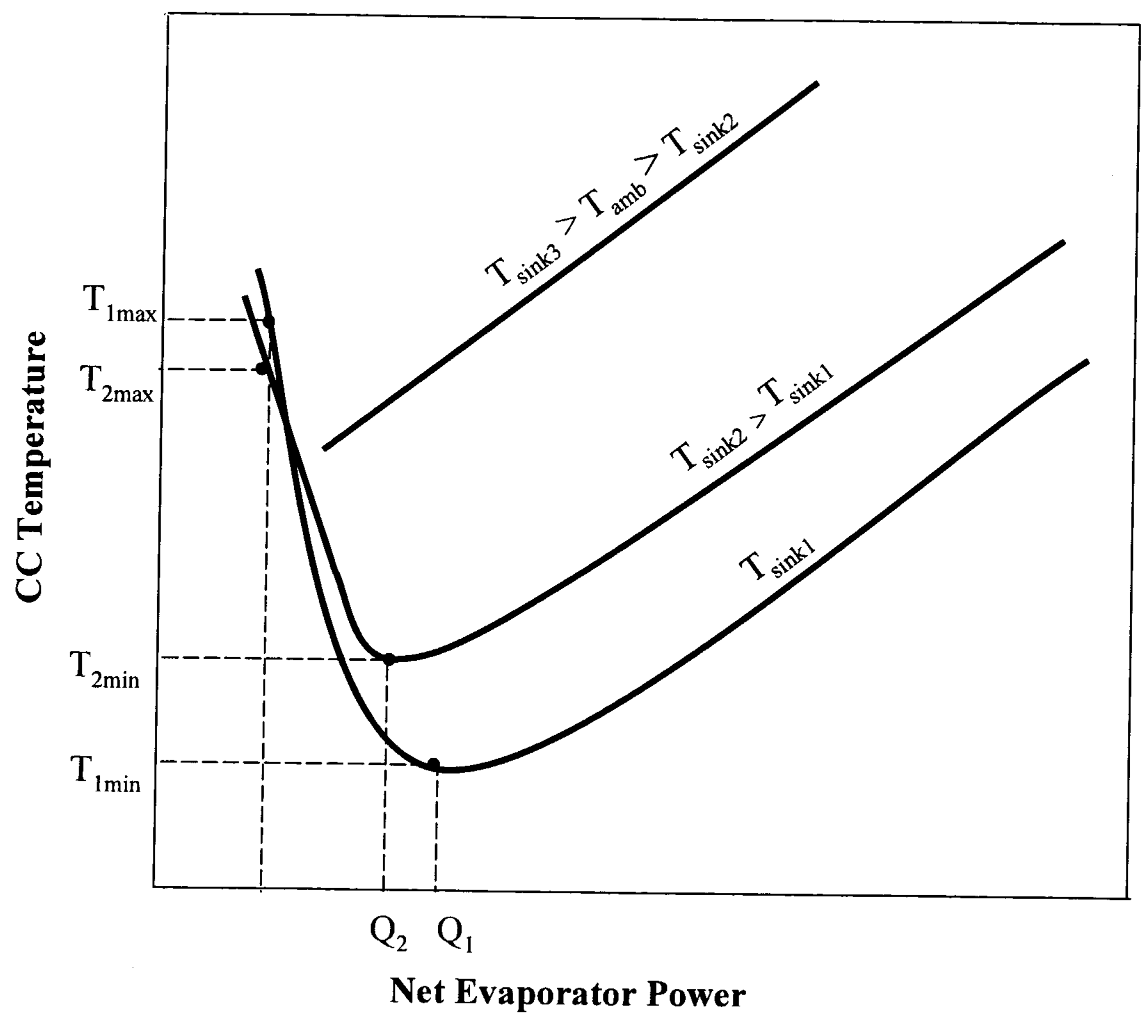
Temperature Oscillation in TES LHP EDU
(20W/263K)



Temperature Oscillation in TES LHP EDU
(50W/268K)

