
# Analysis of Liquid Cryogen-Water Experiments with the MELCOR Code

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# ANALYSIS OF LIQUID CRYOGEN-WATER EXPERIMENTS WITH THE MELCOR CODE

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## ABSTRACT

Vapor explosions are processes involving significant energy exchange between a hot and colder, more volatile liquid. This phenomenon can cause significant pressurization and may cause damage to structures. Historically, vapor explosions have been of interest in industrial processes with molten metals, and postulated accident scenarios involving molten fuel and water in current light water reactors. With the potential use of superconducting magnets in fusion designs, postulated accident scenarios involving water used to cool various structures and cryogenic materials (i.e., helium and nitrogen) required for magnet cooling have to be addressed. A rapid increase in pressure may be seen if liquid nitrogen or helium comes into contact with water. Because of significant temperature differences between the water and cryogenic materials, a rapid heat transfer event similar to a vapor explosion may be observed with the cryogen as the 'coolant' and the water as the 'fuel'. Experiments to quantify this phenomenon were performed at the University of Wisconsin-Madison. This paper reviews these experiments and presents comparison analyses using the systems code, MELCOR. Experimental results showed that no large 'shock' pressures were observed. Thus, one can consider the 'fuel-coolant' interaction to be a boiling event controlled by 'bulk thermodynamics'. We hope to benchmark the code and show its usefulness in determining potential critical issues involving these fusion systems.

## I. INTRODUCTION

When significant energy exchange takes place between a hot liquid and a colder, more volatile liquid, vapor explosions can occur. A vapor film layer is created between the two liquids when they come in contact, with the possibility that the vapor film may break down, due to fluid instabilities, and drive the hotter fluid to fragment rapidly. As the surface area between the fluids increases fragmentation is accelerated, which can lead to rapid vapor pressure increases with 'shock' explosive characteristics.[1]

Historically, fuel-coolant interaction phenomena (vapor explosions) have been associated with industrial accidents involving molten metals, and with melt accidents in fission reactors. When hot liquid metal comes in contact with water, rapid pressurization rates due to vapor production and even explosions can be generated. A review of the relevant literature was done by Corradini.[2] Recently the possibilities of cryogenic vapor explosions have been identified in fusion reactor systems like the ITER. Contact between liquid helium or nitrogen, used to cool superconducting magnets, and water in the secondary side could generate significant pressurization rates and possibly vapor explosions.[1]

Previous studies have shown that vapor explosions occur when near equal volumes of liquid nitrogen and water are brought together and mixed.[3] Initially, a stable vapor film is formed between the two liquids. An ice layer, separating the two fluids, may form and has to be broken by an externally generated pressure. This results in the mixing of the two liquids. The results from the current liquid helium-water experiments indicate that the pressure may climb as fast as 800 kPa/s.[1]

MELCOR system/thermodynamic calculations were performed to determine whether the pressurization rate could be simulated. This paper reviews these liquid helium/nitrogen-water experiments and then utilizes MELCOR to simulate integral system pressurization rates for liquid helium-water interactions.

## II. EXPERIMENT[1]

Experimental facilities have been built to characterize the interaction between liquid helium or liquid nitrogen with subcooled, pressurized water. A schematic of the liquid helium-water interaction experiment is shown in Figure 1.

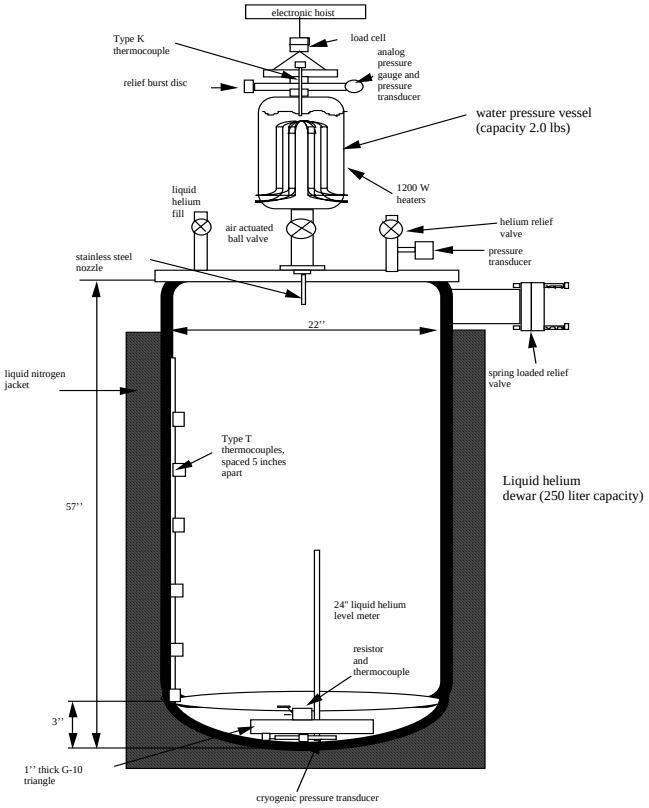


Figure 1. Liquid helium-water experimental facility.

