SAND2016-10016PE

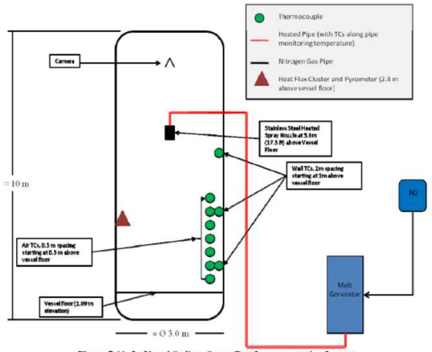
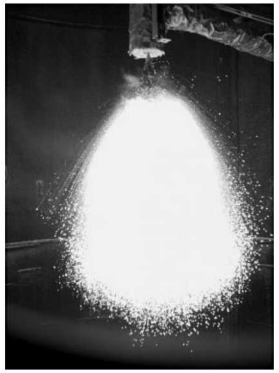
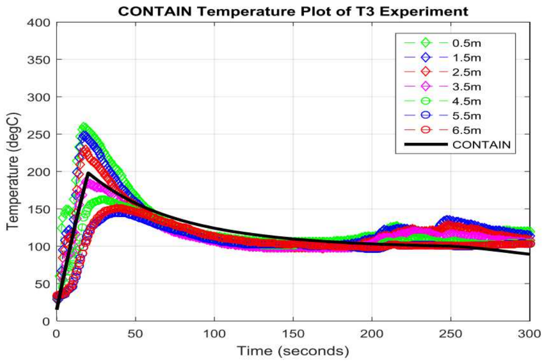


Figure 7-11: In-Vessel Sodium Spray Test Instrumentation Layout





2010 LDRD Sodium Fires and MELCOR-Na

Matthew Denman

Andrew Clark, Larry Humphries, David Louie

Severe Accident Analysis and Risk and Reliability Analysis

Presentation to the IRSN

October 10th 2016

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia Sodium Reactor Safety Research

NRC CRBR Sodium Experimental Research

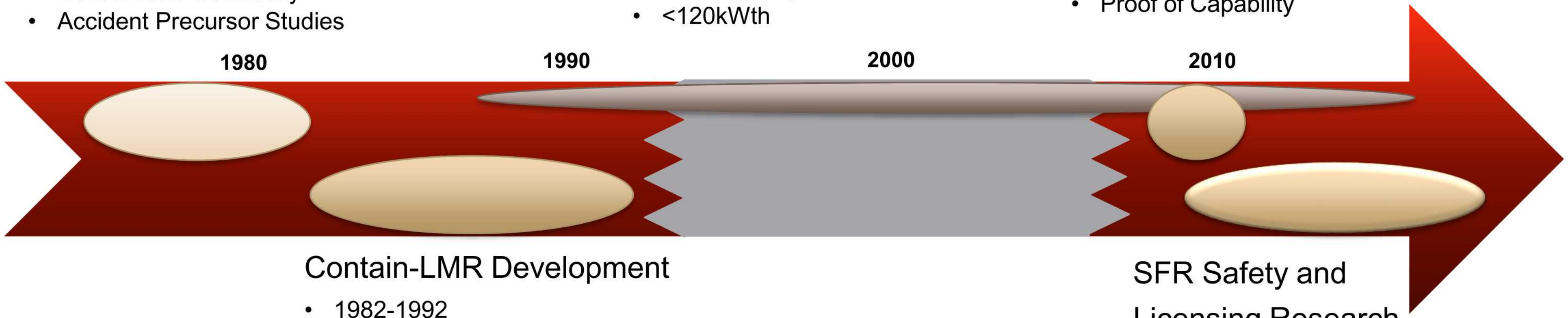
- 1975-1982
- Fuel Vaporization
- Core Debris Coolability
- Accident Precursor Studies

Solar Tower Sodium Heat Pipe Tests

- 1984-Present
- Small Boiling Sodium Loops
- <120kWth

Sodium Fire Experiments

- 2008-2010
- Pool and Spray Fires
- Proof of Capability



Contain-LMR Development

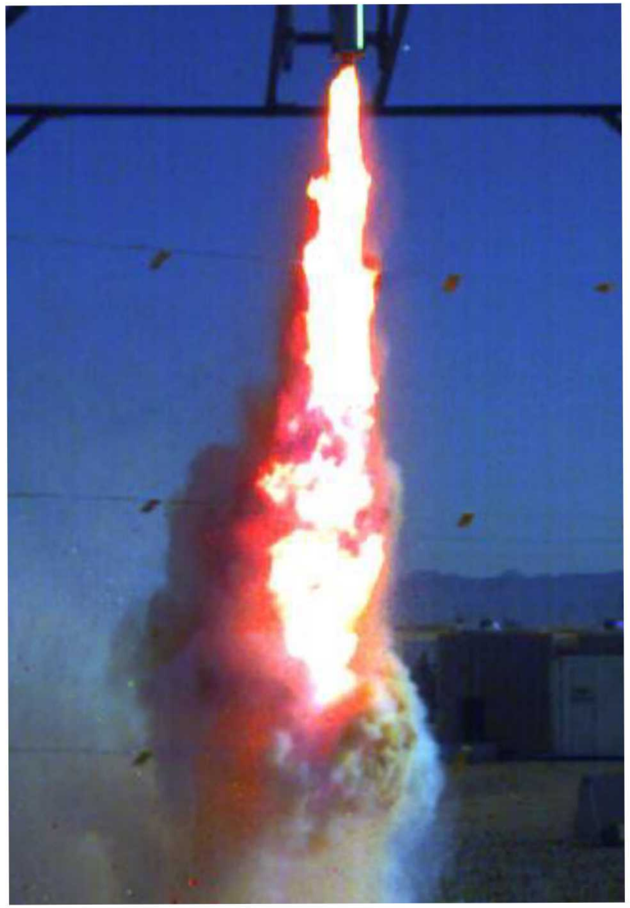
- 1982-1992
- Models sodium fires and aerosol transport
- Contain-LMR used in the GE-PRISM Level 3 PRA
- Multiple Containment and Source Term Assessments

SFR Safety and Licensing Research

- 2009-2016+
- Lead Multi-Lab Gap Analysis
- Contain-LMR►MELCOR
- Mechanistic Source Term
- CREDO Reliability Database
- Dynamic Probabilistic Risk Assessment
- GIF Task Force

Outline

- MELCOR-Contain/LMR Integration
  - Sodium Fire Testing
    - Outdoor Pool and Spray Fires
    - In-Vessel Fires at Surtsey
  - Sodium Fire Modeling



Sandia National Laboratories

Exceptional service in the national interest

SNL Sodium Fire Testing

2008-2010

Surtsey Facility

Quick overview of Outdoor Tests

In-depth examination of Invessel Tests

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SAND2016-XXXX

Sodium Fire Testing At SNL

- Goals
  - Establish a general metal fire expertise and analysis capability at SNL to address a key safety issue for the next generation of nuclear reactors.
- Sodium Spray Fires Experiments
  - 2 outdoor and 2 in-vessel experiments
  - Measured spray heat fluxes and temperatures
  - Varied average droplet diameters and sodium temperatures
- Sodium Pool Fire Experiments
  - 11 outdoor experiments
  - Measured surface heat fluxes and pool temperatures
  - Varied thickness ratio of the stainless steel substrate to the liquid sodium

Surtsey Pool Fires

- Outdoor experiments, variable wind conditions and humidity (low)
- Various pan sizes and thermal couple layouts were used
- Average Pan temperatures plateaued at ~800^{o}C

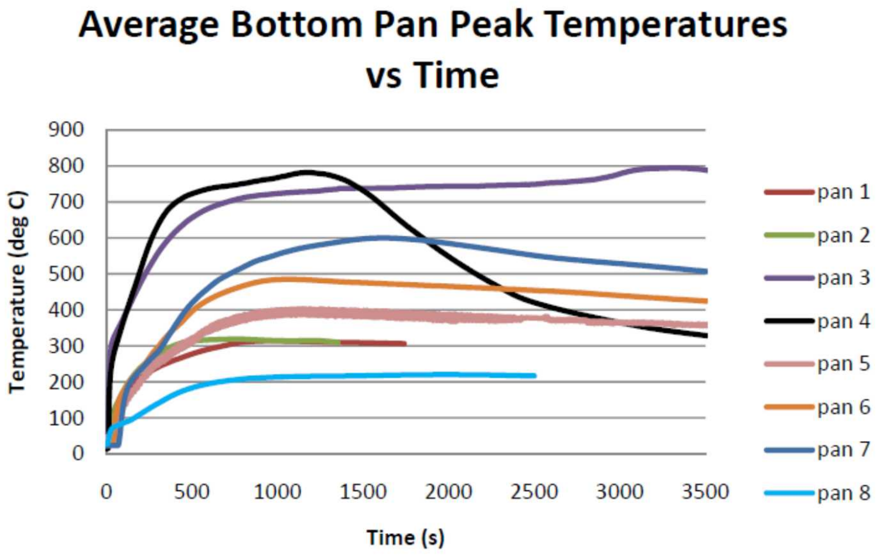
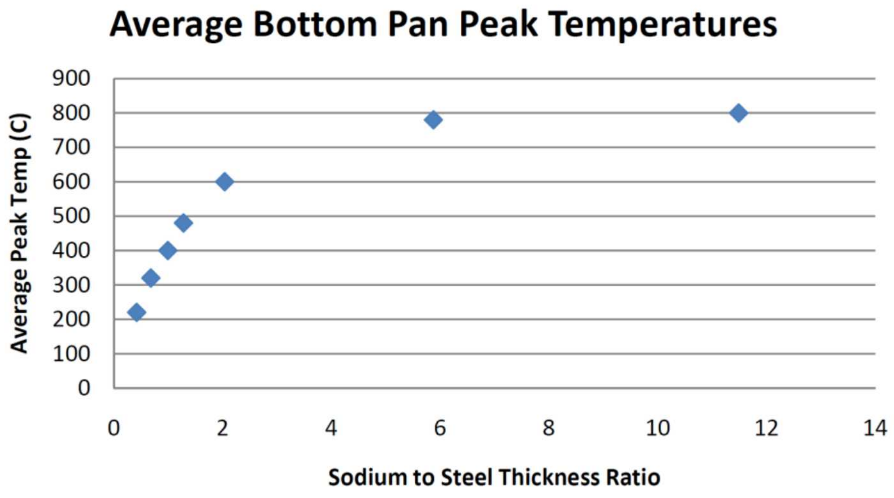


