Resonance and "Rumble":

- The underlying phenomenon is no more complicated than the sound you get from blowing over a soda bottle, like in a jug band.
- The brief summary of the issue below is paraphrased from an article ("Thermoacoustic Vibrations in Industrial Furnaces and Boilers") recommended by one of the experts with whom we have spoken. It describes how flue gas recirculation (FGR -used in boiler 6) of colder partially burned flue gas back into the hot boiler chamber can lead to thermoacoustic vibrations or "*rumble*" (an actual technical term) when the chaotic/unstable mixing environment leads to resonance in the boiler or stack.
  - "Rumble" in industrial boilers is low frequency noise that is closely related to the "singing flame tube" experiment that students often see in a physics class:

    https://www.youtube.com/watch?v=XppfD4r8pQQ (a 13 second video)

    - You can hear the resonant sound of the tube disappear when the flame is removed at about 9 seconds into the video. Imagine this experiment with a huge diameter tube (i.e., the boiler) with a much lower "singing" voice (i.e., rumble).
  - Thermoacoustic vibrations require two key features:
    1) a large temperature gradient (e.g., from FGR or a metal stack as opposed to masonry) and
    2) a gas-filled cavity capable of resonant vibration (e.g., the boiler).
  - Eisinger and Sullivan (2002, 2008) showed in definitive studies that temperature differences between the cold inlet air and the hot combustion gases can cause vibrations/noise to be phase synchronized in industrial-scale boilers, leading to substantial low frequency noise.
  - The phase synchronization allows thermal energy from combustion to be converted into acoustic energy (i.e., noise).
- There is a very nicely done video demonstrating resonance and standing waves at the URL below. It is only 12 minutes long and avoids too much technical detail.

  https://www.youtube.com/watch?v=dihQuwrf9yQ (an excellent 12 minute video)

Eisinger F.L., Sullivan R.E. (2002). Avoiding thermoacoustic vibration in burner/furnace systems. Transactions of the American Society of Mechanical Engineering 124: 418-424.

Eisinger F.L., Sullivan R.E. (2008). Prediction of thermoacoustic vibration of burner/furnace systems in utility boilers. Journal of Pressure Vessel Technology 130.

UVMMC boilers:

- Boilers 1 & 2 are the same size as problematic boilers 5 & 6.
- Boilers 1 & 2 do not have problems with regard to low frequency noise.
- Boilers 1 & 2 have standard burners and exhaust through a wider & taller masonry stack (by 25 feet).
- Boiler 6 uses Flue-Gas Recirculation (FGR), which brings partially burned gases back into the burn chamber and can cause a chaotic/unstable mixing environment in the boiler leading to substantial low frequency noise, where thermal energy from combustion is converted into acoustic energy.

Thermoacoustic Vibrations in Industrial Furnaces and Boilers (continued on the next page …)

Flynn T, Timothy A, Fuller T, Rufener S Finney C, and Daw C. 2017. AFRC Industrial Combustion Symposium.

Thermoacoustic Vibrations in Industrial Furnaces and Boilers

Industrial boilers and furnaces occasionally suffer *low-frequency vibrations* generated by a dynamic feedback process between the burner (or burners) and acoustic modes in adjacent gas-filled cavities in the main combustion chamber or connecting ductwork. This occurs when pressure pulses associated with acoustic resonances propagate to the burner so that they are in phase with combustion rate fluctuations caused by turbulence and reaction dynamics. When these pressure pulses become sufficiently phase-synchronized with fluctuations in heat release from the flame, the forces that normally dissipate the pressure waves are overwhelmed and an amplifying feedback loop is created. In the literature, such oscillations are referred to as thermoacoustic oscillations or 'rumble,' and their basic physics have been the subject of numerous investigations for well over a century. Unfortunately, rumble amplitudes can be large enough to negatively impact thermal efficiency and emissions, and the associated mechanical vibrations they cause can even lead to structural damage.