The goal of this analysis is to determine an upper limit to fuel temperature after a LOCA and to compare that result to the temperature limit imposed by the internal pressurization and subsequent stress on the stainless steel cladding of a standard TRIGA fuel element. The maximum temperature estimate will then inform whether any engineered safety features are required at MNRC to prevent unacceptable fuel temperature during the postulated LOCA event.

Assumptions:

1. The reactor was operating indefinitely at a nominal steady-state power level of 1 MW before primary cooling water began to drain from the reactor tank.
2. The reactor operator initiates a reactor scram immediately after the reactor tank low water level monitor alarms (reactor tank still holds 7,000 gallons at this alarm point).
3. Water drains from the tank through a lower drain valve (1.5 inches in diameter) into bay 1, after an unspecified event. The reactor core begins to become uncovered 60 minutes (3600 s) after this event.
4. The reactor core's hottest fuel element during 1 MW steady-state operation provides the limiting case during this LOCA scenario. Temperatures within all other fuel elements are assumed to be bound by this highest power element.
5. The thermal power produced in the hottest fuel element is 17.69 kW during 1 MW reactor operations.

Source term (hottest element from LCC):

Fuel element heating after reactor shutdown is modeled as a consequence of fission product decay heat and is assumed to be proportional to the thermal power generated by the fuel element during its steady-state operation before the beginning of the accident. Decay heat in a fuel element 3600 seconds after reactor shutdown is estimated to be 1.19% of the thermal power generated by that element during its steady-state operation prior to reactor shutdown. This estimate is calculated using the following time-dependent relationship for the ratio of thermal power from the gamma and beta decay of fission products to the steady-state thermal power before shutdown [From KSU SAR]:

$$R(t) = \frac{0.04856 + 0.1189\ln(\mathrm{t}) - 0.0103\ln(\mathrm{t})^2 + 0.000228\ln(\mathrm{t})^3}{1 + 2.5481\ln(\mathrm{t}) - 0.19632\ln(\mathrm{t})^2 + 0.05417\ln(\mathrm{t})^3}$$

where t is the time, in seconds, after the reactor has been shut down.

The hottest fuel element in the MNRC LCC generates 17.69 kW of thermal power during 1 MW steady-state operation, so the total decay heat from the hottest fuel element when water is drained from the reactor core is 210.5 W, while the total core decay heat is 11,900 W.

Once the reactor pool is completely drained of coolant water the fuel elements would be cooled by air circulation. Calculations and experiments performed by GA have shown that air circulation would be adequate to prevent fuel damage by removing the decay heat of the fuel (Ref.2). General Atomics studies indicated that, given continuous 1.0 MW_t operation, if the highest power TRIGA fuel element power was 19.7 kWt, and the corresponding peak near instantaneous LOCA fuel surface temperature would reach 585 degrees C (1,085 degrees F). This is well below the temperature limit of 950 degrees C (1,742 degrees F) for fuel with a cladding temperature of greater than 500 degrees C (932 degrees F), which ensures that the cladding integrity is maintained. The 500 degrees C (932 degrees F) is used for the cladding temperature due to the air cooling scenario of the LOCA. The maximum peak MNRC fuel element power is 17.69 kWt, and thus, bounded by the GA analysis. Furthermore, a near instantaneous LOCA is not considered credible at MNRC as there are no penetrations in the MNRC reactor tank and the 60 minutes required to uncover the core during the postulated LOCA would only further reduce the peak fuel temperatures.

General Atomics also performed experiments, which concluded that the temperature rise for a partial loss of coolant is less severe than for a complete loss of coolant and that fuel damage would not result (Ref. 2). For a partial LOCA, with a drain time of approximately 15 minutes, the peak fuel temperature would reach 578 degrees C (1,072 degrees F) (Ref. 1).