Table 2-3: Summary of Sodium Pool Fire Tests

Test Number	Diameter of Pan (m)	Height of Pan (m)	Mass of Sodium (kg)	Base Steel Thickness (mm)	Melt Generator Pressure at System Dump Time (psi)	Average Peak Temperature at Bottom of Pan (deg C)	Thickness Ratio (liquid sodium/stainless steel)
Pool 1	0.6	0.0508	2.6	15.875	2.6	320	0.7
Pool 2	0.6	0.0508	2.6	15.875	2.2	320	0.7
Pool 3	0.3	0.127	4.4	6.35	2.4	800	11.5
Pool 4	0.2	0.1778	1.0	6.35	2.5	780	5.9
Pool 6	0.6	0.0508	4.8	15.875	3.2	480	1.3
Pool 7	0.6	0.0508	7.8	15.875	3.4	600	2.0
Pool 8	0.6	0.0508	1.6	15.875	3.6	220	0.4
Pool 9	0.6	0.0508	6.0	15.875	3.6	490	1.6
Pool 10	0.6	0.1016	11.6	15.875	3.2	746	3.0
Pool 11	0.6	0.1016	9.6	15.875	3.9	648	2.5



Pan 9 – D=0.6m, R=1.6, M=6kg Na
Top View

Pan 9 – D=0.6m, R=1.6, M=6kg Na
Side View

Thermal Camera Imaging Pool Fire

Outdoor Spray Fire Tests

Table 1: Summary of Outdoor Sodium Spray Fire Experiments

Location	Height of Spray (ft)	Amount of Na (kg)	Flow rate (kg/s)	Width of Spray at Ground (ft)	Median Particle Size Diameter (mm)	Temperature of Sodium (deg C)
Outdoor	15	4	1	2.4	~6	500
Outdoor	15	4	0.5	1.2	~10	500

- Objective: Understand the impact of flow rate and particle diameter on spray fires
- Sprays were directed onto a steal pan below the spray nozzle
- The slower and large diameter sprays resulted in subsequent pool fire

High Pressure Spray (T1)

Low Pressure Spray (T2) (1 of 2)

Low Pressure Spray (T2) (2 of 2)

Surtsey In-vessel Spray Fires

- Spray fire experiments conducted at Surtsey Facility at SNL
  - T3 sodium is near the ignition point.
  - T4 port failure causes a 6” diameter hole ~ 10 seconds into the accident
  - Sodium was sprayed onto a 5000 PSI limestone(?) concrete floor at the bottom of the vessel

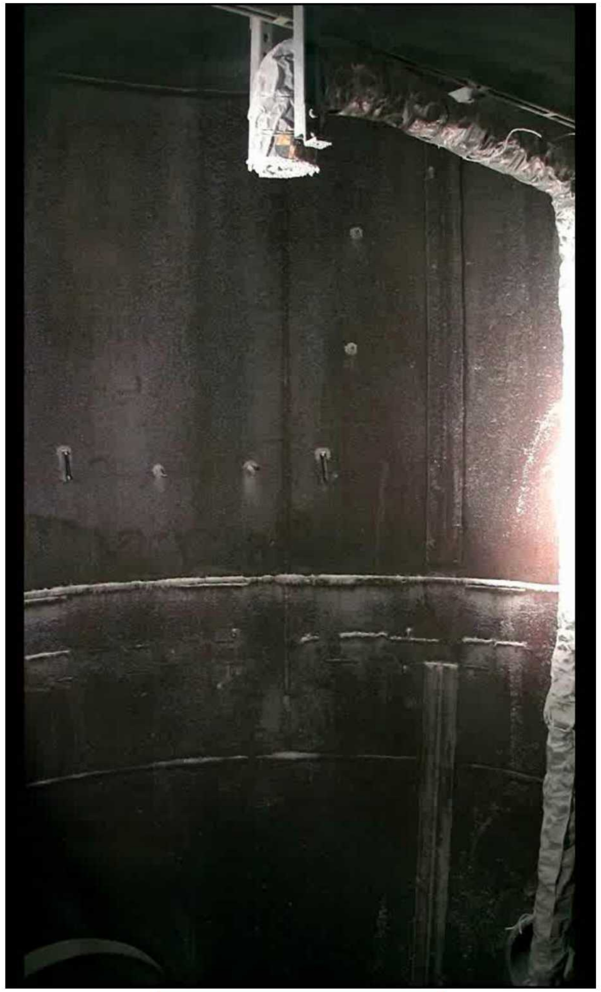
Test #	T1	T2	T3	T4
Location	Outside	Outside	In-Vessel	In-Vessel
Height of Spray (m)	4.6	4.6	5.3	5.3
Amount of Na (kg)	4	4	20	20
Flow rate (kg/s)	1	0.5	1	1
Initial temperature of sodium (°C)	500	500	200	500
Melt generator pressure at system dump time (MPa)	2.14	0.196	2.12	2.12