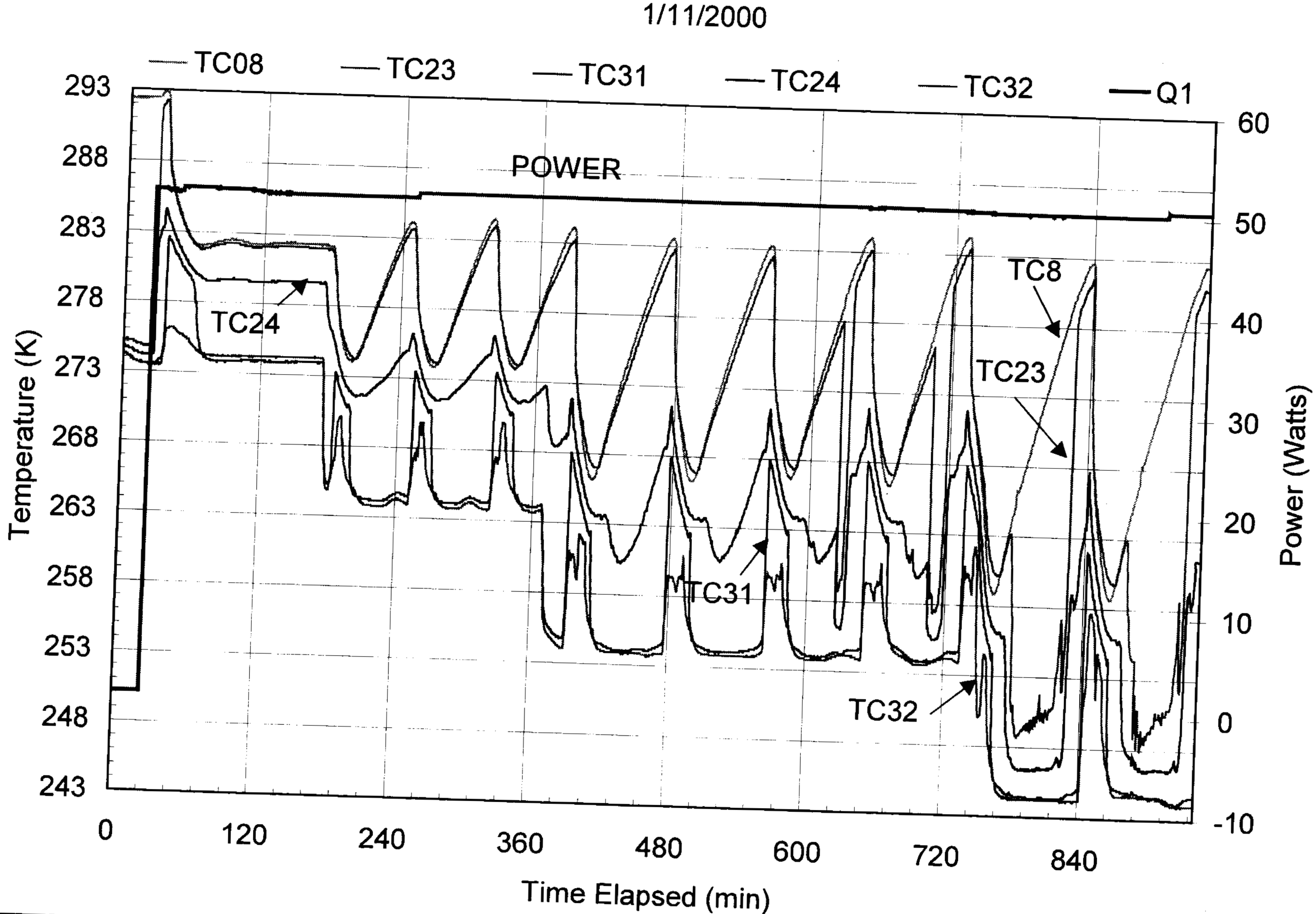


Effect of Sink Temperature on CC Temperature