An explanation of the operation of the facility is provided elsewhere by Duckworth, Pfotenhauer and Corradini.[4] A summary of the experimental procedure is given below. The initial water temperature and pressure was set through the use of a fixed amount of water (1.5013 lbs) in a pressurized vessel located on the top of the dewar. After the water was added and the desired nozzle diameter (2 mm to 12 mm) in which the water entered the dewar was selected, it was attached and pressurized using 1500 W tubular heaters. Initial temperatures and pressures varied between 120 $^{o}$C and 150 $^{o}$C and 310 kPa and 520 kPa respectively. After evacuating and precooling the dewar, liquid helium was added to cool the remaining structure to 4.2 $^{o}$K and until the desired amount of liquid was reached. After system equilibration, water is injected into the pressure vessel. Global and local temperatures are monitored during the event. The initial mass of the vessel without water is compared to the final mass to determine the amount of water injected. This procedure was repeated for different initial conditions and nozzle diameters to accurately characterize the interaction between the cryogens and water.

## III. EXPERIMENTAL RESULTS

Local gauge pressure as a function of time is presented in Figure 2 for liquid helium-water interactions. Since the liquid helium dewar pressure exceeded the maximum measurable pressure, only the initial measured rate of pressurization was used to characterize this interaction.

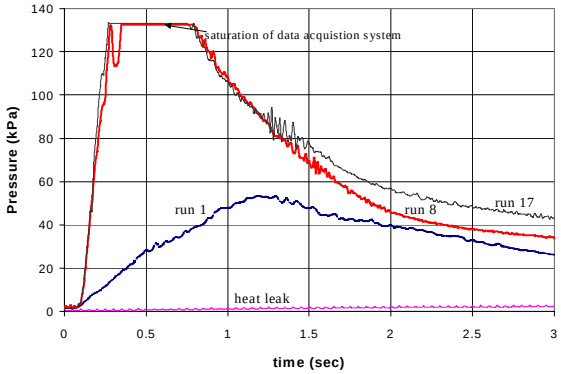


Figure 2. Multiple liquid helium-water interaction experimental pressure histories.

During initial cryogen-water mixing, measurements of rate of pressure increase, dP/dt were obtained via a linear fit. A summary of the initial pressure histories is given in Table 1.[1]

Table 1. Summary of liquid helium-water experiments and data analysis.

| Run | D mm | $P_w$ kPa | $T_w$ C | $m_w$ kg | t s | $V_{he}$ L | dP/dt kPa/s |
|---|---|---|---|---|---|---|---|
| 1 | 2.0 | 490 | 147.0 | 0.165 | 0.960 | 19.8 | 58.96 |
| 2 | 2.0 | 352 | 142.1 | 0.104 | 0.500 | 19.8 | 29.90 |
| 5 | 2.0 | 401 | 134.0 | 0.067 | 0.720 | 20.8 | 1.471 |
| 6 | 2.0 | 402 | 134.1 | 0.074 | 0.385 | 20.8 | 44.51 |
| 7 | 2.0 | 317 | 122.0 | 0.036 | 0.480 | 20.8 | 1.033 |
| 8 | 12.0 | 317 | 122.0 | 0.384 | 0.355 | 7.05 | 821.9 |
| 9 | 2.0 | 307 | 121.8 | 0.047 | 0.275 | 7.05 | 31.53 |
| 10 | 2.0 | 307 | 121.5 | 0.038 | 0.255 | 3.28 | 1.663 |
| 11 | 2.0 | 314 | 121.9 | 0.073 | 0.605 | 3.28 | 31.03 |
| 12 | 2.0 | 312 | 122.8 | 0.107 | 0.565 | 2.22 | 30.82 |
| 13 | 8.1 | 320 | 123.0 | 0.229 | 0.295 | 7.05 | 527.5 |
| 14 | 5.0 | 306 | 120.0 | 0.152 | 0.325 | 5.73 | 139.7 |
| 15 | 5.0 | 318 | 122.1 | 0.194 | 0.750 | 7.05 | 179.3 |
| 16 | 10.0 | 300 | 121.1 | 0.358 | 0.430 | 7.05 | 790.0 |
| 17 | 10.0 | 300 | 121.8 | 0.289 | 0.220 | 7.05 | 704.4 |
| 18 | 2.0 | 405 | 134.0 | 0.106 | 0.230 | 7.05 | 33.04 |