In-Vessel Na Spray Fire Tests
Side View

T3 Experiment

SAND2016-6688 PE

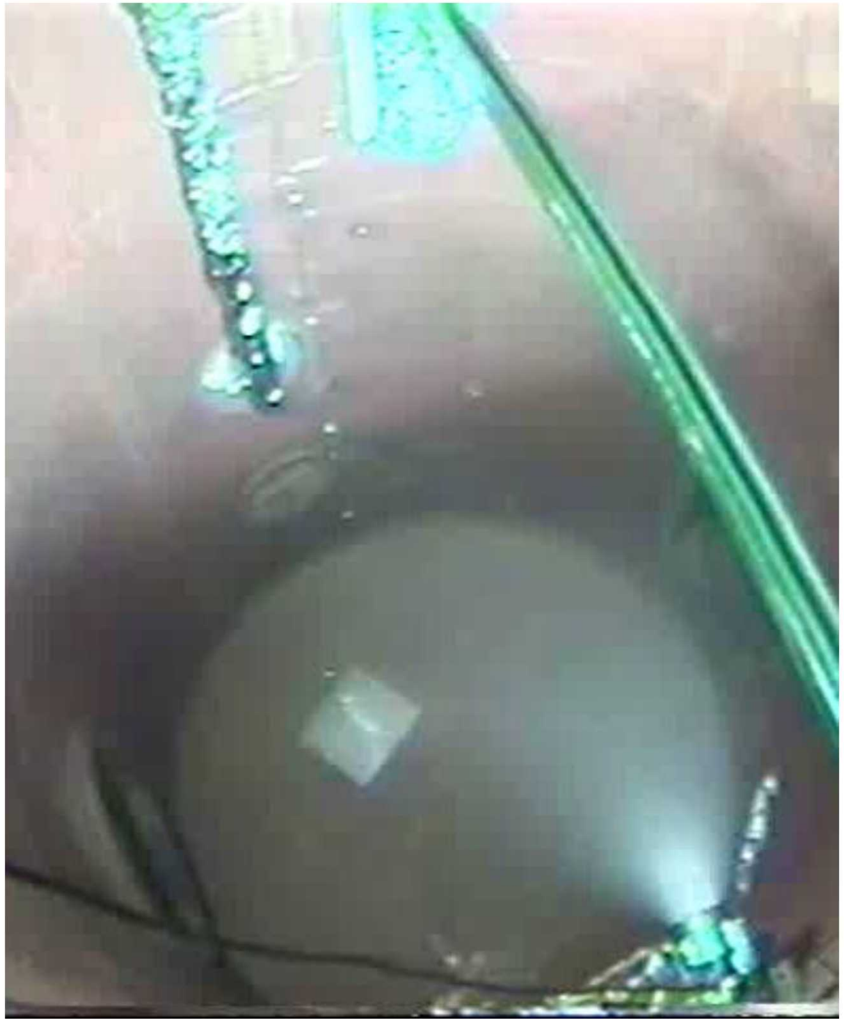
T4 Experiment



SAND2016-6688 PE

In-Vessel Na Spray Fire Tests
Top View

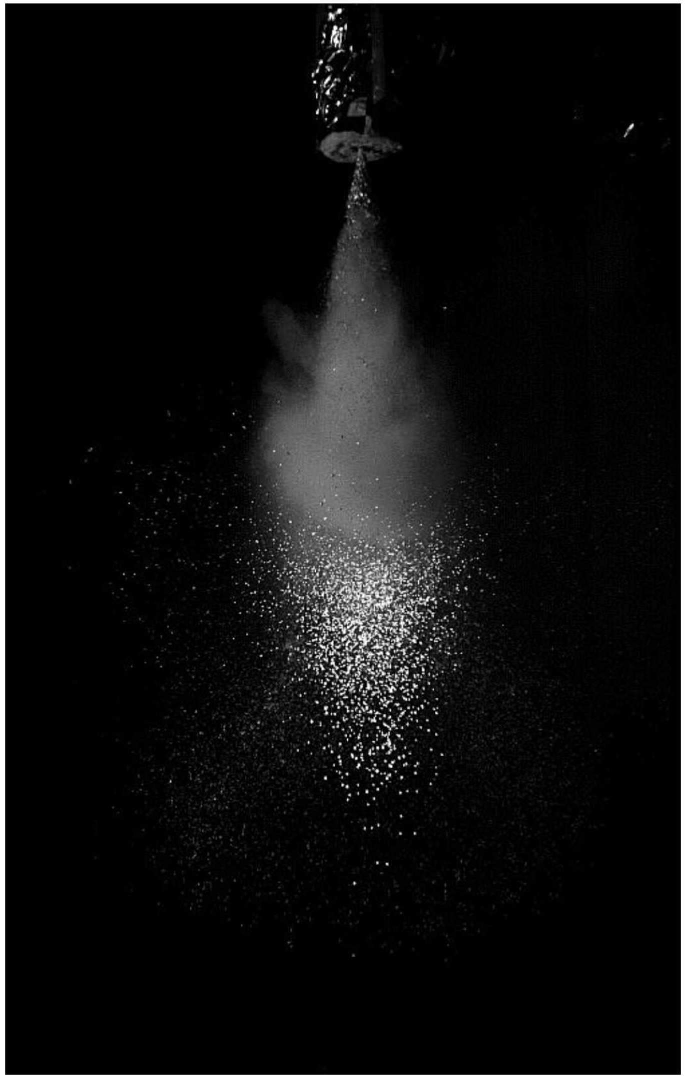
T3 Experiment

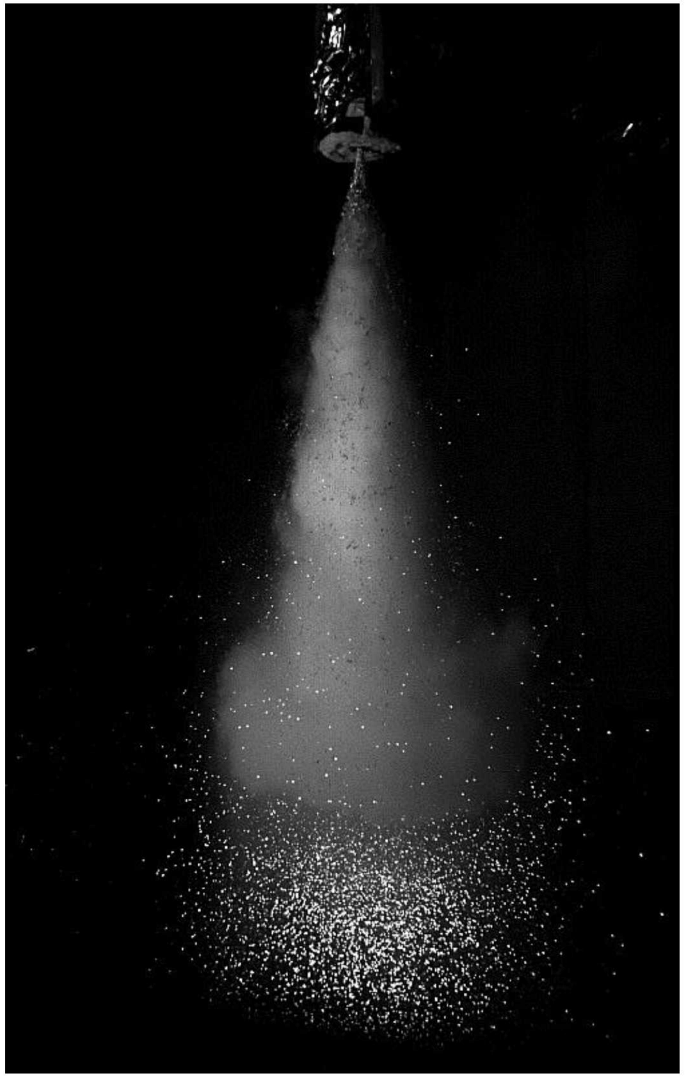


T4 Experiment

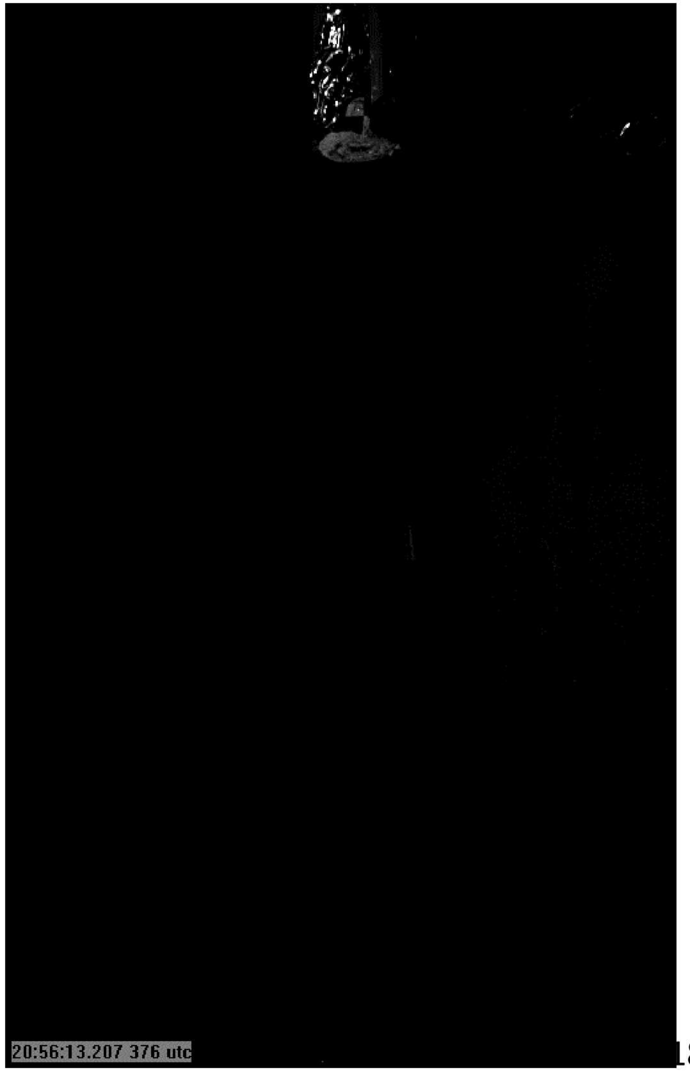
