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Undulator Hall Air Temperature Fault Scenarios *

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Abstract

Recent experience indicates that the LCLS undulator segments must not, at any time following tuning, be allowed to change temperature by more than about $\pm 2.5\ C$ or the magnetic center will irreversibly shift outside of acceptable tolerances. This vulnerability raises a concern that under fault conditions the ambient temperature in the Unduator Hall might go outside of the safe range and potentially could require removal and retuning of all the segments.

In this note we estimate changes that can be expected in the Undulator Hall air temperature for three fault scenarios:

1. System-wide power failure
2. Heating Ventilation and Air Conditioning (HVAC) system shutdown
3. HVAC system temperature regulation fault

We find that for either a system-wide power failure or an HVAC system shutdown (with the technical equipment left on), the short-term temperature changes of the air would be modest due to the ability of the walls and floor to act as a heat ballast. No action would be needed to protect the undulator system in the event of a system-wide power failure. Some action to adjust the heat balance, in the case of the HVAC power failure with the equipment left on, might be desirable but is not required. On the other hand, a temperature regulation failure of the HVAC system can quickly cause large excursions in air temperature and prompt action would be required to avoid damage to the undulator system.

1 Description

The Undulator Hall is a 170 m long section of straight underground tunnel with concrete floor and Shotcrete walls. Temperature controlled air is supplied to the west end of the tunnel and returned to the HVAC system from the east end to maintain an average temperature of 20.0 C. The HVAC system consists of two identical Air Handling Units (AHU) each with a supply and return fan, a cooling coiling and a re-heat coil. The capacity of each AHU is 280 $m^2/minute$ (10,000 cfm). See Figure 1.[1]

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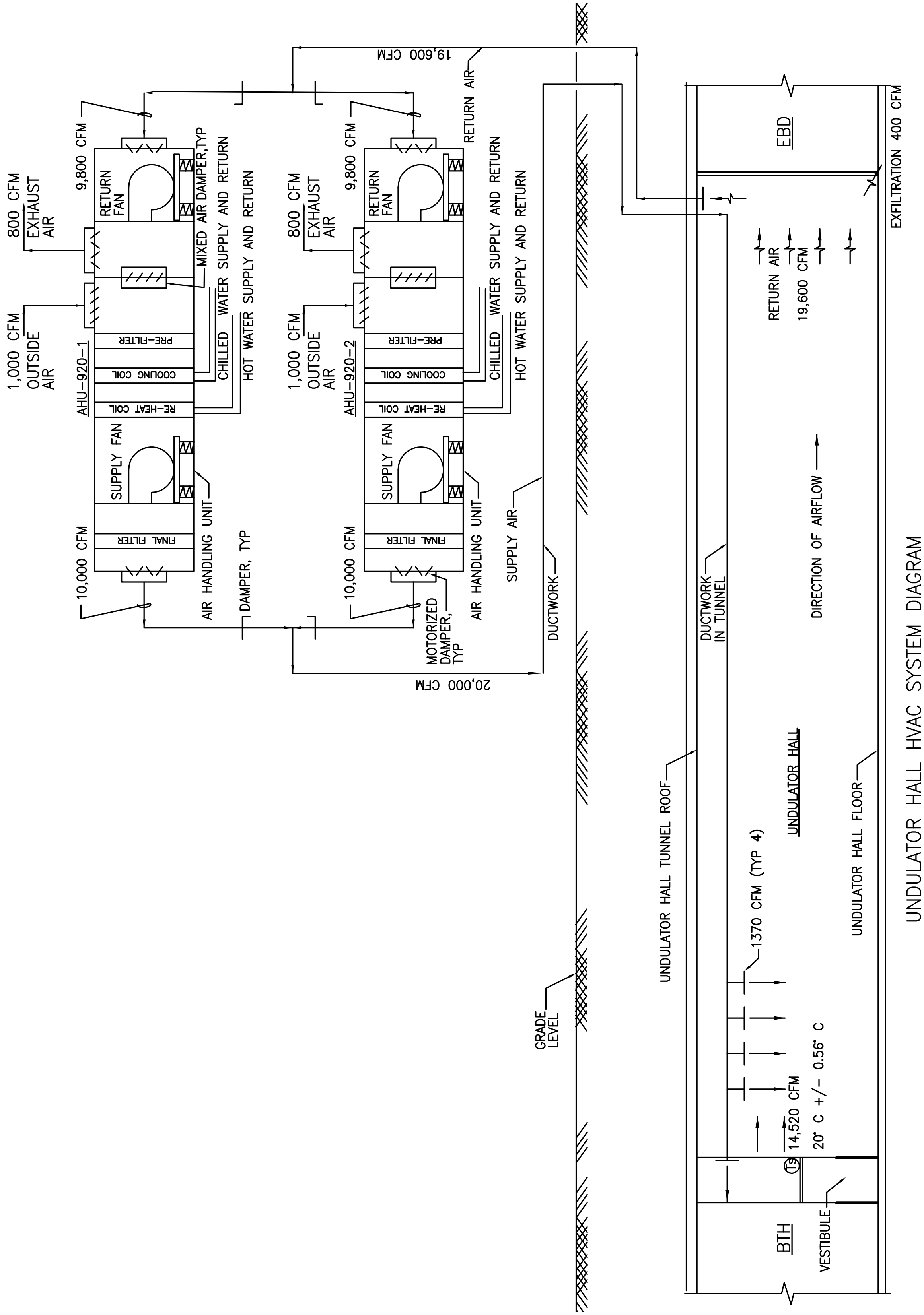

