Analysis of Liquid Cryogen-Water Experiments with the MELCOR Code

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Introduction

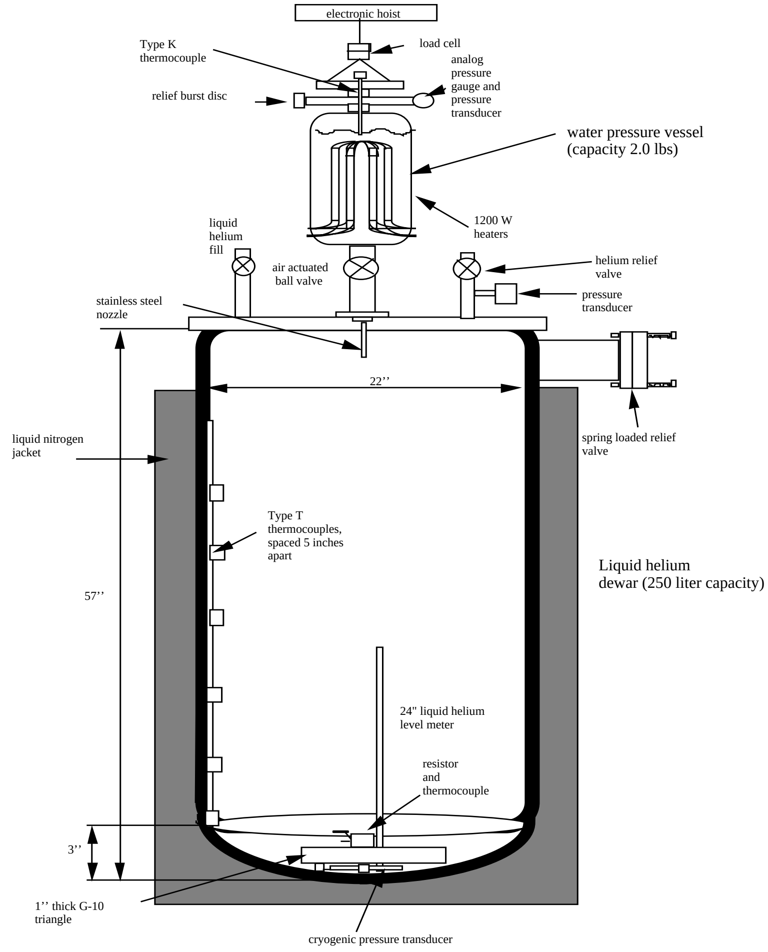
- When significant energy exchange takes place between a hotter and colder liquid, vapor explosions can occur
- A vapor film can be created and it may break down from fluid instabilities driving the hotter fluid to fragment rapidly
- Surface area increases accelerating fragmentation which can lead to 'shock' explosive characteristics
- Historically FCIs are associated with industrial accidents involving molten metals and postulated melt accidents in fission reactors
- The possibility of cryogenic vapor explosions in fusion systems has been identified (ITER)

Introduction (continued)

- Previous studies have shown that vapor explosions occur when near equal volumes of LN_2 and water are brought together
  - Theoretical analyses (constant pressure or volume)
  - Thermodynamics dominates (mass hot material, not kinetic)
- For LHe-water interactions the pressure may climb as fast as 800 kPa/s
- MELCOR calculations were performed to determine whether the pressurization rate can be simulated
- This paper reviews these experiments and utilizes MELCOR to simulate the experiments

Experimental Apparatus

- Original facility was used for LHe (free volume 250 l)
- Experiments with LHe completed (NHTC 2000)
- New facility operational for LN_2 (free volume 2500 l)
- Experiments with LN_2 underway (this fiscal year)
- Both experiments show similar trends