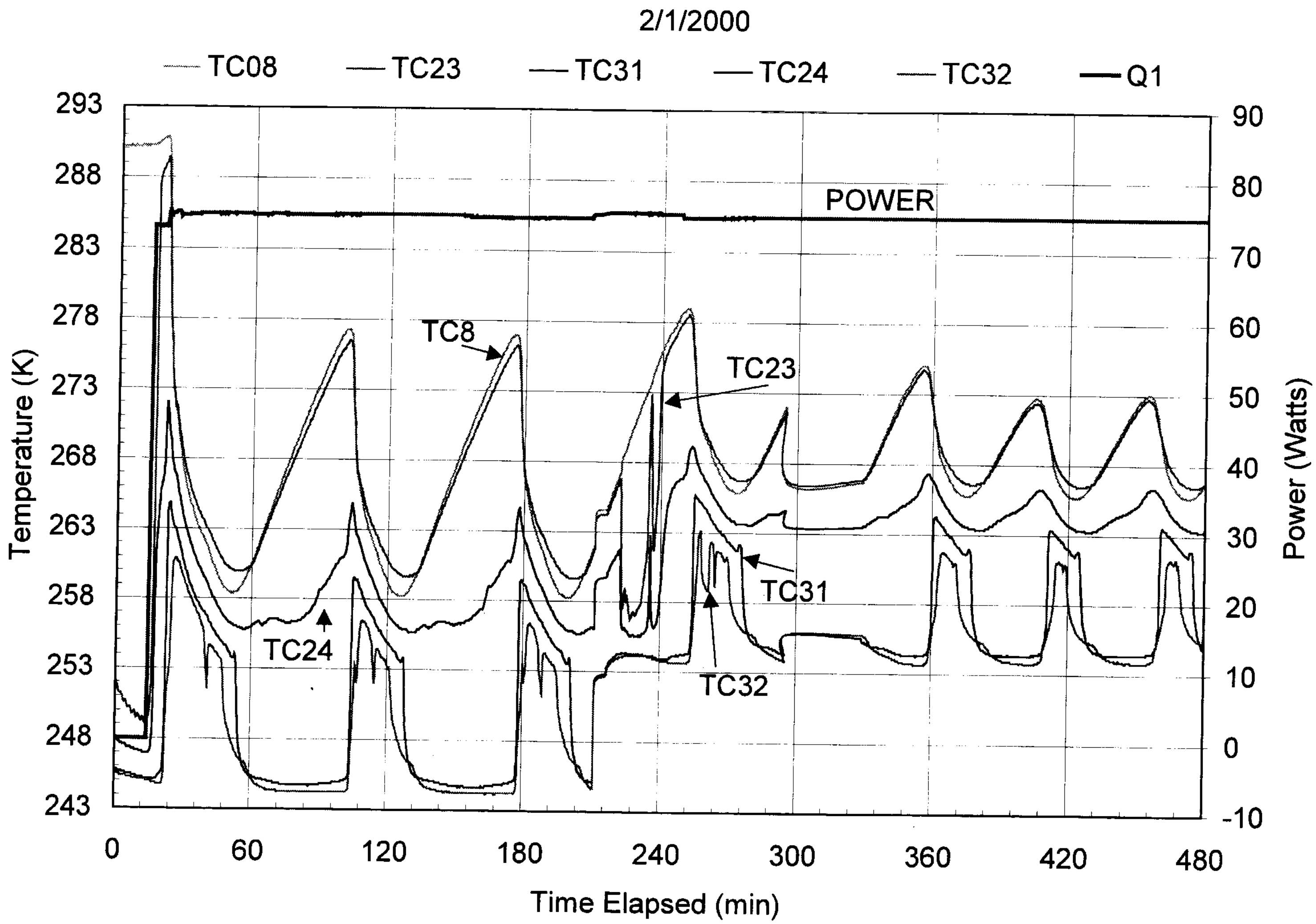
Temperature Oscillation in TES LHP EDU

(50W, 273K/ 263K/ 253K/ 243K)