Figure 1: Schematic of air flow in the Undulator Hall

Table 1: Assumed conditions in the Undulator Hall during normal operation.

20.0 C	Undulator Hall Air Temperature
19.0 C	Surface temperature of walls
13000 W	Heating load, all sources
4000 W	Cooling from walls and floor
1000 W	Cooling from chilled water lines
8000 W	Cooling by HVAC system

2 Preconditions

Initial temperatures For simplicity we assume the power balance and temperatures as given in Table 1, which includes a uniform air temperature of 20.0 C, and a uniform steady state temperature for the surface of the walls and floor of 19.0 C. In reality the temperature profile of the walls and floor depends on the location in the Undulator Hall, with roughly 0.5 C cooler temperatures at the west end and 0.5 C warmer temperatures at the east end. It also depend on the past history of the Undulator Hall air temperature. When the HVAC system is first started up the walls and floor are close to 18.0 C, and the heat flux conducted from the air to the walls and floor is relatively large. The assumed value of 19.0 C represents the temperature of the walls and floor expected for the middle of the Undulator Hall about three months after initial HVAC turn on. After three months the temperature of the walls and floor increases very slowly [2].

Initial power balance The assumed heat balance prior to the fault given in Table 1 is based on a detailed thermal model containing estimates of the heat dissipated to air of individual pieces of equipment, estimates of the heat transfer rate to the walls and floor and chilled water lines, and a model of the ground temperature [2]. The loads are rounded to the nearest kW for clarity.

3 System-wide Power Failure

The System-wide Power Failure scenario consists of a general power failure to the HVAC system and all the equipment, lights, etc., that generate heat in the Undulator Hall. In this scenario, after the power failure, the temperature of the air and the equipment in the Undulator Hall will first equilibrate with the walls and floor and then cool very slowly. It is assumed that no action is taken in response to this event.

At the time of the power failure the walls and floor, according to the assumptions in Table 1 would be at 19 C. The ambient ground temperature is about 18 C [2], so over a period of months, if the power failure condition is allowed to continue (a shutdown, for example), the walls and floor would cool an additional degree on the average. As mentioned in the section on preconditions, the west end of the tunnel would start out roughly 0.5 C cooler and the east end roughly 0.5 C warmer than the nominal 19.0 C.

The time dependence of the air temperature just after a power failure is governed by the heat capacity of the tunnel equipment and the air. It also depends on the heat transfer rate from the equipment to the tunnel air, and on the heat transfer rate from the tunnel air to the walls and floor. We assume that the tunnel air always stays in thermal equilibrium with undulator equipment. The rate of change of the air (or equipment) temperature is then governed by,

$$(m_{air} + m_{eq})c_p \frac{dT}{dt} = -hA(T - T_w)$$

where the variable definitions and values assumed are given in Table 2. The specific heat of the air is assumed to be the same as that of the equipment. The equipment mass was based on the measured weights provided by Poling [3] of the undulator segments, girders, vacuum chamber and other miscellaneous components riding on the girder, as well as the empty pedestals. An estimate for the weight of the sand in the pedestals was also included the weight. Using a variable heat transfer coefficient that incorporates free convection (AHU fans are off) and radiation, the differential equation was integrated numerically to produce the plot in Figure 2.