The pressurization rate data will be compared to MELCOR simulations using the same initial conditions. Water injection nozzle diameter was also varied and will have an effect on water breakup and subsequent heat transfer rate to the cryogen. Based on previous analyses of the experiments,[1] thermodynamic considerations, primarily

mass ($m_w$) and energy of the injected water, drove the pressurization rate. A maximum pressurization rate of 821 kPa/s was found for a mass of liquid helium to mass of water ratio of 2.3.

If one considers mass and energy for the cryogen vapor one finds:

$$dP/dt \sim \gamma RT(dQ_{wat})/[Vol(Q_{lat})] \quad (1)$$

$dP/dt$= pressurization rate
$dQ_{wat}$= energy given up by water
Vol= volume of vessel
$Q_{lat}$= latent heat
$\gamma$= specific heat ratio
R= universal gas constant
T= temperature.

The phase change of the water is reflected in the energy given up to the cryogen. Because of the small quantity of injected water ($m_w$) and based on the injection and freezing of the water, changes in free volume space are neglected. For similar mass injection quantities and associated heat transfer ($dQ_{wat}$ is a function of dM/dt, mass entering) from water to cryogen, the peak pressurization will be much less for the liquid nitrogen-water experiments than for the liquid helium interaction experiments. The liquid nitrogen-water interaction experiment has a significantly larger expansion volume than the liquid helium-water experiments. Figure 3 provides a schematic of the liquid nitrogen-water interaction experiments.

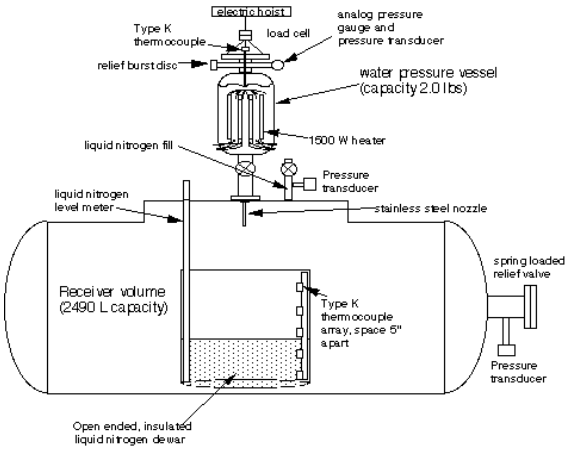


Figure 3. Liquid nitrogen-water interaction experimental apparatus.

## IV. MELCOR CODE UPDATE

MELCOR is a computer code that has been used to model accident progression in light water nuclear reactors. It is primarily used as a control-volume systems code for thermal-hydraulic analysis. The code was originally developed at Sandia National Laboratories (SNL) for the U.S. Nuclear Regulatory Commission (NRC). Initially viewed as a parametric systems code, MELCOR has been incrementally updated with more detailed models. MELCOR is a general and flexible code, which requires no specific nodalization on the part of the user. This allows the user to define the degree of detail appropriate to the modeling task. In our case we are using MELCOR in a very simplistic way, a single defined control volume, to model the system pressurization when water is added to the cryogen liquid in the test dewar.

A modified version of MELCOR was utilized in this study.[5,6] This version, modified by the Idaho National Engineering and Environmental Laboratory (INEEL), can treat fluids other than water as the designated 'phase change' material. However, at this time this version does not allow water and cryogens to be combined in the same calculation. Because of this limitation, the cryogen was modeled as the 'phase change' fluid and the injected water was simulated by a 'water-wall' heat structure with its temperature and surface area parametrically varied to match to the transient injection rate. Future modifications are planned for MELCOR to allow the simulation of the injected water by the MELCOR fuel dispersal interaction (FDI) model. In our case, the injected 'water-wall' is used to simulate the heat transfer effects of the injected water. For initial pressurization rate data (~ 1 second) a constant heat transfer coefficient was assumed. Because Run #1, from the liquid helium-water interaction experiments, did not reach the pressure relief point the entire pressure history can be simulated. This became the nominal simulation.