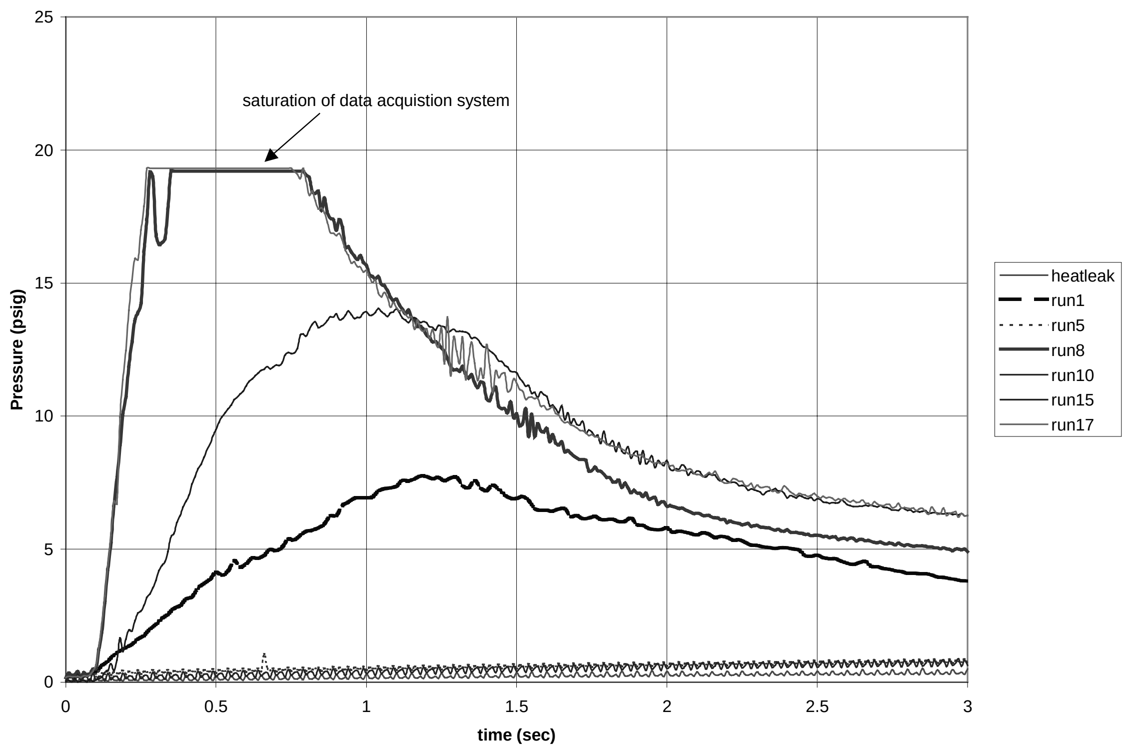


Experimental Procedure

- Water mass and initial conditions set in pressure vessel
  - 0.682 kg, T= 120 to 150 C
- Desired nozzle size between 2 and12 mm
- Cryo vessel closed and evacuated to $2.0X10^{-4}$ Torr (LHe or LN_2)
  - Continual pumping reduces chance of water contamination
- Cryo gas is added [up to 14.7 psia] (LHe or LN_2)
- Dewar cooled to 175 K with LN_2 jacket
- Water is heated and pressurized
- Cryo liquid transferred, cools components to desired temp
  - LHe ~ 4 K, LN_2 ~ 77 K
- When cryogen and water reach initial conditions experiment starts

Pressure Time Plots

- Pressure versus time (LHe and water)