The approach to the new equilibrium temperature

Table 2: Parameters assumed in the model of the approach to equilibrium following a complete power failure event.

m_{air}	4600 kg	tunnel air mas
m_{eq}	$155,000$ kg	equipment mass
c_p	1000 $Jkg^{-1}C^{-1}$	specific heat
T	variable	air temperature
T_w	19.0 C	wall temperature
h	0.8 $Wm^{-2}C^{-1}$	heat transfer coef.

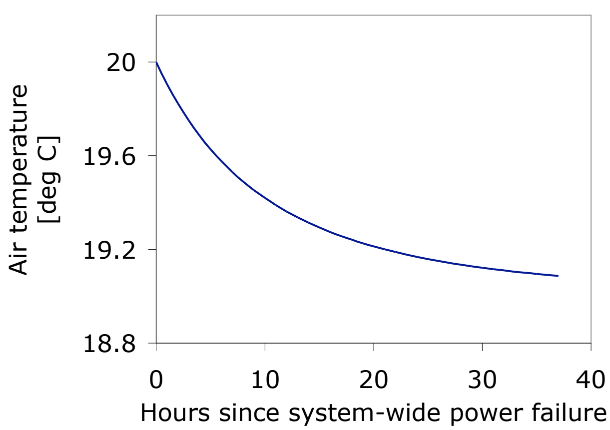

Figure 2: Transient response of the tunnel air expected after a complete loss of power to equipment and the HVAC system assuming the tunnel walls and floor are at a steady state temperature of 19 C.

is tempered by the low heat transfer rate between the tunnel air and the tunnel walls and floor. The convective heat transfer coefficient, which was already low (1.3 $Wm^{-2}C^{-1}$) under normal operation with forced convection, gets even lower (initially 0.8 $Wm^{-2}C^{-1}$) when the ventilation goes off and forced convection is no longer active. And, as the air cools and the temperature difference drops between the air and the walls and floor, the free convection heat transfer rate decreases further. Convective heat transfer rates were taken from Kleyn[4] and Mark[5].

4 HVAC System Shutdown

The HVAC System Shutdown scenario consists of a complete shutdown of the Undulator Hall HVAC system so that there is no forced air flow in the Undulator Hall, but the heat loads are left on as in normal operations. This situation might occur for maintenance reasons, or by request from the Alignment Engineering Group, or by a fault in the HVAC controls. In this scenario the air temperature will increase until the heat generated by the equipment is balanced by cooling from the tunnel walls and floor.

Short time scale On a short time scale (hours) two things happen after the air flow stops: the heat transfer coefficient decreases due to the lack of air flow, and the air temperature rises until the temperature drop between the air and the surface of the walls and floor is high enough to transfer the new larger heat flow. According to the assumptions in Table 1 the air heats up to an equilibrium value such that 13000 W of power must be absorbed by the walls and floor instead of 4000 W under normal operation conditions.[1] Fortunately, as the air and equipment warm up radiative cooling becomes increasingly important for heat transfer, and by the time equilibrium conditions are reached, radiative cooling dominates over free convection. A calculation that includes free

[1]The chilled water lines would normally absorb about 1000 W of heat. In this model we assume that they go off-line with the HVAC system and don't contribute any cooling effect.

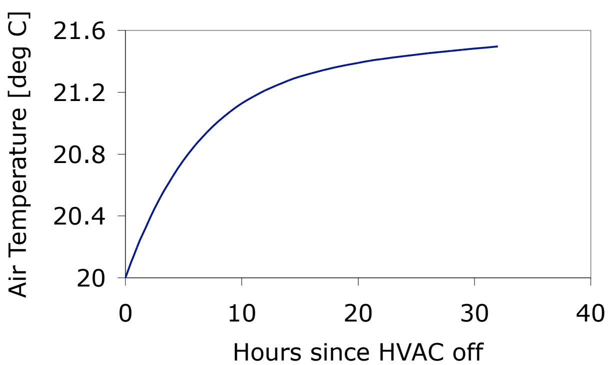

Figure 3: The transient behavior of the air temperature of the tunnel air following a shutdown of the HVAC system assuming the heat loads are left on.

convection and radiation was carried out and the result is that qausi-static temperature for the air at which 13000 W is absorbed is 2.4 C warmer than the surface of the walls and floor. Since the surface temperature is approximately 19 C the air temperature goes up to 21.4 C just after the HVAC system goes off.