An initial simulation to parametrically determine the heat structure surface area was performed. Using a constant calculated value for the film boiling heat transfer coefficient (30 $W/m^2$-$^oK$), which is calculated below, the heat structure surface area was determined that allowed the MECLCOR simulation to match the experimental pressurization rate. Then, complete pressure histories can be simulated by utilizing the determined heat structure surface area with a decreasing heat transfer coefficient. Because we simulated the heat structure, in MELCOR, as having constant area and temperature, the only way to effectively stop heat transfer to the cryogen (thermal equilibrium) is by systematically reducing the heat transfer coefficient to zero at the point equilibrium is reached. A linearized heat transfer coefficient, decreasing with time, was utilized to simulate the eventual state where nitrogen and water (heat structure) are in thermal equilibrium. A pressurization profile was generated and compared to data from the experiment. Because the water is analogous to the fuel in an FCI, estimating its fragmentation rate and subsequent surface area for heat transfer is extremely important. An initial heat transfer coefficient was estimated

by using a film boiling heat transfer coefficient over a vertical surface (equations 2 and 3 below):[7]

$$h=\{k_g/Z\}(0.943)[Z^3 g\rho_g(\Delta\rho)\Delta H_{vap}/(k_g\mu_g\Delta T)]^{1/4} \quad (2)$$

$$Z=[\sigma/(\Delta\rho g)]^{1/2} \quad (3)$$

$k_g$= thermal conductivity of gas
g= gravitational constant
$\rho_g$= density of vapor
$\Delta\rho$= density difference between liquid and vapor
$\Delta H_{vap}$= heat of vaporization
$\mu_g$= viscosity of vapor
$\Delta T$= temperature difference between fluids
$\sigma$= surface tension.

The heat transfer coefficient was estimated to start at 30 W/m$^2$-$^o$K and decrease linearly from that point. Based on experimental data, a time when the cryogen-water system reached thermal equilibrium was determined. Then the heat transfer coefficient was linearized to zero at that point. This simulation was run and pressurization rate data was compared to the liquid helium-water interaction.

## V. MELCOR SIMULATION RESULTS FOR CRYOGEN-WATER INTERACTIONS

Run #1 (Table 1) was used as a representative liquid helium-water experiment for MELCOR simulation. Figure 4 shows pressure history plots utilizing a parametric comparison of heat structure surface area. As surface area increases heat transfer increases and pressurization is more rapid. Nominal MELCOR simulation inputs are provided below (Table 2).

Table 2. Nominal liquid helium-water simulation inputs.

| | | |
|---|---|---|
| Helium Temperature | 4.2 | $^o$K |
| Helium Pressure | $10^5$ | Pa |
| Helium Mass | 2.5 | kg |
| Tank Volume | .250 | m$^3$ |
| Injected Water (heat structure) | | |
| Temperature | 420 | $^o$K |
| | 147 | $^o$C |
| Heat Transfer Coeff | 30.0 | W/m$^2$-$^o$K |
| Surface Area | 0.1 to 3.2 | m$^2$ |

From Figure 4 it is apparent that an initial pressurization rate of 60 kPa/s is obtained when a heat structure surface area of 3.2 m$^2$ is assumed. This area will be compared to that predicted by the FDI fracture model in future studies. This provides verification of the MELCOR modeling capability for simple initial pressurization rates for liquid helium-water interactions. Subsequently, because we are analyzing only a short time interval at the beginning of the experiment (for initial pressurization rate), a constant heat transfer coefficient (about 30 W/m$^2$-$^o$K) can be assumed.

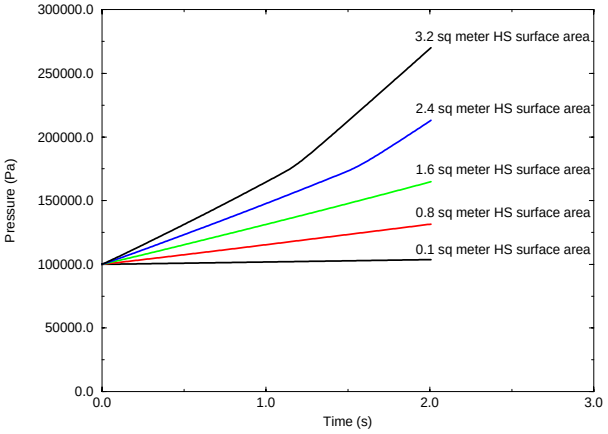


Figure 4. Pressurization data for liquid helium-water interactions, varying heat structure area from 0.1 to 3.2 m$^2$.