Screen Capture from T3 Early

Screen Capture from T3 Late



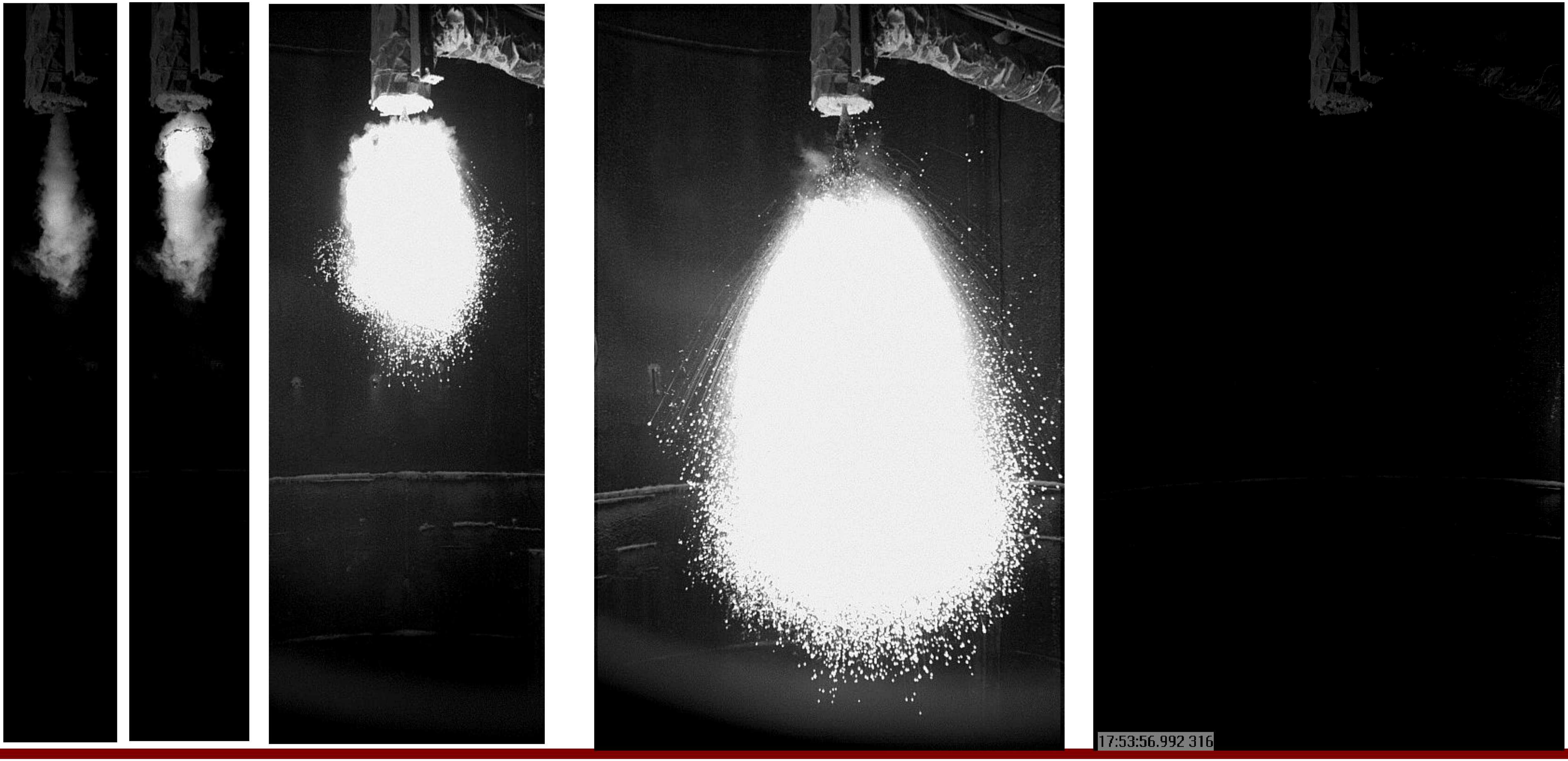


SAND 2010-6911P



Screen Capture from T4

SAND2011-8856C



Concrete Ablation

Data Collected

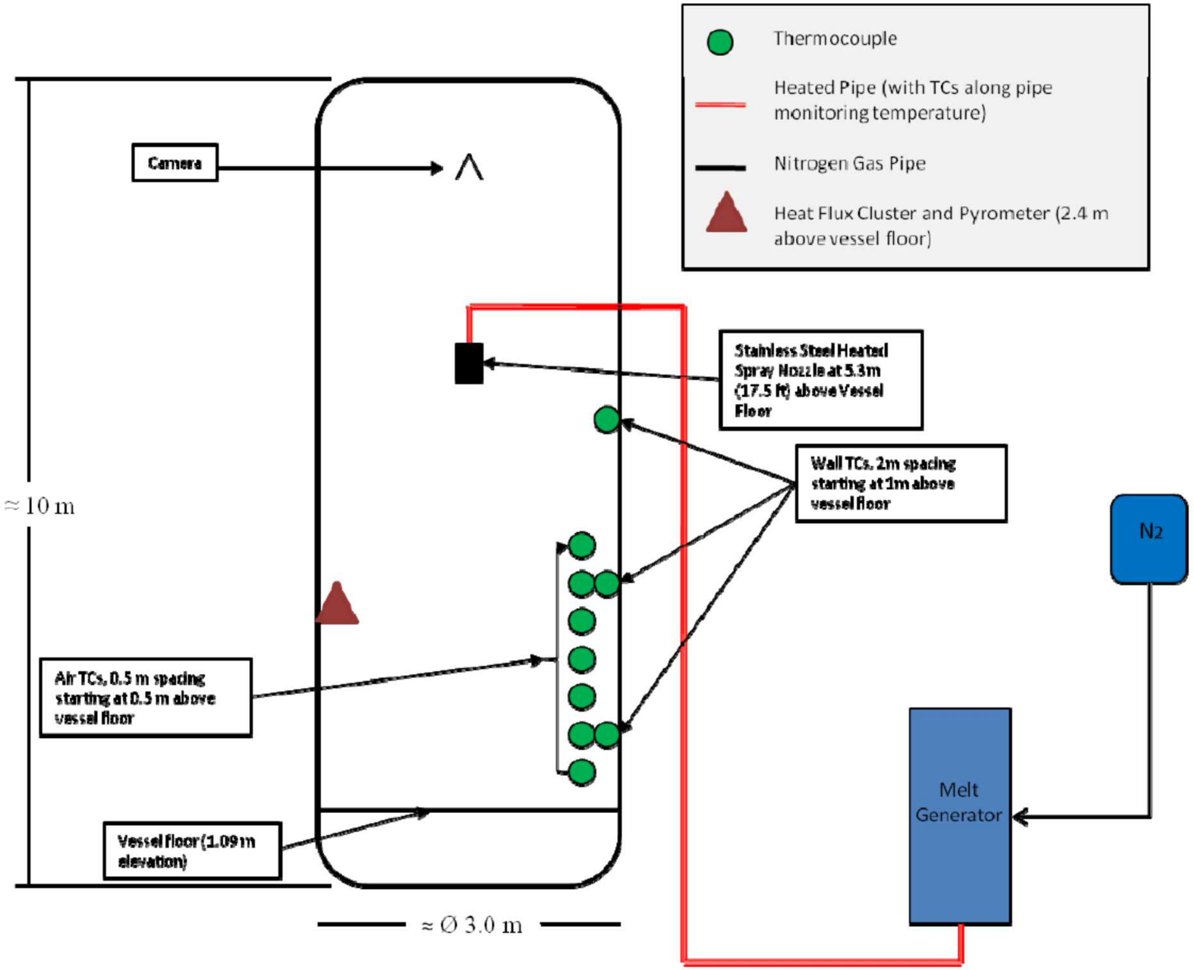
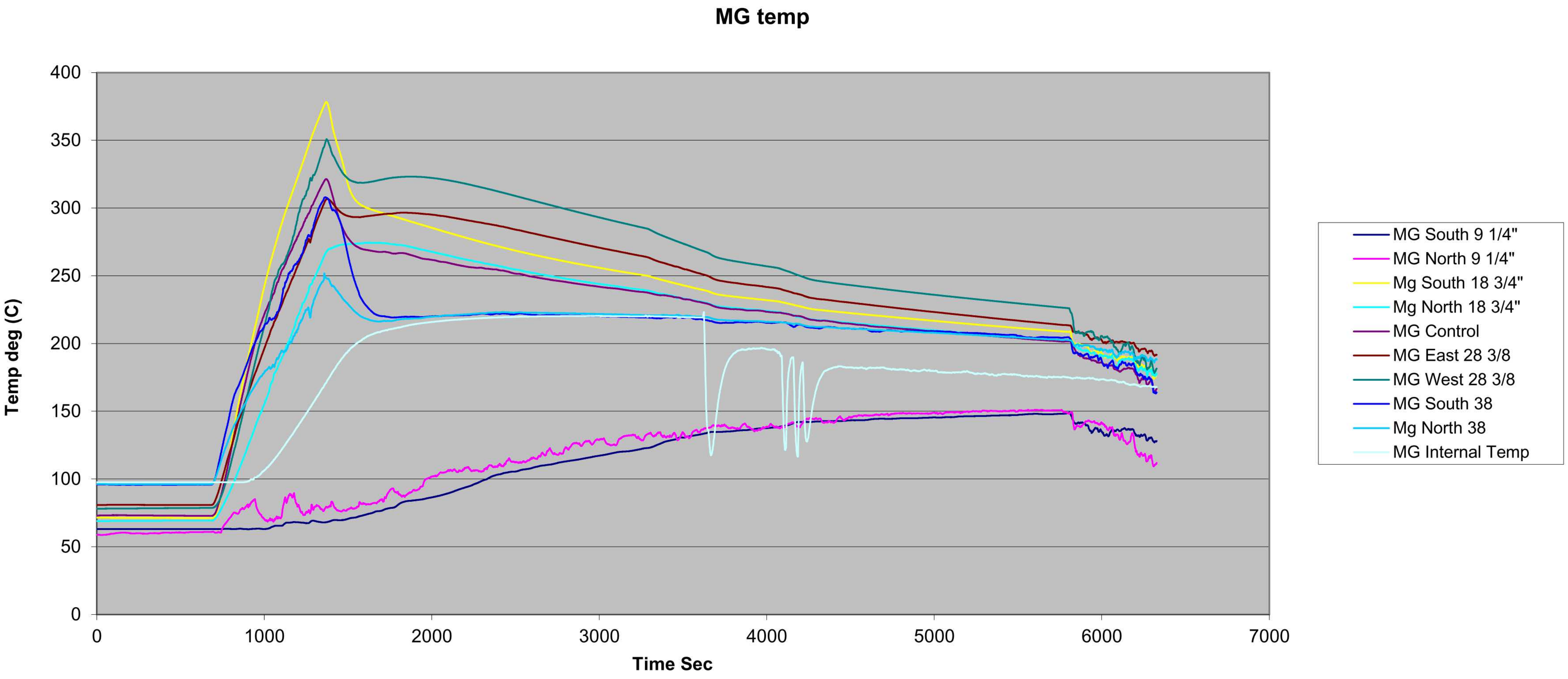
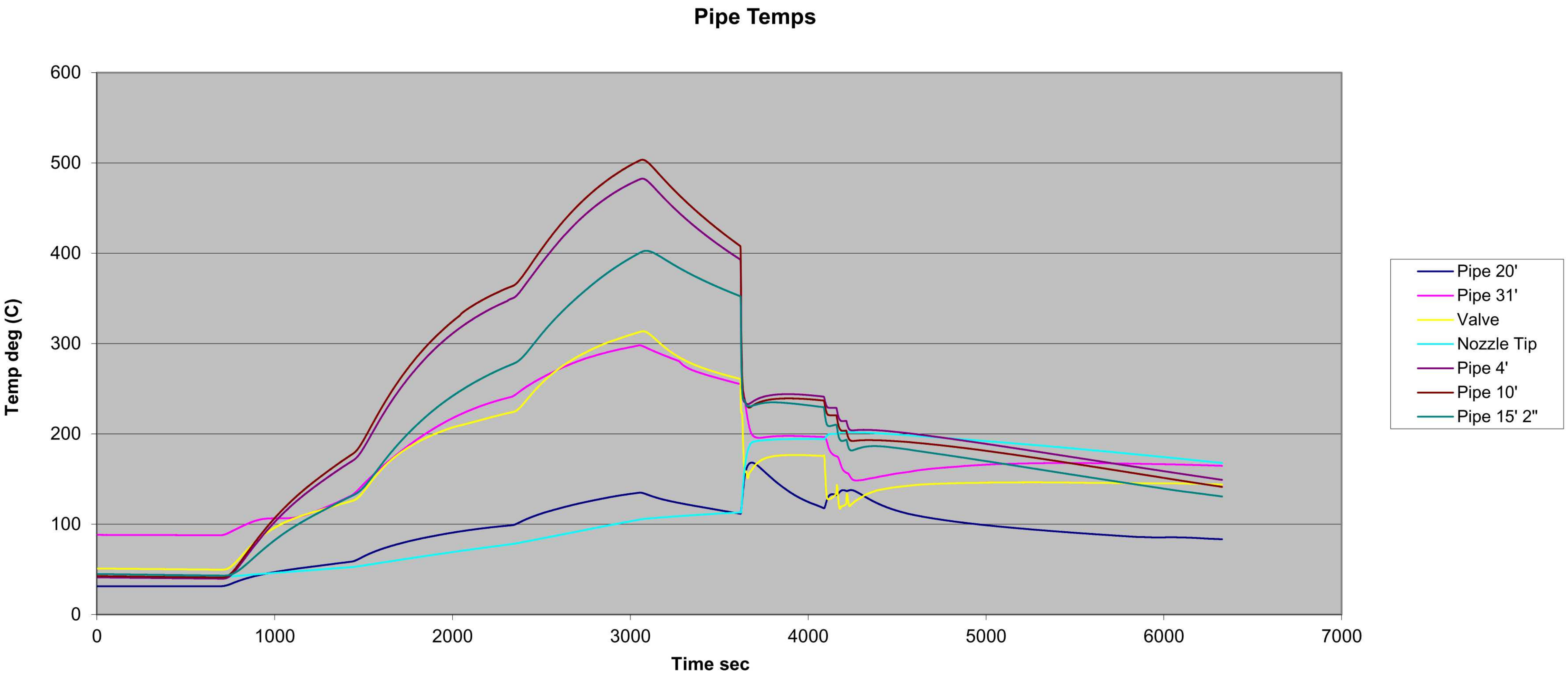