Long time scale On a longer time scale there is a slow rise in surface temperature of the walls and floor, as the ground heats up, which brings the air temperature up slowly. An ANSYS model of the response of the ground temperature to a step function heat flux was run previously using appropriate soil parameters for a heat flux of 3.62 Wm^{-2}. It yielded a rise of the wall temperature of 0.145 C in the first day, with a slowly decreasing rate of rise thereafter. In the HVAC failure case the heat flux is $13000/3000 = 4.3$ Wm^{-2} so we scale the ANSYS prediction up by a factor of 4.3/3.62 to estimate the initial rate of rise of the temperature rise of the walls and floor surfaces of 0.17 C per day.

The short and long term effects are combined and the result is shown in Figure 3.

5 HVAC System Temperature Regulation Failure

The HVAC system has the cooling and heating capacity to supply air that is well above or below the safe range of exposure for the undulator segments. Of the three fault scenarios discussed, a fault in the temperature regulation of the HVAC system can produce the greatest possible temperature changes in the tunnel air temperature.

The maximum cooling the HVAC system can conceivably produce under a reasonable fault scenario would occur if for some reason the chilled water control valve opens 100% and the hot water control valve is completely closed. In this case the temperature of the air supplied to the west end of the tunnel would tend toward to the chilled water temperature of 6.7 C. This cold air mass would fill the entire length of the tunnel within about 6 minutes.

Similarly, the worst case of overheated air the HVAC system can conceivably produced would occur if the hot water control valve is 100% open and the chilled water control valve is completely closed. In this failure mode the temperature of the supplied air would tend toward the hot water temperature of 85 C and would also fill the tunnel in 6 minutes.

Even if the Undulator Hall HVAC system components are working properly, the supply air temperature depends on the temperatures of chilled and hot water from the Central Utility Plant which are subject to breakdown of components and maintenance interruptions.

6 Recommendations

1. If for any reason the supply air temperature, measured at the discharge of the air handler units, differs from the 20.0 C by more than ± 2.0 C, we recommend setting off an audible alarm in the control room, and if the condition persists for more than one minute, activating an automatic shutdown of the Undulator Hall HVAC fans. This should protect the undulator segments against HVAC temperature regulation faults of all types. Some means of bypass will be

necessary to get back to normal operation and to effect testing and repairs of the HVAC system.

2. If air flow to the tunnel is less than approximately 90% of normal, we recommend a visual alarm in the control room so that the operator is made aware that there is a flow problem. In such a case the operator should monitor air temperatures in the Undulator Hall and notify a responsible representative of the undulator system, who should decide whether to turn on or off undulator equipment to help stabilize the temperature. This action should ameliorate the temperature rise that would otherwise occur in the Undulator Hall and reduce the time required to re-establish the normal operational temperatures.

3. If complete power failure occurs such that the HVAC system and the equipment in the tunnel are both without power, we recommend only that the doors that isolate the Undulator Hall from the adjoining Beam Transport Hall and Beam Dump Hall not be left open. If the Undulator Hall air is kept more-or-less isolated we expect a complete power failure to be a be fail-safe situation with respect to the undulator segment temperature tolerance.

References

[1] Schematic is adapted from constructions drawings and HVAC System Control drawings provided by Jacobs Engineering

[2] "Air Temperature in the Undulator Hall", LCLS-TN-06-2, J. Welch (2006)

[3] Ben Poling, private communication.

[4] LCLS Undulator Hall Tunnel Thermal Performance Analysis, SCS-SLAC-R-0001, J. Kleyn. From SCS Solutions, Sunnyvale Ca.,12/21/05, 46p.

[5] Mark's Standard Handbook for Mechanical Engineers, 10th edition.