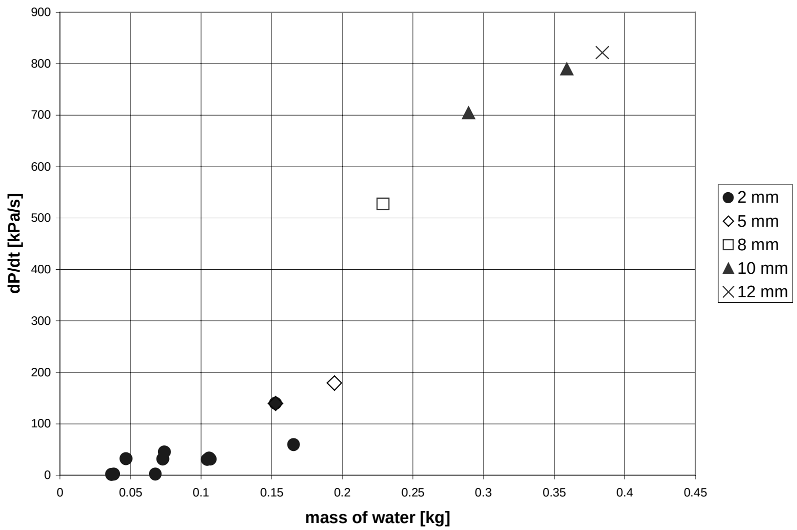
Summary of Test Initial Conditions

- Initial conditions and results of LHe-water experiments

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

Pressurization Rate vs. Water Mass

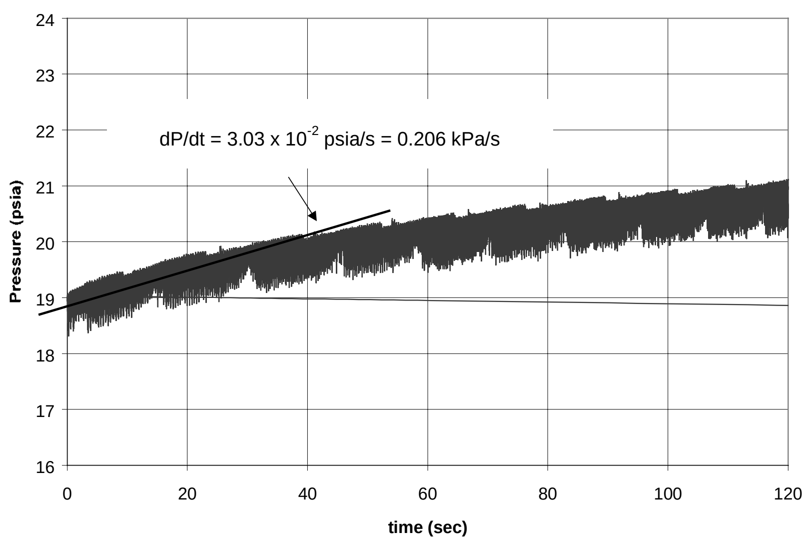
- Pressurization rate in LHe dewar versus water injected



- Results indicate cryogen-water interaction is dominated by the thermodynamics; i.e., mass, composition and temperature (kinetics are 2nd order effect)

Liquid N_2 Experiments

- Preliminary results of LN_2 test consistent with LHe tests
- Thermodynamics dominate (dP/dt ~ γRTQ_{vap}/(Vol*Latent Heat)
- For similar mass, pressurization is much less for LN_2-water interaction because of large free volume (with no vapor explosion)
- Below is initial pressurization for an LN_2-water experiment



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MELCOR Code

- Control-volume systems code for thermal-hydraulic analysis (SANDIA National Lab)
- Control volumes connected via orificed flow paths
- UW cryogenic experiments suited for MELCOR analysis
- Experimental pressurization can be modeled by MELCOR
- Benchmark the code against selected UW experiments
- Determine MELCOR utility in predicting cryogenic-water interactions in fusion system designs

Implementation of MELCOR Code

- Currently two versions of the code exist (developed INEEL)
  - One allows water with phase change (and freeze)
  - One will allow various fluids interacting with phase change (e.g. LHe, LN_2)
  - These versions currently can not be integrated
- Current MELCOR model for UW tests:
  - A ‘water-wall’ (in the form of a heat structure, HS) is used to simulate water injection with variable heat transfer coefficient (HTC) and constant surface area
- Using a predetermined film boiling HTC for the cryogen, MELCOR simulations were run varying HS surface area

Implementation of MELCOR Code (continued)

- With the calculated HTC (film boiling regime) the HS surface area is parametrically determined by matching pressurization rate data from the experiment
- Again, Water in the system is modeled as a ‘water wall’ where its surface area and temperature are held constant throughout the MELCOR simulation
- The HTC must be varied to reflect the approach to system thermal equilibrium reached in the experiment
- Using this methodology, final system pressure histories are produced and compared to the test results

He Film Boiling Coefficient

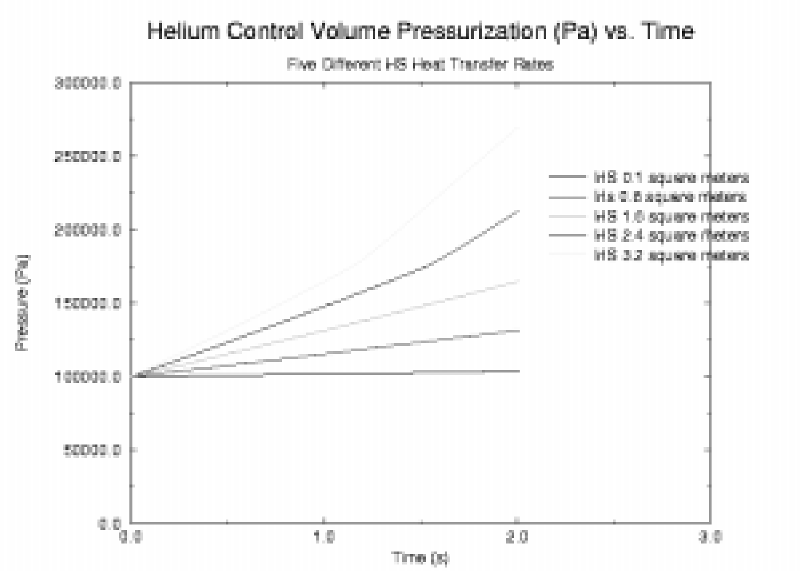
- "Convective Boiling and Condensation", Collier

$$\left[\frac{(HTC)A}{k_g}\right] = 0.943\left[\frac{A^3 g\rho_g(\rho_f - \rho_g)i_{fg}}{k_g\mu_g\Delta T}\right]^{1/4} \qquad A = \sqrt{\frac{\sigma}{\Delta\rho g}}$$