Figure 7-11: In-Vessel Sodium Spray Test Instrumentation Layout

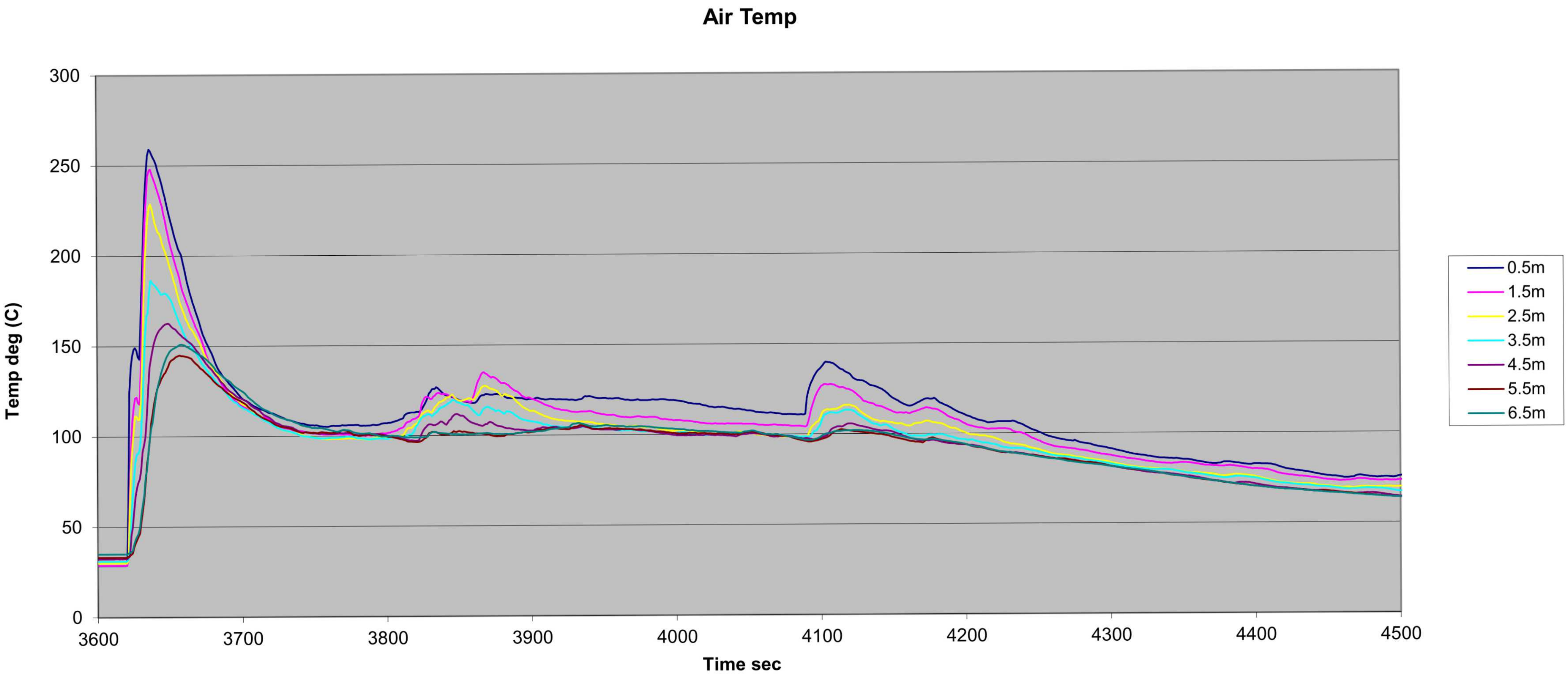
T3 Data
Melt Generator Temperature



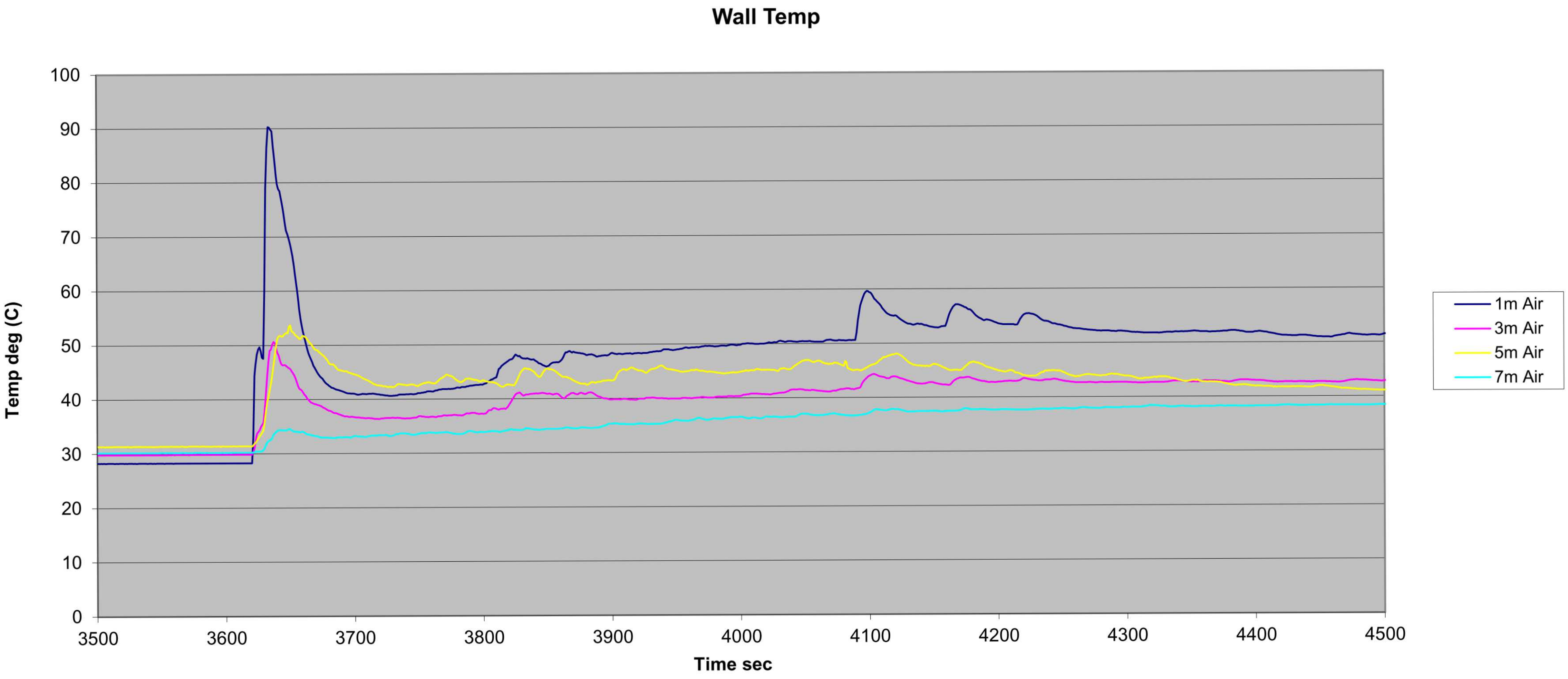
T3 Data
Pipe Temperatures



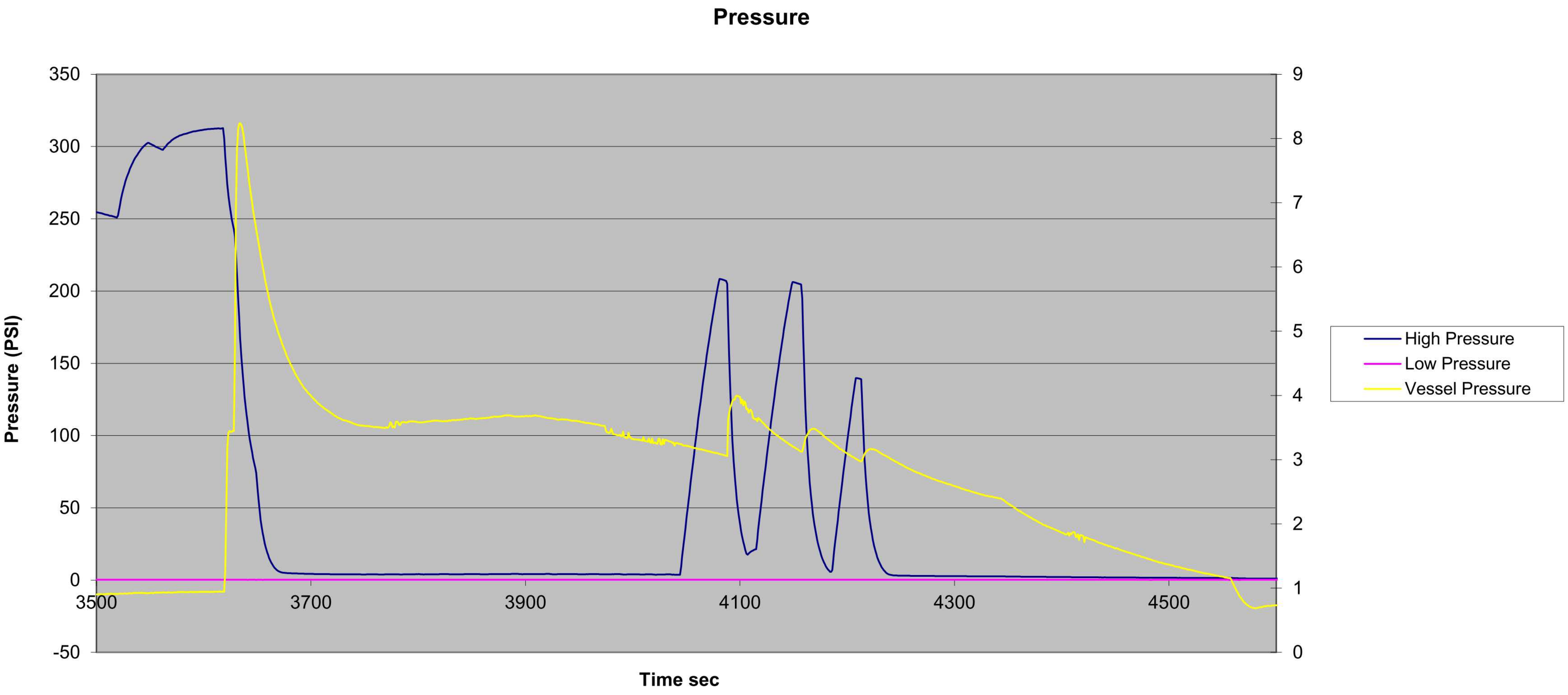
T3 Data
Air Temperature



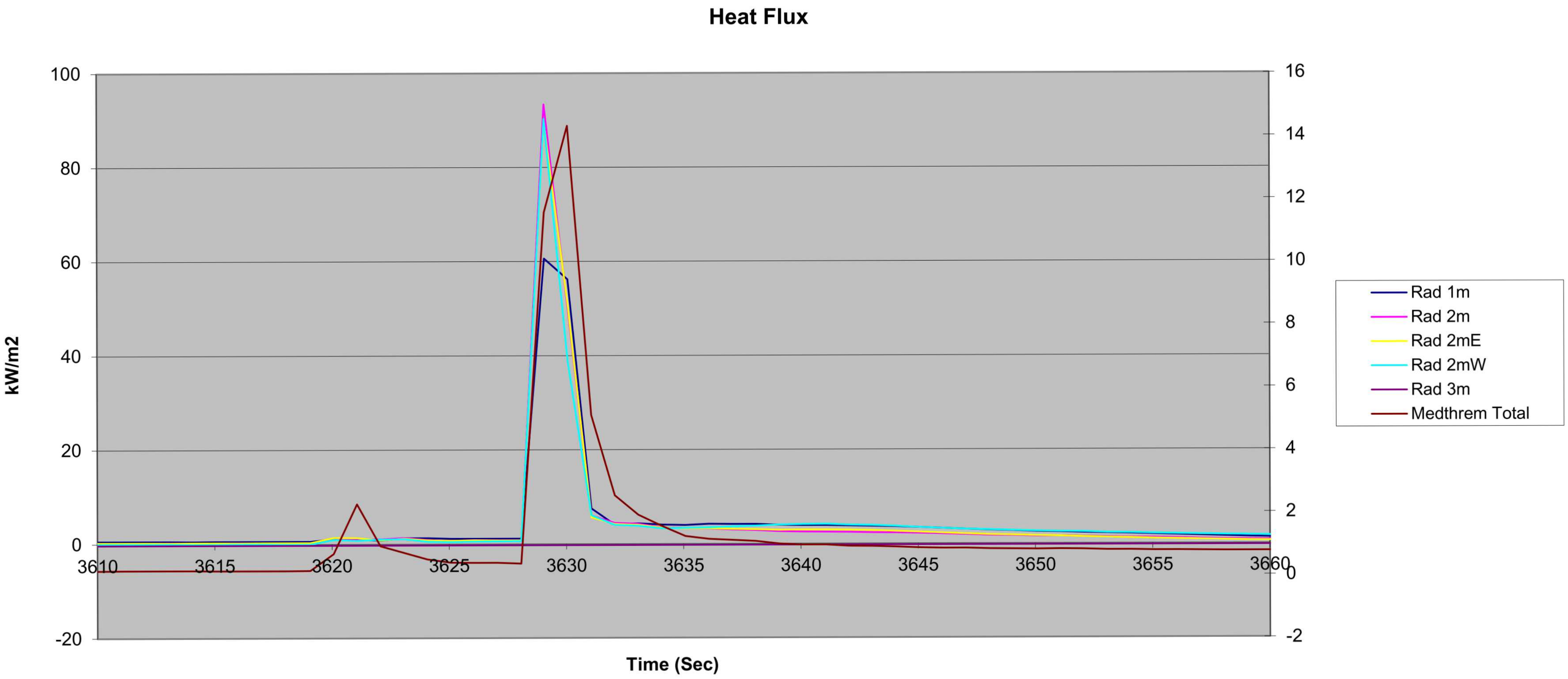
T3 Data
Wall Temperature



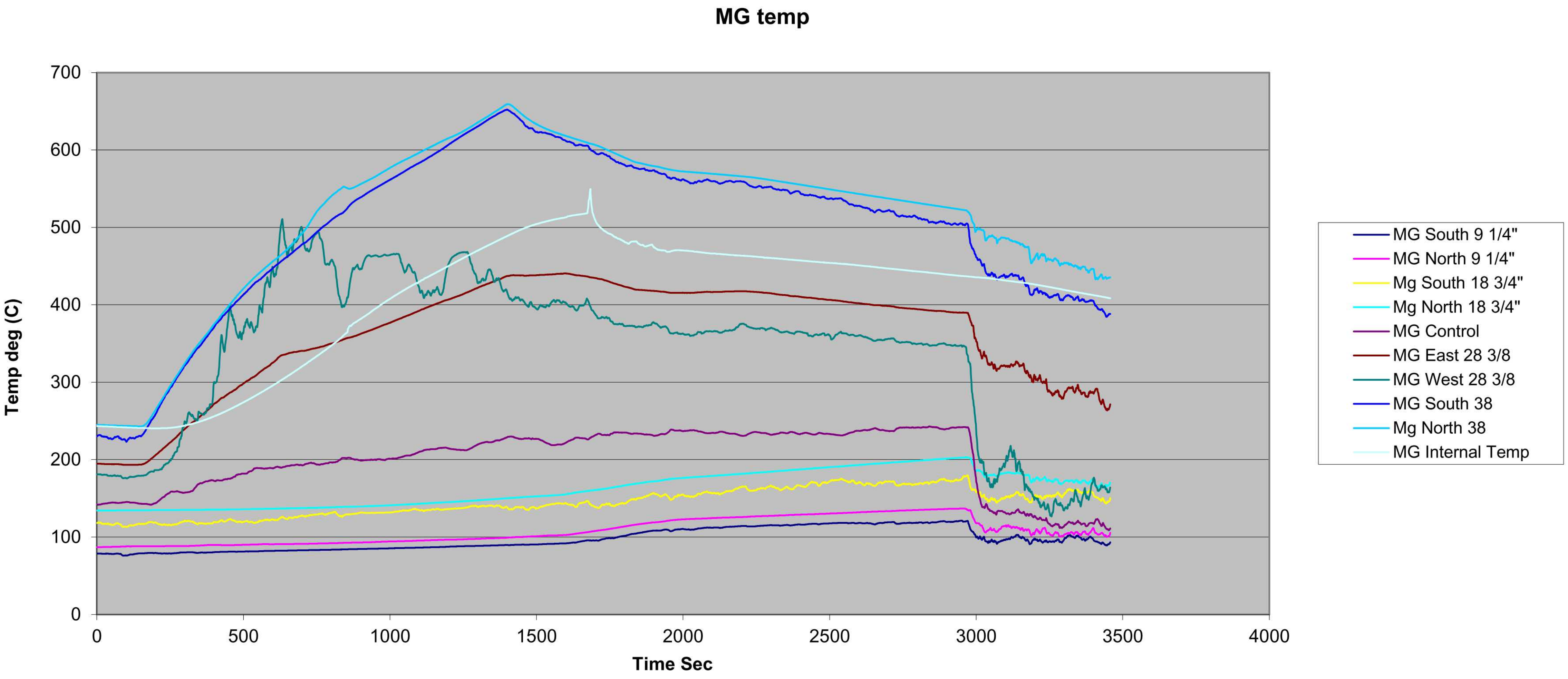
T3 Data
Pressures