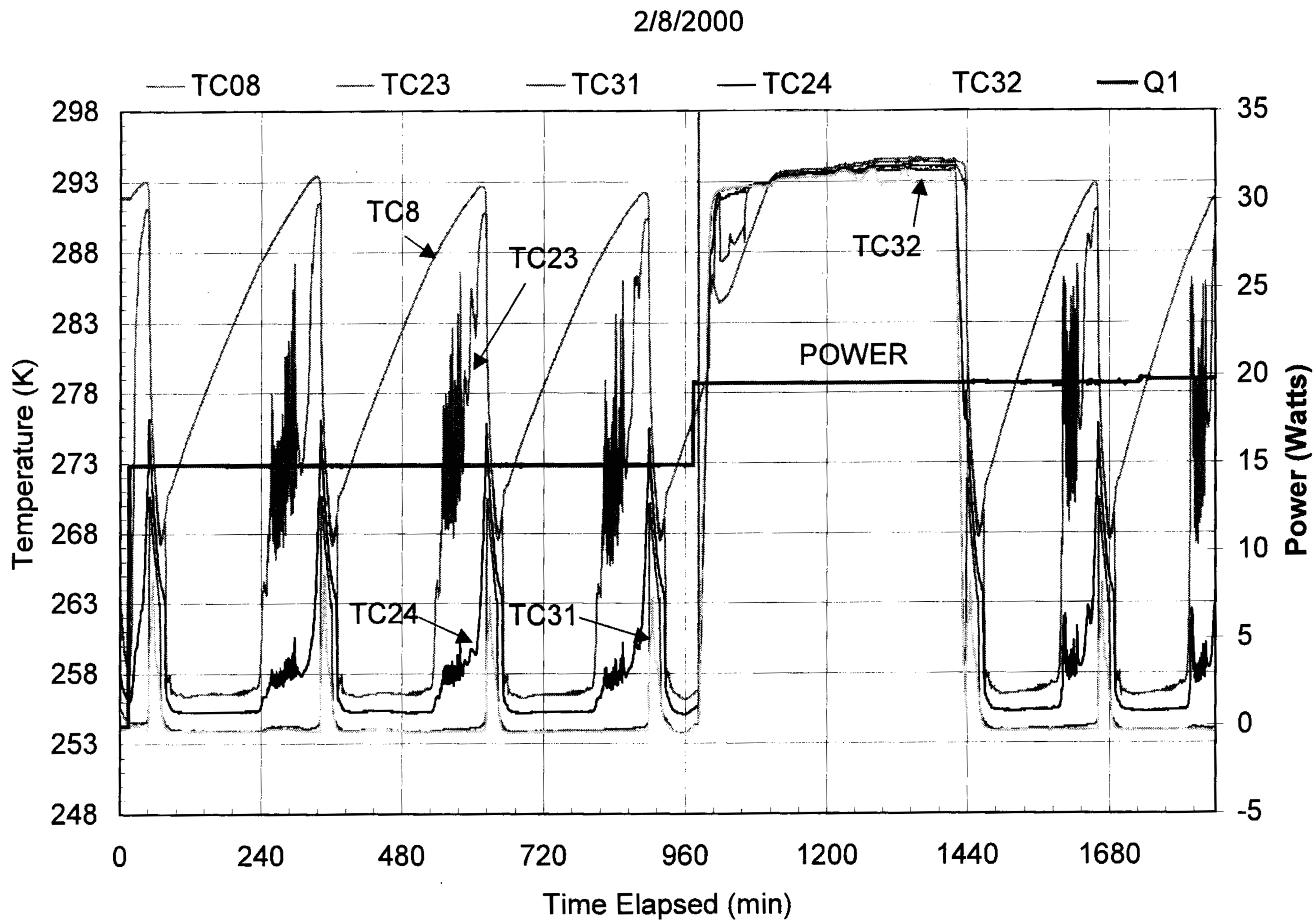


Temperature Oscillation in TES LHP EDU