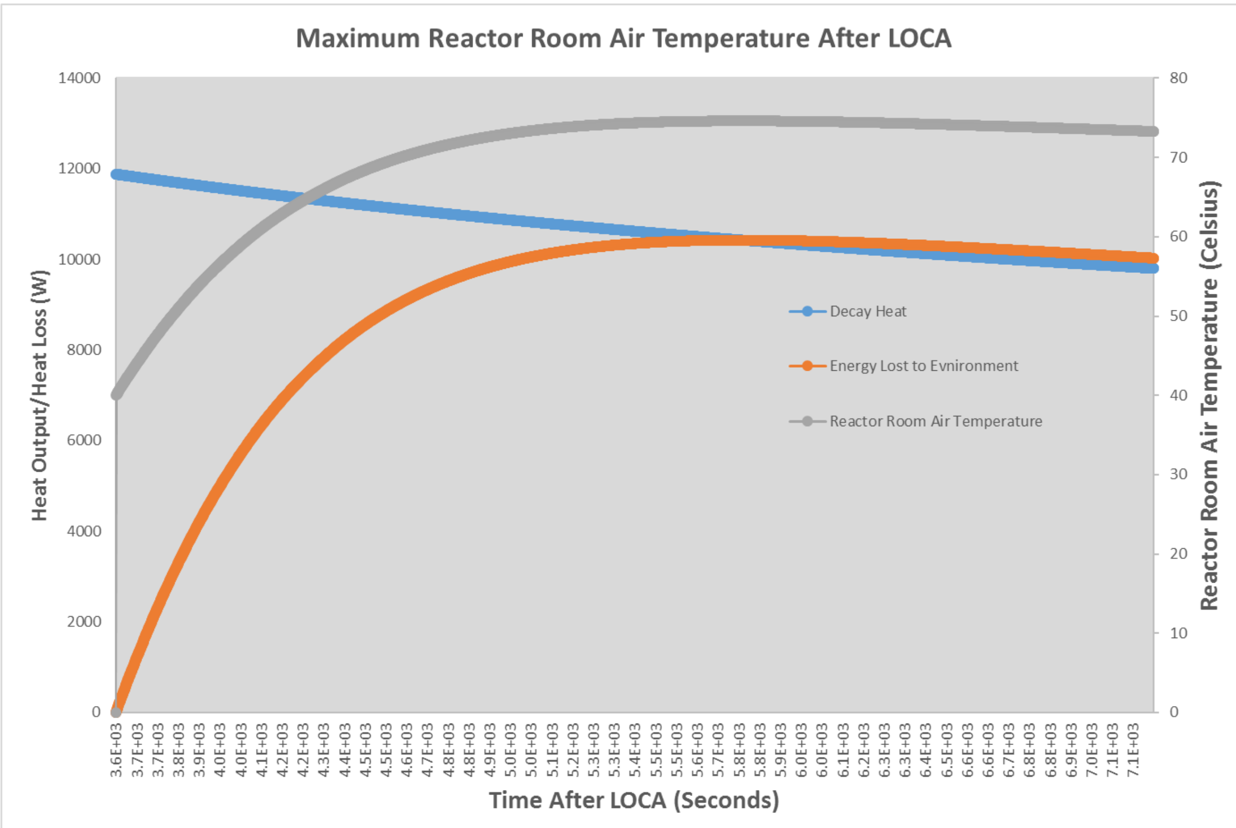
An alternative scenario than complete draining of the reactor pool is that the core is only partially uncovered. GA performed experiments that concluded that the temperature rise for a partial loss of coolant is less severe than for a complete loss of coolant (Ref. 3). These conclusions are supported by studies performed for TRIGA fuels which show that, in general, as long as the operating power is less than 1.5 MWt, the fuel cladding should not breach during a partial LOCA (Ref. 2 and Ref. 3).

Effect of Reactor Room Heating:

One concern unique to the MNRC is the facility's relatively small reactor room. That is to say if the ventilation system in the reactor room was inoperable during a LOCA, the inlet air temperature to the reactor will rise noticeably. If the air becomes sufficiently warm, the ability for the air to cool the reactor may be diminished enough to invalidate the comparison between MNRC LOCA to the General Atomics LOCA analysis.

It is assumed that decay heat from the core is transferred into the reactor room air, then transferred through the walls and ceiling of the reactor room to the outside atmosphere which acts as the ultimate heat sink. It is assumed no heat is transferred to any other materials inside the reactor room. The volume of the reactor room is 8,550 ft^3 with a surface area of 2,170 ft^2 (ceiling and walls). The reactor walls are made of 6-inch-thick cinder blocks with an assumed R value of 3.8 h ft^2 F/BTU. This value was chosen intentionally large to make the walls more insulating to produce a higher (more conservative) maximum air temperature. While the reactor room roof is metal (more conductive) is was also assumed to be made of the same cinder block material as the walls. Starting temperature of both the air inside the reactor room and outside (heat sink) were selected to be 40 C (typical midday summer conditions). The results can be seen in the figure below with reactor room air temperatures peaking at 74 C approximately 37 minutes after the core becomes uncovered. After this peaking in reactor room temperature a gradual decrease in temperature can be seen as a result of the slowly decreasing source term (decay heat).

The result is an increase in inlet cooling air temperature of potentially 34 degrees C. The GA analysis of the instantaneous LOCA for a 19.7 kW element maintains a safety margin of 365 degrees C between peak fuel temperature and the expected fuel cladding failure point. The postulated MNRC LOCA involves a less power dense hottest element and a significant decay time of one hour, therefore the safety margin between peak fuel temperature and the expected fuel cladding failure point is at least 365 degrees C. It is highly unlikely an increase of inlet air cooling of 34 degrees C would significantly degrade this safety margin. The result is that no engineered safety features are needed to mitigate the postulated MNRC LOCA.



References:

1. Texas A&M University System, "Response to NRC Request for Additional Information Questions 1 through 37 (Non-Financial) for the Nuclear Science Center Reactor," May 27, 2011, ADAMS Accession No. ML111950372.

2. General Atomics, J.R. Shoptaugh, Jr., "Simulated Loss-of-Coolant-Accident for TRIGA Reactors," GA-6596, August 18, 1965.

3. General Atomics, N.L. Baldwin, F.C. Foushee, and J.S. Greenwood, "Fission Product Release from TRIGA-LEU Fuels," October 1980.