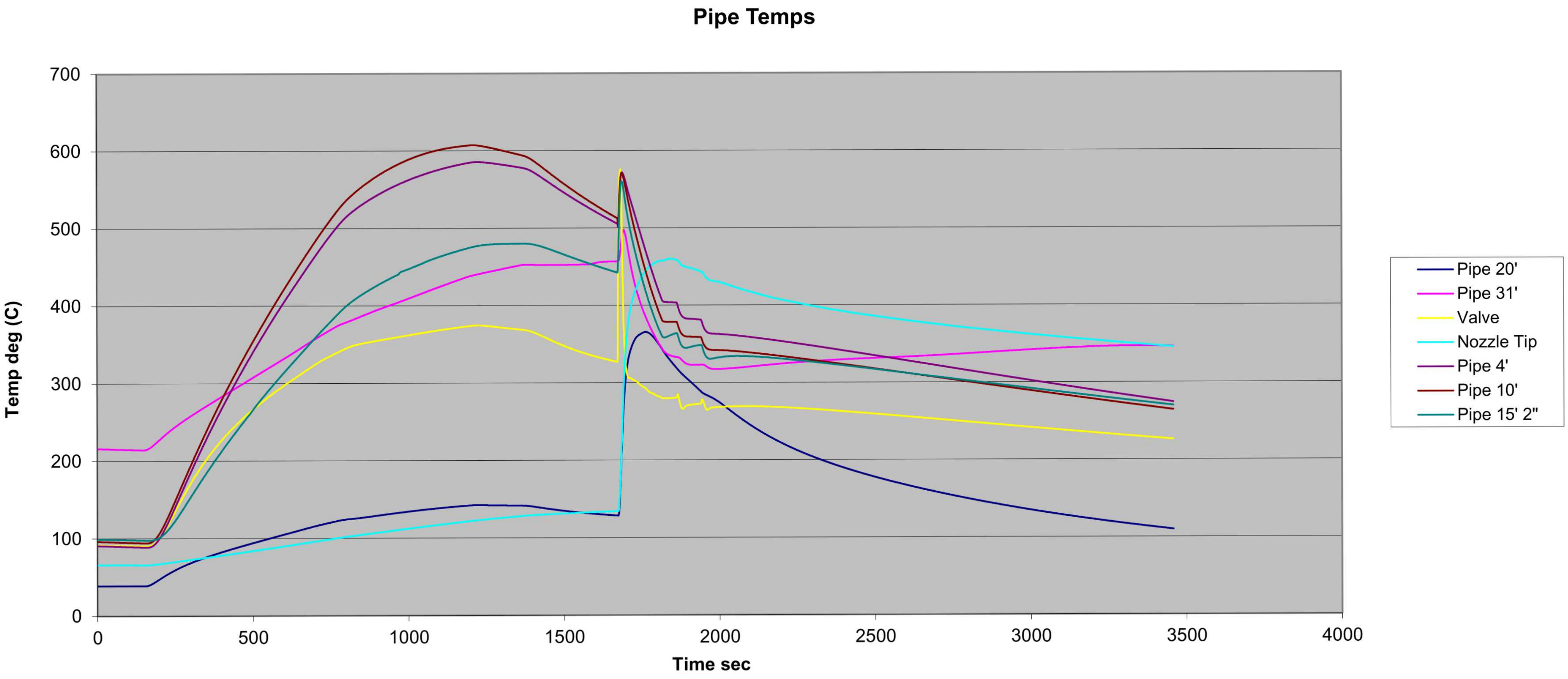
T3 Data
Heat Flux



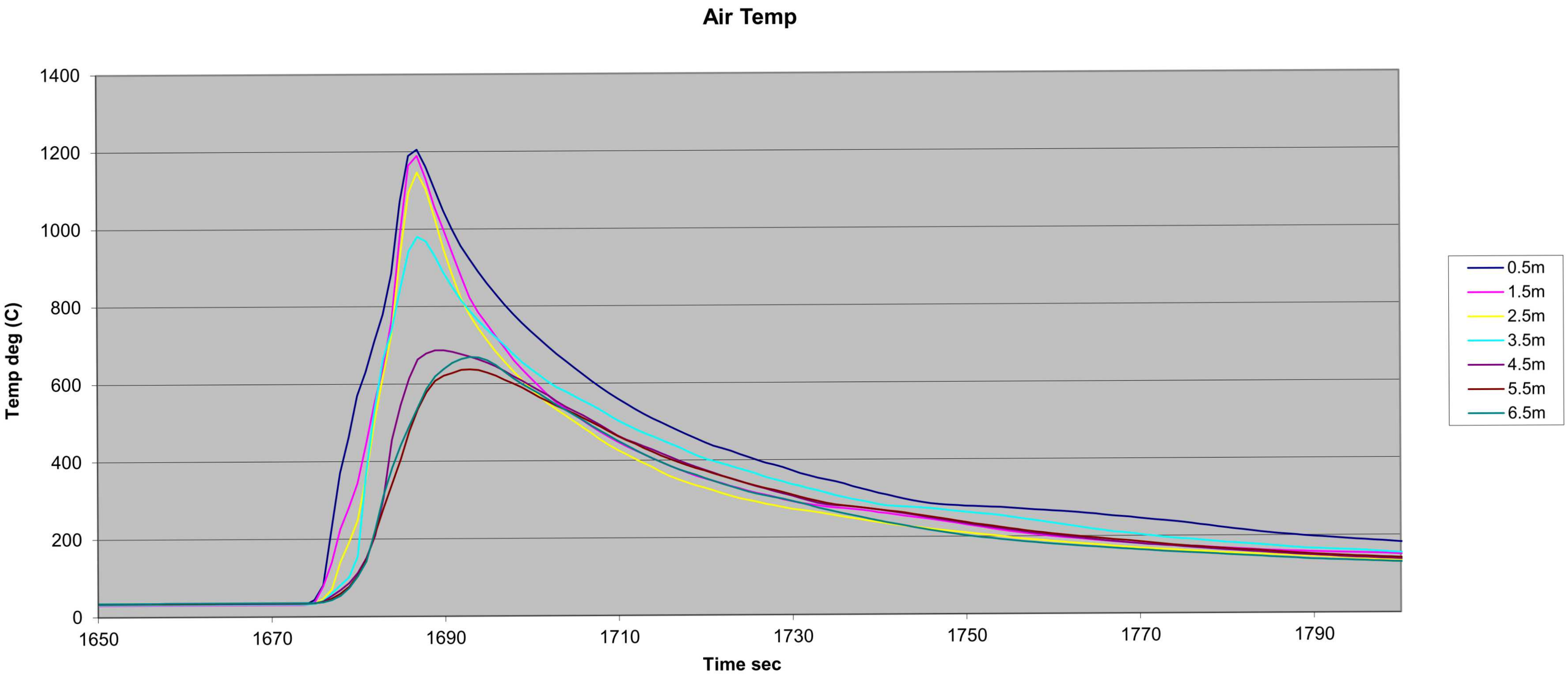
T4 Data
Melt Generator Temperature



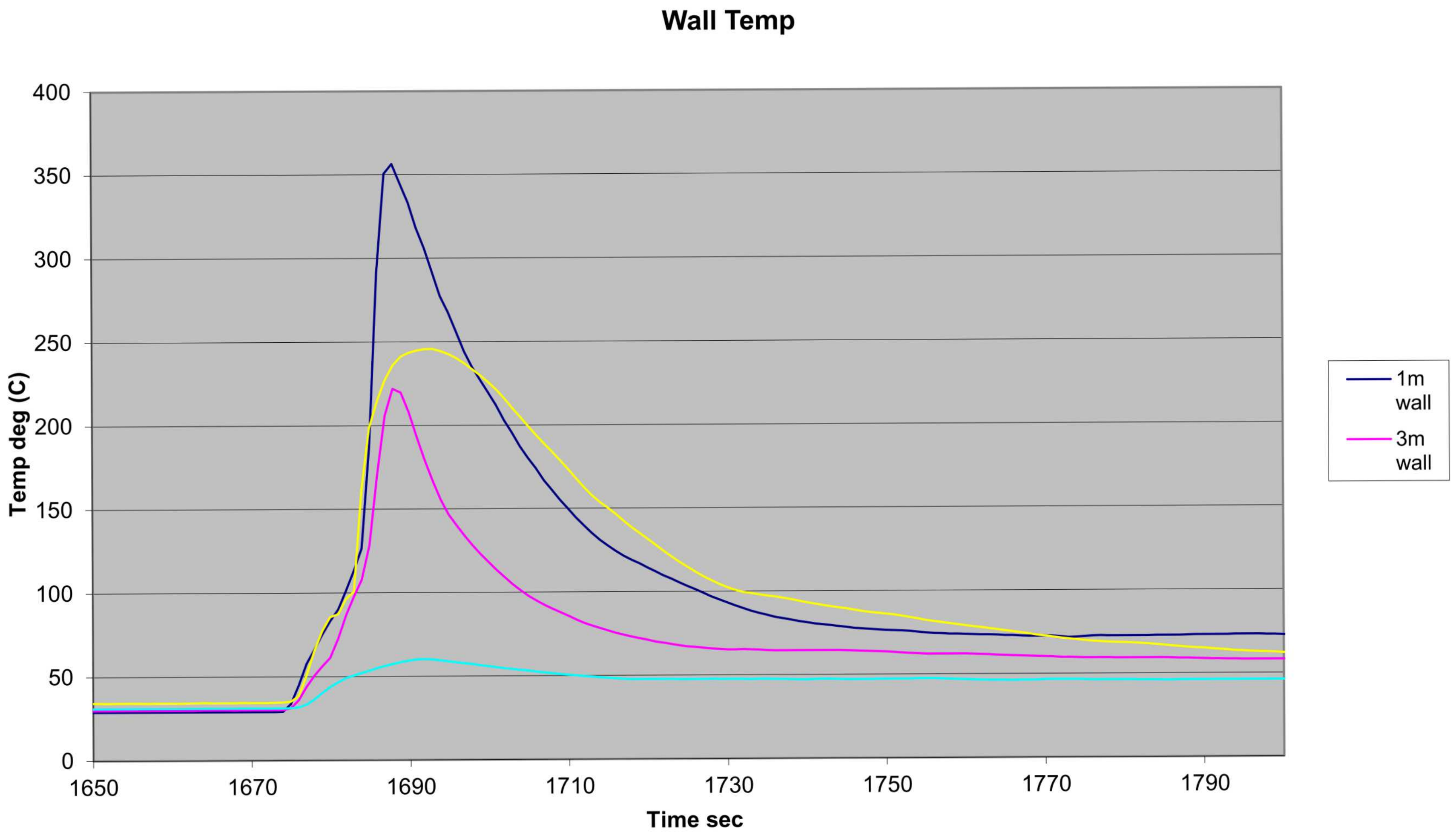
T4 Data
Pipe Temperatures



T4 Data
Air Temperature

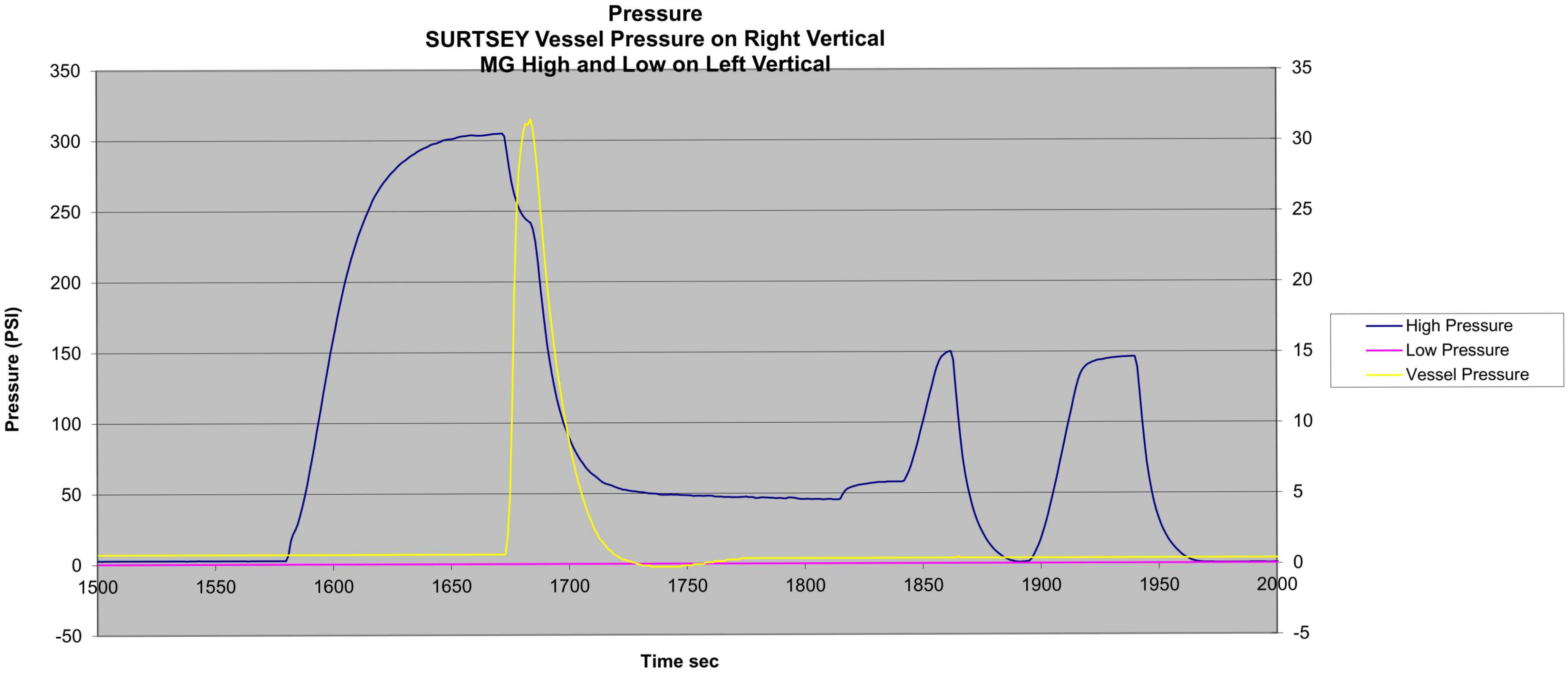


T4 Data
Wall Temperature

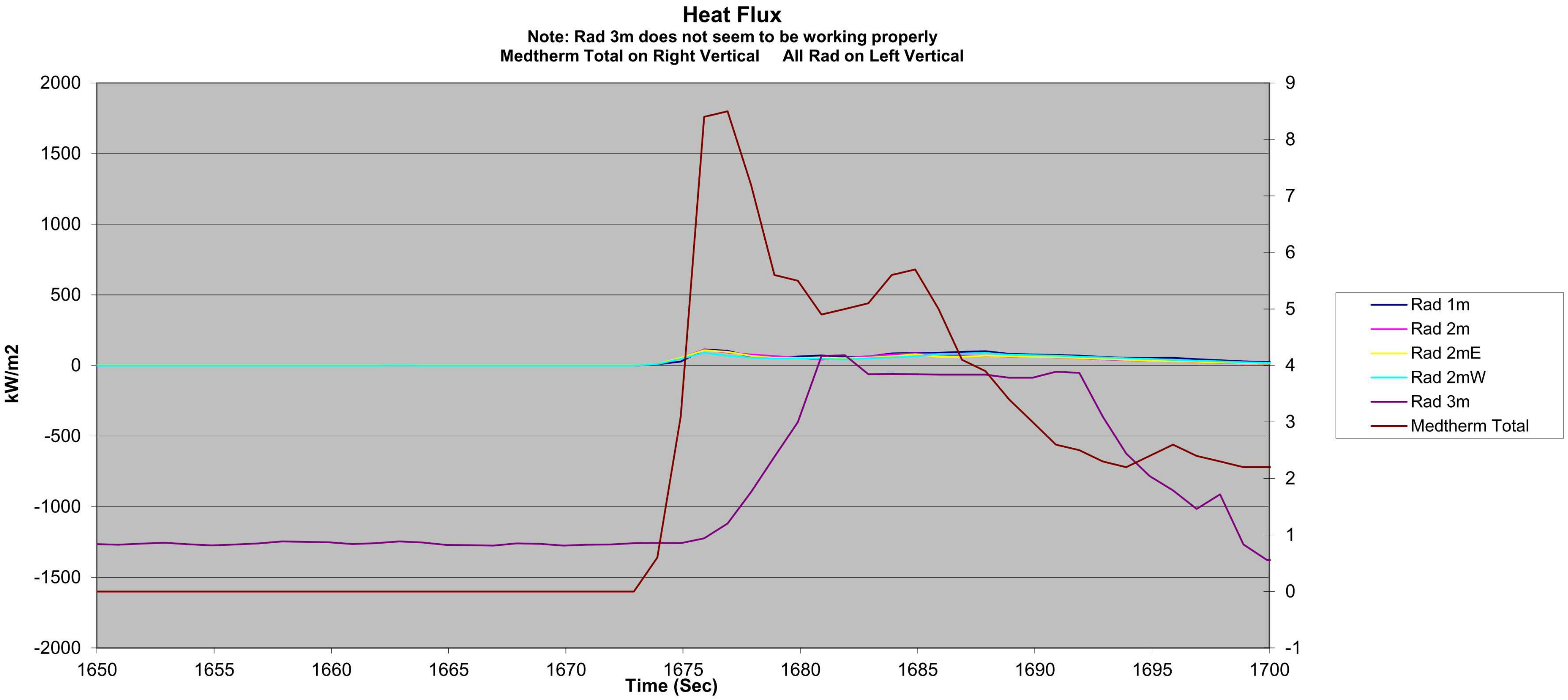


T4 Data
Pressures

Sandia National Laboratories



T4 Data
Heat Flux



Open T3&T4 Collaboration Questions

- How do we treat the multiple ignitions in the T3?
- Do we re-evaluate the DME for the spray fires?
- Do we model the concrete in the bottom of Surtsey?
  - MELCOR cannot yet do sodium concrete interactions.
- Do we only model the initial pressurization rise in T4?
  - If we model beyond the 6 inch diameter port failure, do we model leakage prior to the complete depressurization?