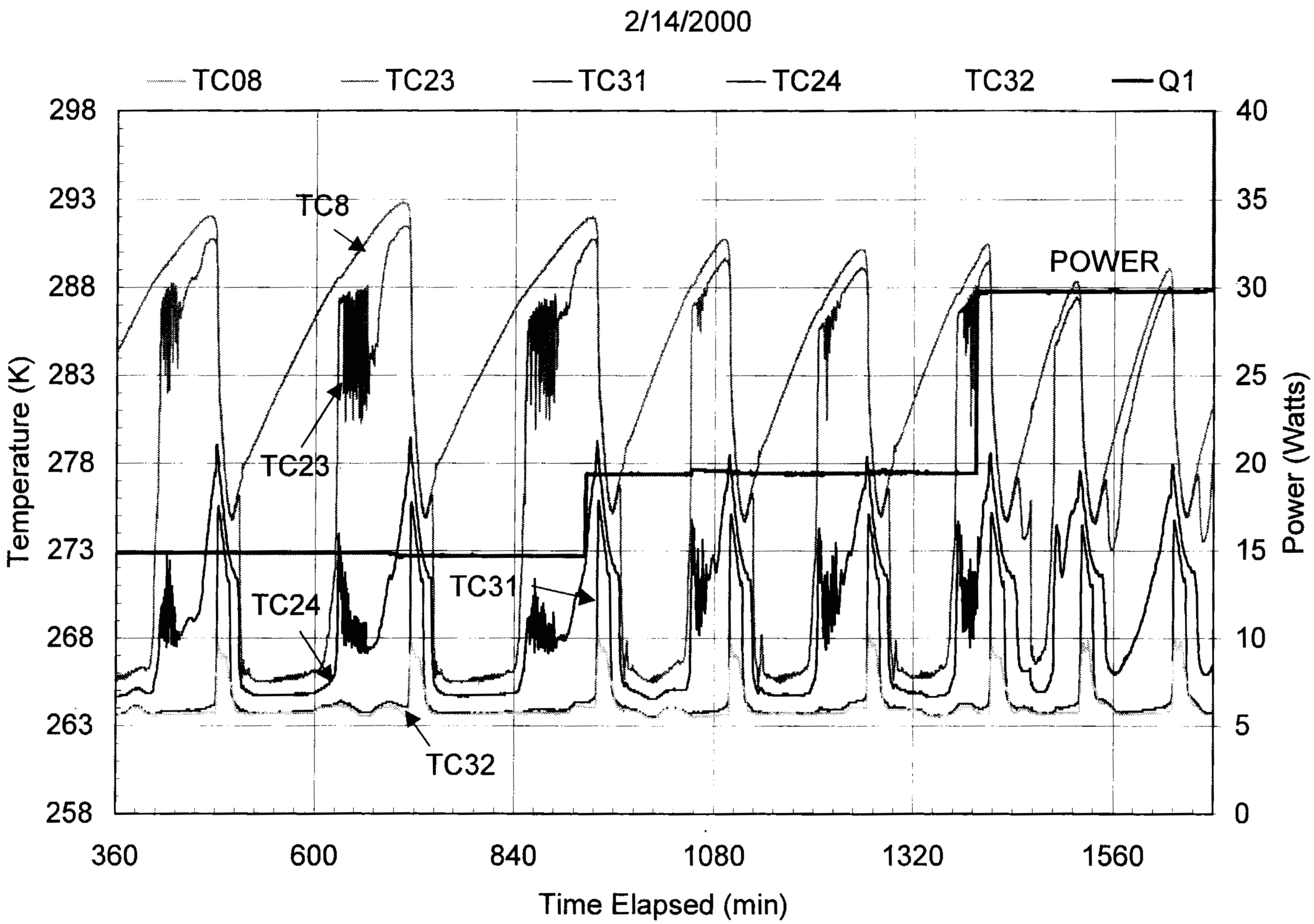
(75W, 243K/ 253K)