- HTC (heat transfer coefficient) ~ 30 W/m^2-^{o}K
- Estimates made for HS surface area (0.1 to 3.2 m^2)
  - Corresponds to fragmenting surface area of water
  - Match pressurization rate with experiment
  - Use above film boiling HTC

Pressurization vs. Time (MELCOR)

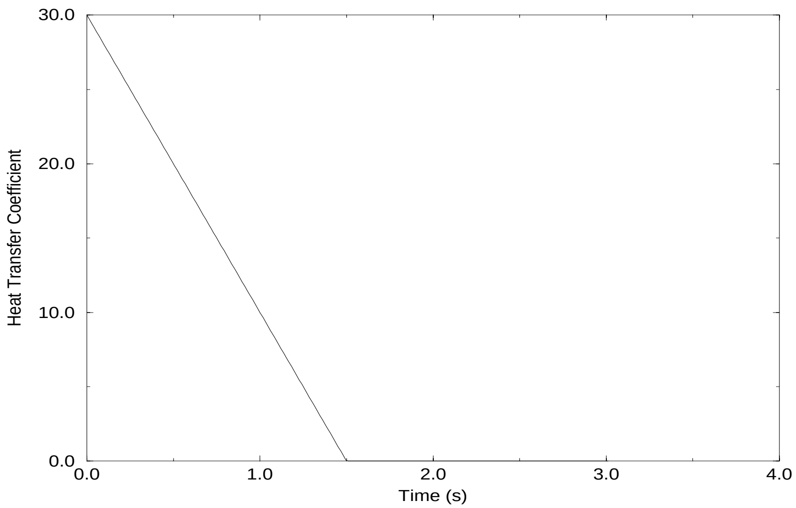
- Pressurization rate varying HS surface area to LHe



- Parametric results suggest a HS area of 3.2 m^2 matches initial experimental pressurization rate data
- Water freezing and jet quench needs to be considered after a few seconds in MELCOR to complete the model

Heat Transfer Coefficient vs. Time

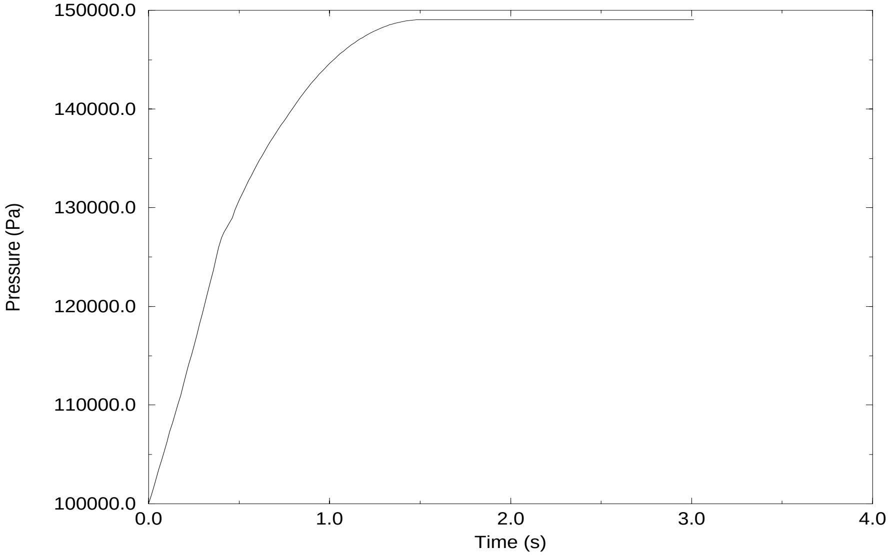
- MELCOR time dependent HTC



- HTC used in MELCOR to simulate thermal equilibrium with HS surface area 0f 3.2 m^2
- Pressurization ends at 1.5 sec, with HTC linearized to zero

Calculated Pressure History Run#1

- MELCOR pressure history trace



- Calculated pressure history Run#1 using linearized HTC and HS surface area of 3.2 m^2
- Compares with pressurization rate data for Run#1

Conclusion/Discussion

- Matching the MELCOR model to the system pressure history allows us to determine the proper HTC and HS areas
- Experimental results showed run #1 to have a pressurization rate of about 60 kPa/s, which was closely matched by assuming a HS surface area of about 3.2 square meters (consistent with jet breakup) and a HTC of 30 $W/m^2\text{-}^oK$
- Total pressure histories, up to thermal equlibrium, are obtained with a linearly decreasing HTC and previously determined HS surface area from initial pressurization data.

Conclusion/Discussion (continued)

- The same methodology will be used to model the LN_2-water experiments
- As other data are obtained they will be compared to the MELCOR simulation to qualify the modeling capability for cryogenic-water interactions