Sodium Mass Injected	20 kg
Duration of Sodium Spray	Approximately 20 seconds
Spray Height	5.3 m
Sodium Mass Flowrate	1 kg/s
Sodium Outlet Nozzle Velocity	9.34 m/s
Outlet Nozzle Pressure	2.01 MPa (291 psi)
Initial Sodium Temperature	200°C, 500°C
Nozzle Orifice Diameter	1.23 cm
Mean Droplet Diameter (DME)	2.0 mm
Vessel Free Volume	99 m^3
Vessel Thickness	1 cm

Sandia National Laboratories

Exceptional service in the national interest

SNL Sodium Fire Modeling

Experiments

MELCOR/Contain-LMR

CNWG

U.S. DEPARTMENT OF ENERGY

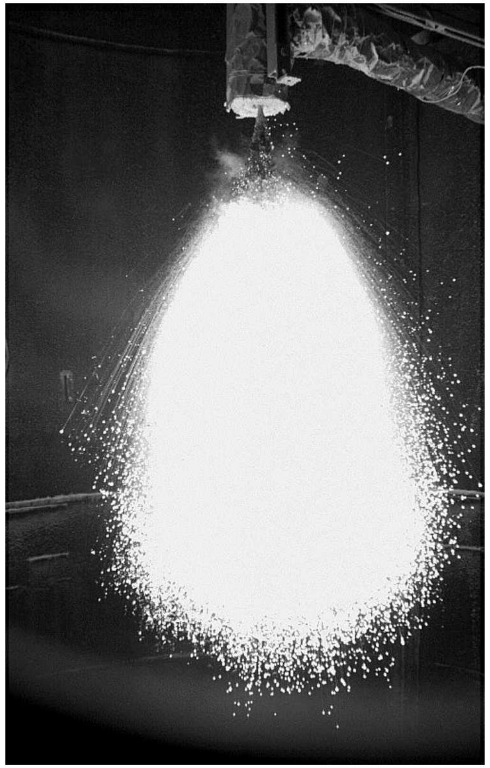
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SAND2016-XXXX

MELCOR and CONTAIN-LMR Integration

- Motivation:
  - Provide CONTAIN-LMR sodium accident analysis capability under MELCOR integrated severe accident code for SFR source term assessments, level 2/3 PRA, and containment DBA analyses.
- Current Status:
  - Sodium chemistry models from CONTAIN-LMR are being implemented into MELCOR 2.1
  - Data structures for the newly created Sodium Chemistry Package for MELCOR are being developed
  - Additional interface data variables are being added for the atmosphere chemistry model.
- Expected Schedule:
  - Implementation of all Na chemistry models by the end of FY16
  - A combination of experimental and code-to-code and benchmarking studies will be conducted in FY17
- The MELCOR sodium models will be used in:
  - Trial source term calculations funded by DOE or private vendors
  - JAEA Sodium Fire modeling collaboration with SNL and JAEA experiments
  - Planned MELCOR and ASTEC-Na crosswalk



MELCOR Integration Work Scope

- Project Motivation and Objective
  - Address the regulatory infrastructures requirements regarding accident analyses for reactor systems,
    - A sodium coolant accident analysis code is necessary to provide regulators with a means to perform confirmatory analyses for future sodium reactor submissions.
- Solution Strategy
  - Implementation of sodium phenomenology models into an integrated, full-featured, actively maintained, severe accident code
    - CONTAIN-LMR models implemented into the MELCOR code
    - MELCOR is a mature integrated severe accident code
      - Used by NRC for level 2 and level 3 PRA analysis for LWR as well as
      - Used for containment DBA analysis
      - 30 years of development
    - New modeling added to MELCOR will be enabled only when sodium models are specified by user, and will not impact code performance.

Sodium Coolant in MELCOR 2.1

- Sodium Working fluid
  - Implement Sodium Equations of State (EOS)
  - Implement Sodium thermal-mechanical properties
- Two models implemented
  - Fusion safety database (FSD)
  - SIMMER database with supplemental SAS4a information
- Sodium properties for FSD are mainly read from an input file, so it is easy to adapt for other liquid metal fluids
- Test problems have been created demonstrating model capability
- Some improvement, particularly for FSD, may require additional assessment and development

Sodium Models from CONTAIN-LMR

- DOE has funded Sandia starting from FY13
  - We are Integrating all sodium physics and chemistry models into MELCOR 2.1 with the sodium coolant fluid capability
    - Spray fire chemistry
    - Pool fire chemistry
    - Atmosphere chemistry
    - Two condensable options (in atmosphere)
      - Sodium condensation
      - Water condensation
    - Sodium concrete interaction (SLAM model)
    - Sodium/debris interactions (no interest from DOE)
  - Internally, we are upgrading CONTAIN2 (last version) with CONTAIN-LMR sodium models

Spray Fire Chemistry

- Based on NACOM spray model from BNL
  - Input requirement: fall height, mean diameter and source
  - Internal droplet size distribution (11 bins) from Nukiyama-Tanasama correlation
  - Reactions considered:
    - (S1) $2\ \mathrm{Na} + {}^{1}/_{2}\,\mathrm{O_2} \rightarrow \mathrm{Na_2O}$,
    - (S2) $2\ \mathrm{Na} + \mathrm{O_2} \rightarrow \mathrm{Na_2O_2}$
  - Fixed ratio of peroxide and monoxide $\left(\frac{1.3478 \cdot \mathrm{F}_{Na_2O_2}}{1.6957 - 0.3479 \cdot \mathrm{F}_{Na_2O_2}}\right)$
  - CONTAIN Routine Ported to MELCOR: SPRAY
  - Tracked quantities include:
    - Mass of Na (spray, burned, pool), O_2(consumed), Na_2O_2+ Na_2O(produced)
    - Energy of reactions

Pool Fire Chemistry

- Based on SOFIRE II code from ANL
  - Reactions considered:
    - (P1) $2\ \mathrm{Na} + \mathrm{O_2} \rightarrow \mathrm{Na_2O_2}$,
    - (P2) $4\ \mathrm{Na} + \mathrm{O_2} \rightarrow 2\ \mathrm{Na_2O}$
  - Reactions depend on the oxygen diffusion as: $\mathrm{D} = \frac{6.4315\times10^{-5}}{\mathrm{P}} \mathrm{T}^{1.823}$
  - Input requirement:
    - F1 – fraction of O_2 consumed for monoxide,
    - F2 – fraction of reaction heat to pool,
    - F3 – fraction of peroxide mass to pool, &
    - F4 – fraction of monoxide mass to pool
  - PFIRE routine will be ported to MELCOR 2.1
- Sodium pool modeling – heat transfer
- Tracked quantities:
  - Mass of Na(pool, burned), O_2(consumed), Na_2O_2+Na_2O(produced)
  - Energy of reactions

Atmospheric Chemistry

- A number of reactions have been considered:
  - (A1) $Na(l) + H_2O\ (l) \rightarrow NaOH(a) + \frac{1}{2}H_2$
  - (A2) $2\ Na(g,l) + H_2O\ (g,l) \rightarrow Na_2O(a) + H_2$
  - (A3) $2\ Na(g,l,a) + \frac{1}{2}O_2$ or $O_2 \rightarrow Na_2O(a)$ or $Na_2O_2(a)$
  - (A4) $Na_2O_2(a) + 2\ Na(g,l) \rightarrow 2\ Na_2O(a)$
  - (A5)
    - $Na_2O(a) + H_2O\ (g,l) \rightarrow 2NaOH(a)$
    - $Na_2O_2(a) + H_2O\ (g,l) \rightarrow 2NaOH(a) + 0.5O_2$
- All these reactions are assumed to occur:
  - Atmosphere (g), aerosol, surfaces (i.e., HS)
  - The order of the reactions are given

Atmospheric Chemistry (concluded)

- Porting routines:
  - CHEMRX - main driven routine to call:
    - CHMGAS – gas-to-gas reactions
    - CHMAER – aerosol-to-gas reactions
    - CHMDEP – deposited aerosol reactions
    - CHMREP – aerosol-to-liquid reactions on surfaces
  - Interface variables – RN, CVH, NCG, BUR packages
- Outputs
  - Reaction number, reaction energy, byproducts (Na classes, H_2), gas and liquid consumed (Na, H_2O, O_2)
  - In MELCOR, H_2 burn is not calculated in CHEMRX. Instead, user needs to invoke BUR package

Sodium Chemistry (NAC) Package Development (in progress)

- To better manage the sodium related models, particular for chemistry models
- Create “new” NAC Package
  - Data structures – in module (M_NAC)
    - NaCL(5), old-new variables, input parameters
  - RN to NAC class structure – tracks aerosol products
  - Na modeled as condensable, H2O modeled as aerosol
  - Sensitivity coefficient development (a minimum set for now)
  - Interface variables, interface with many packages, for examples:
    - NCG – O_2 and H_2
    - HS – condensate, deposits
    - CVH – H_2O, reaction energies
    - RN – aerosol interactions
  - Calling sequence for NAC model executions

Aerosol Mapping

RN Class

Class	Class Name	Chemical Group	Representative	Member Elements
1	XE	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	CS	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	BA	Alkaline Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	I2	Halogens	I_2	F, Cl, Br, I, At
5	TE	Chalcogens	Te	O, S, Se, Te, Po
6	RU	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	MO	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	CE	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	LA	Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10	UO2	Uranium	UO_2	U
11	CD	More Volatile Main Group	Cd	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12	AG	Less Volatile Main Group	Ag	Ga, Ge, In, Sn, Ag
13	BO2	Boron	BO_2	B, Si, P
14	H2O	Water	H_2O	H_2O
15	CON	Concrete	CON	- – -
16	CSI	Cesium iodide	CsI	CsI
17	CSM	Cesium Molybdate	CsM[1]	CsM[1]

RN Class to NAC Class

Rn Class	NAC Class
H2O (CL 14)	NaCL(1)
Na (New)	NaCL(2)
NaOH (new)	NaCL(3)
Na2O (new)	NaCL(4)
Na2O2 (new)	NaCL(5)

Specified Details on NAC Package

- MELGEN records
  - NAC_INPUT
  - NAC_RNCLASS
  - NAC_ATMCHEM
  - NAC_SPRAY
  - NAC_PFIRE
  - NAC_CONDENSE
  - NAC_SLAM
  - NAC_SC
- Plot and control function variables
- Outputs

Summary

- With the new Sodium Fire Modeling capabilities being added into MELCOR, the US is poised address identified safety and licensing gaps for US sodium reactors
  - Validation of these new tools remains a key component to ongoing SFR safety related research
  - IRSN/SNL collaboration is key to improving the understanding of sodium fire phenomenology

Acknowledgement

- The Sodium Fire Tests were funded under a SNL LDRD from 2007-2010.
- MELCOR-Na development is funded by the Office of Nuclear Energy of U.S. Department of Energy WP#: AT-17SN170204.
- SNL/IRSN collaborative research is covered under the existing NRC/IRSN MOU. SNL work related to this collaboration is funded under the MELCOR/ASTEC crosswalk.

Thank You