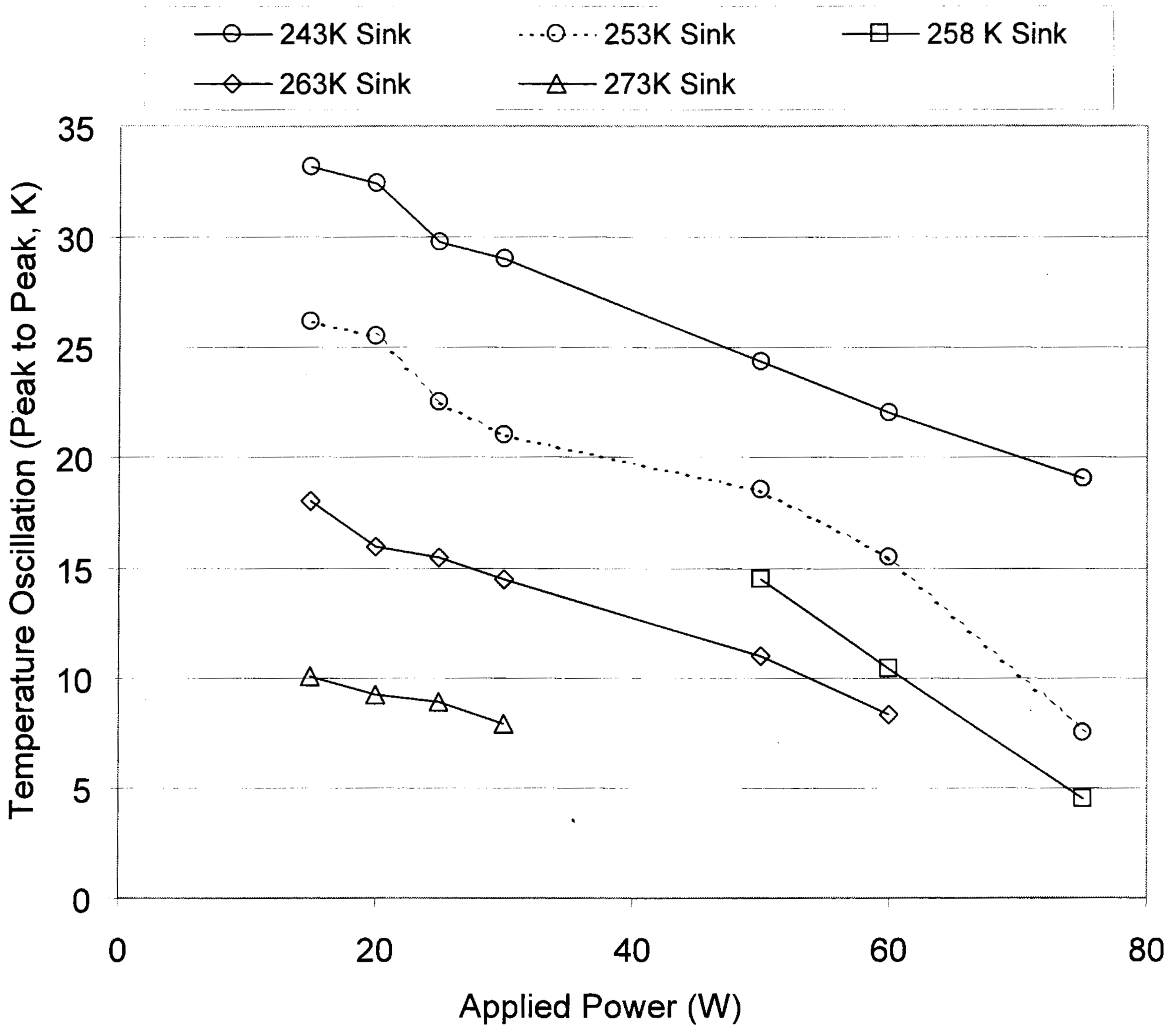
Temperature Oscillation in TES LHP EDU
(15W/253K, 20W/293K, 20W/253K)