Utilizing the determined heat structure surface area of 3.2 m$^2$ with an initial heat transfer coefficient of 30 W/m$^2$-$^o$K, a comprehensive simulation was performed out to 3.0 seconds. Figure 5 shows the linearized and decreasing heat transfer coefficient used to match the pressure history of Run #1, Figure 2. Figure 6 shows the calculated pressure history for Run #1 of the liquid helium-water interaction experiments. When compared to the pressurization curve in Figure 2 (Run #1), they appear to match quite well. The decrease in pressure seen in Figure 2 is the result of a heat leak in the pressure vessel system. MELCOR did not easily simulate this, so only peak pressure is attained under adiabatic conditions.

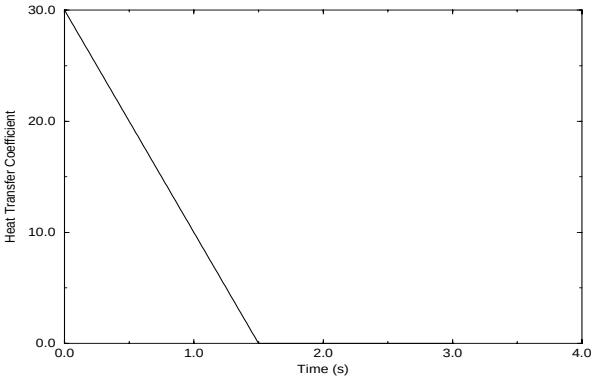


Figure 5. Heat transfer coefficient versus time for MELCOR simulation.

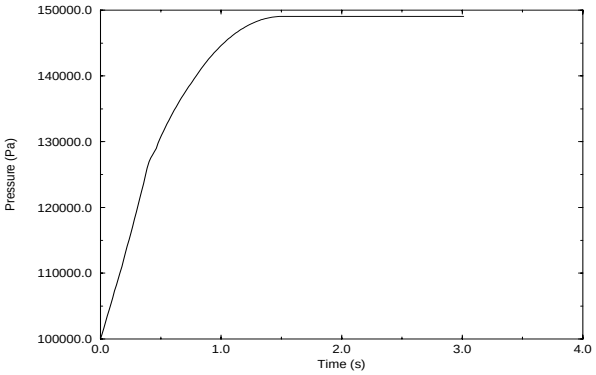


Figure 6. Calculated pressure history Run #1.

For the liquid nitrogen-water interaction experiments there is no limitation on peak pressure with the experimental system, thus allowing thermal equilibrium of the experiment. Subsequently, pressurization rate data and complete pressure histories will be available and can be simulated for all experiments. Because we are able to look at more than initial pressurization rate, and restricted by our use of a 'water-wall' (heat structure) to model the injected water, a decreasing heat transfer coefficient will be used to simulate the system reaching thermal equilibrium. The nitrogen free volume space is significantly larger (2.5 $m^3$ to 0.25 $m^3$) than the helium system.

## VI. CONCLUSIONS

Matching the MELCOR model to a system pressurization rate (liquid helium-water interactions) allows us to determine heat structure surface area that can be used, along with a linearly decreasing heat transfer coefficient, to simulate experimental pressure histories. A liquid helium-water interaction experiment (Run #1) showed a pressurization rate of about 60 kPa/s, which was closely matched by assuming a heat structure surface area of 3.2 $m^2$ and a heat transfer coefficient of 30 $W/m^2$-$^oK$. At this time this is the only experiment that has been simulated. Other experiments will be analyzed to determine the effectiveness of this method in predicting pressurization rates. Total pressure histories, up to thermal equilibrium, are obtained by utilizing the previously determined heat structure surface area and utilizing a linearly decreasing heat transfer coefficient. Again, the heat transfer coefficient must be decreasing in order to simulate eventual thermal equilibrium. This is done because MELCOR utilizes constant area and temperature for its heat structure. The simulation results compare very favorably with the experiment. This same methodology will be used to analyze liquid nitrogen-water experiments that have been run at UW-Madison. As other data are obtained they will be compared to the MELCOR simulation to characterize the modeling capability for cryogenic-water interactions.

## ACKNOWLEDGMENT

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