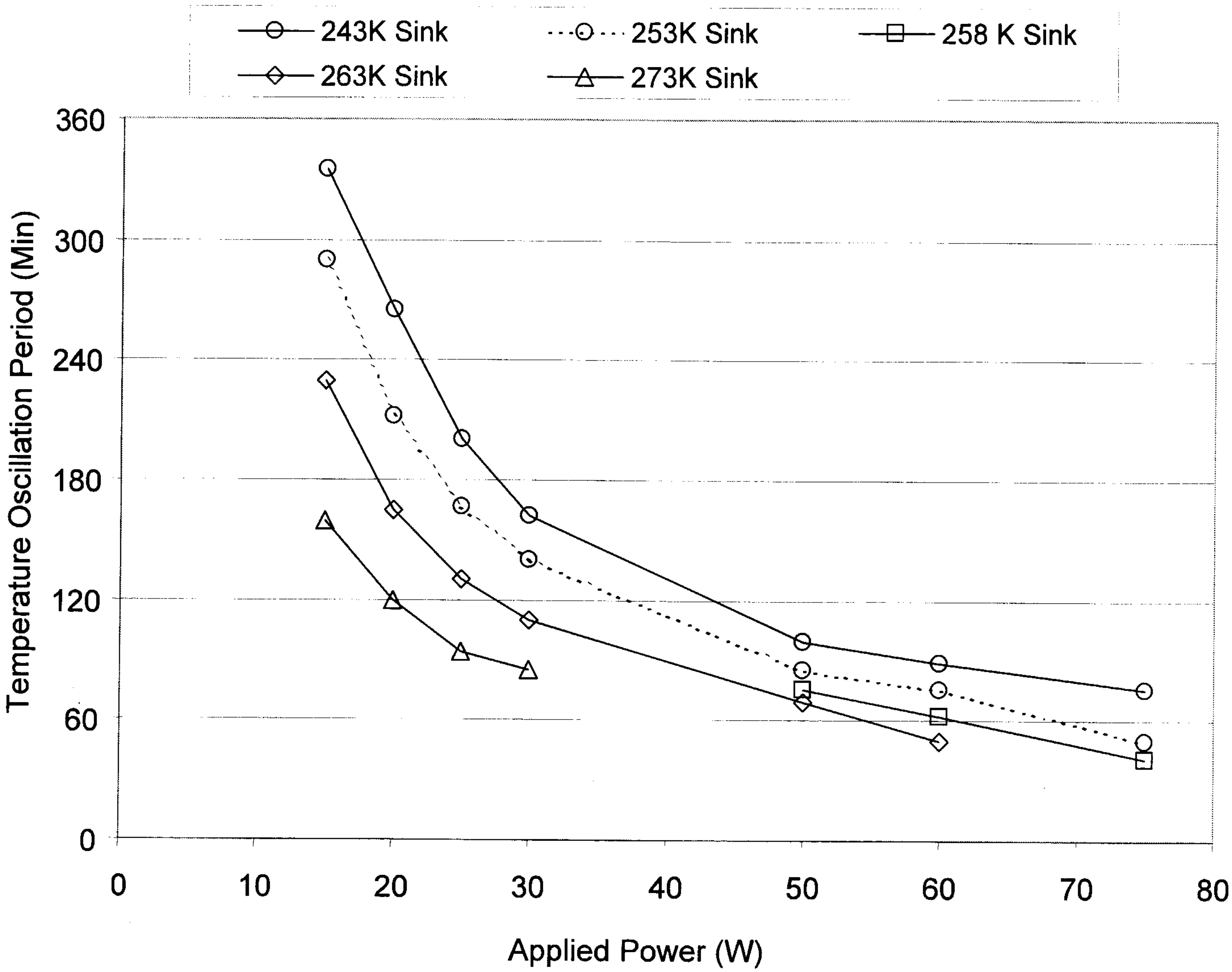
Temperature Oscillation in TES LHP EDU
(263K, 15W/ 20W/ 30W)



Amplitude of Temperature Oscillation vs Applied Power and Sink Temperature



Period of Temperature Oscillation vs Applied Power and Sink Temperature



Summary

- Under certain conditions, the thermal mass can modulate the constant applied power into an oscillating heat input to the evaporator.
  - The oscillating evaporator power has a maximum that is greater than the applied power and a minimum that is smaller than the applied power.
  - Ultimate source of the temperature oscillation
- In order to sustain a low frequency, high amplitude temperature oscillation, all of the following three conditions must prevail:
  - A large thermal mass is attached to the evaporator.
  - A small power is applied to the thermal mass.
  - The sink temperature is colder than the ambient temperature.
- The combination of the above three parameters governs the temperature oscillation.
  - In general, the amplitude and period of the temperature oscillation increase with an increasing thermal mass, a decreasing applied power, and a decreasing sink temperature.
- Once it has started, the temperature can continue indefinitely until the operating condition changes.
- The proposed theory agrees well with experimental data.

Conclusions

- In space applications, the evaporator is attached to large thermal masses and the radiator may be exposed to a cold environment over a long period of time, thus a high amplitude temperature oscillation can occur.
- Several methods can be used to reduce or eliminate high amplitude temperature oscillations.
  - Actively control the CC temperature.
  - Reduce the heat leak from the evaporator to CC.
  - Reduce heat leak from ambient to the liquid line.
  - Heat the vapor line to prevent vapor condensation in the vapor line.
  - Increase the thermal conductance between the evaporator and thermal mass
- Recommended future studies
  - Verify the oscillating evaporator power by placing a sufficient number of temperature sensors in the thermal mass.
  - Investigate the effect of thermal diffusivity of the thermal mass.
  - Develop an analytical model to predict conditions under which high amplitude temperature oscillation will occur.
  - Develop an analytical model to predict the amplitude and frequency of the temperature oscillation.