IAEA Technical Meeting on Compatibility Between Coolants and Materials for Fusion Facilities and Advanced Fission Reactors

Egyptian
Atomic Energy

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Title: Effect of Water Addition on Mitigation of Severe Accident Consequences in Nuclear Reactors

Presented by

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Introduction

- The injection of water to cool the degrading core is one of the main measures that is used to control the severe accidents in light water reactors.

- The interaction of water with the cladding material has a great impact on the accident progression. In the present work, an input deck is developed for RELAP-SCDAPSIM to study the loss of coolant scenarios in a typical PWR nuclear fuel bundle.

- Effect of water addition on mitigating loss of bundle cooling is studied at different operating pressure and different simulation times.

Numerical Simulation (cont.)

Problem Descriptions

A fuel bundle consists of 32 identical fuel rods is studied under loss of coolant scenario. The bundle is 0.9144 m in height .The fuel rods in the bundle have an outer diameter of 9.63 mm and a pitch of 12.80 mm. The fuel pellet radius is 4.135 mm, inner cladding radius of 4.215 mm, and Outer cladding radius of 4.815 mm. Except for height, the design of the fuel rods is typical of PWR fuel rods. The flow area of the bundle of fuel rods is equal to 3.685 x 10^{-3} m^2. The bundle of fuel rods is surrounded by an adiabatic boundary through which no flow of heat occurs. The SCDAP/RELAP5 code represented the fuel bundle as eight equally sized axial nodes and eight equally sized hydrodynamic control volumes. The model include:

- ❑ Two identical bundles with 32 rods in 6X6 array of 0.91 m in height and high decay heat of 58.5 Kw (2.0 Kw/m per rod).
- ❑ One bundle modeled using RELAP5 heat structure – 1D heat conduction only and the other with SCDAP fuel rod component – 2D heat conduction, oxidation, ballooning and rupture, material liquefaction.

Numerical Simulation (cont.)

Problem Descriptions (Cont.)

- ☐ Water quenching at simulation times of 250, 260, and 270 s.
- ☐ 9 axial volumes in pipe . Pipe component 100 represented by SCDAP and pipe component 300 represented by RELAP5.
- ☐ Bundles filled with water at 550K and inlet pressure of 1.9, 3.9, 6.9, 10.9, 19.9 23, and 25 MPa. The initial temperature are 550, 500 K.
- ☐ Outlet BC – Water at 1.89, 3.89, 6.89, 10.89, 19.89 22.9, and 24.9 MPa. The 550, 500 K.
- ☐ Zirconium cladding is used for operating pressure of 1.9, 3.9, 6.9, 10.9, and 19.9 MPa. The proposed cladding material for supercritical reactor, alloy MA956 which has excellent strength at high temperatures due to dispersion of yttrium oxide (Y_2O_3) is used as a cladding material at operating pressure of 23, and 25 MPa. Composition of MA956: 74.5 wt% Fe, 20 wt% Cr, 4.5 wt% Al, 0.5 wt% Y_2O_3.

Numerical Simulation (cont.)

Problem Descriptions (Cont.)

Mass flow that cools the bundle changes with time.

Time, s	Water flow rate (Kg/s)
0	1
50	1
100	0.001
900	0.001

Axial power factor for each of the eight axial node.

Axial node	1	2	3	4	5	6	7	8
Power factor	0.60	0.95	1.20	1.34	1.34	1.20	0.92	0.53

Numerical Simulation (cont.)

Problem Descriptions (Cont.)

Conditions at which bundle water quenching occur.

Bundle heat generation (kw)	Rate of water addition (kg/s)	Time of water quenching (s)
58.5 (2.0 kw/m per rod).	0.1	250
50	0.1	260
60	0.1	270
70	-	-

Numerical Simulation (cont.)

Bundle nodalization

0, 1, 1, 1, 1, 0

1, 1, 1, 1, 1, 1
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1, 1, 1, 1, 1, 1
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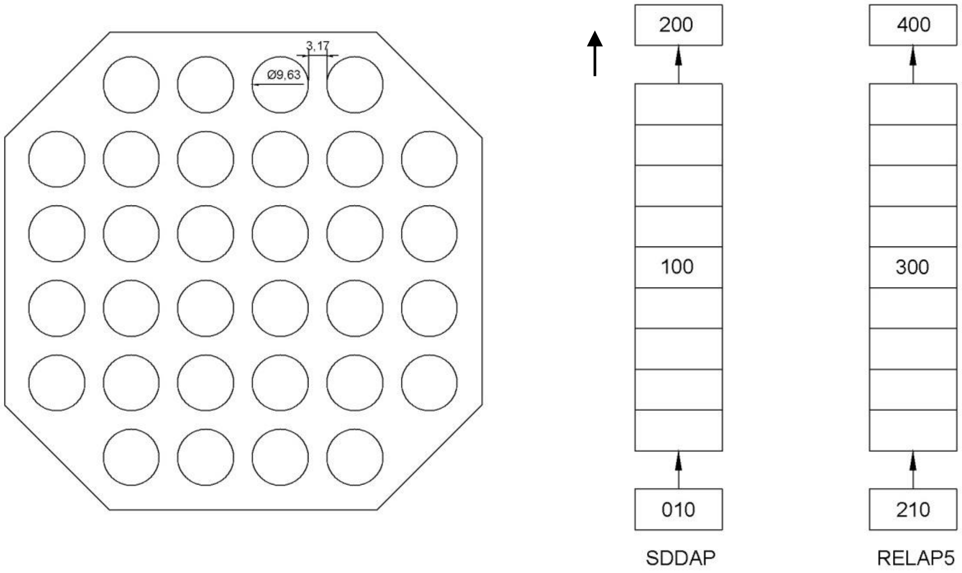


Bundle modeling & nodalization

Numerical Simulation

RELAP-SCDAPSIM modeling

- ❑ It consists of three coupled sub-models (Reactor point kinetics, Thermal hydraulics and reactivity feedback sub-model).

- ❑RELAP-SCDAPSIM is a non-homogenous, non-equilibrium code that solves six hydrodynamic partial differential equations (conservation of mass, energy and momentum for liquid and gaseous phase).

- ❑The fluid and energy flow paths are approximated by the one-dimensional stream tube and one-dimensional conduction model.

Numerical Simulation (cont.)

RELAP5 Describtion

- ❑The code contains system component models special to nuclear reactors. In particular, a point neutronic model, pumps, turbines, steam generators, valves, separators and reactor control systems can be simulated.

- ❑Additionally, it solves the conservation of mass for non-condensable gases.

- ❑The equation of state for each phase, interphase mass and energy transfer and friction are calculated.

- ❑An extensive wall heat transfer correlation package is available.

Numerical Simulation (cont.)

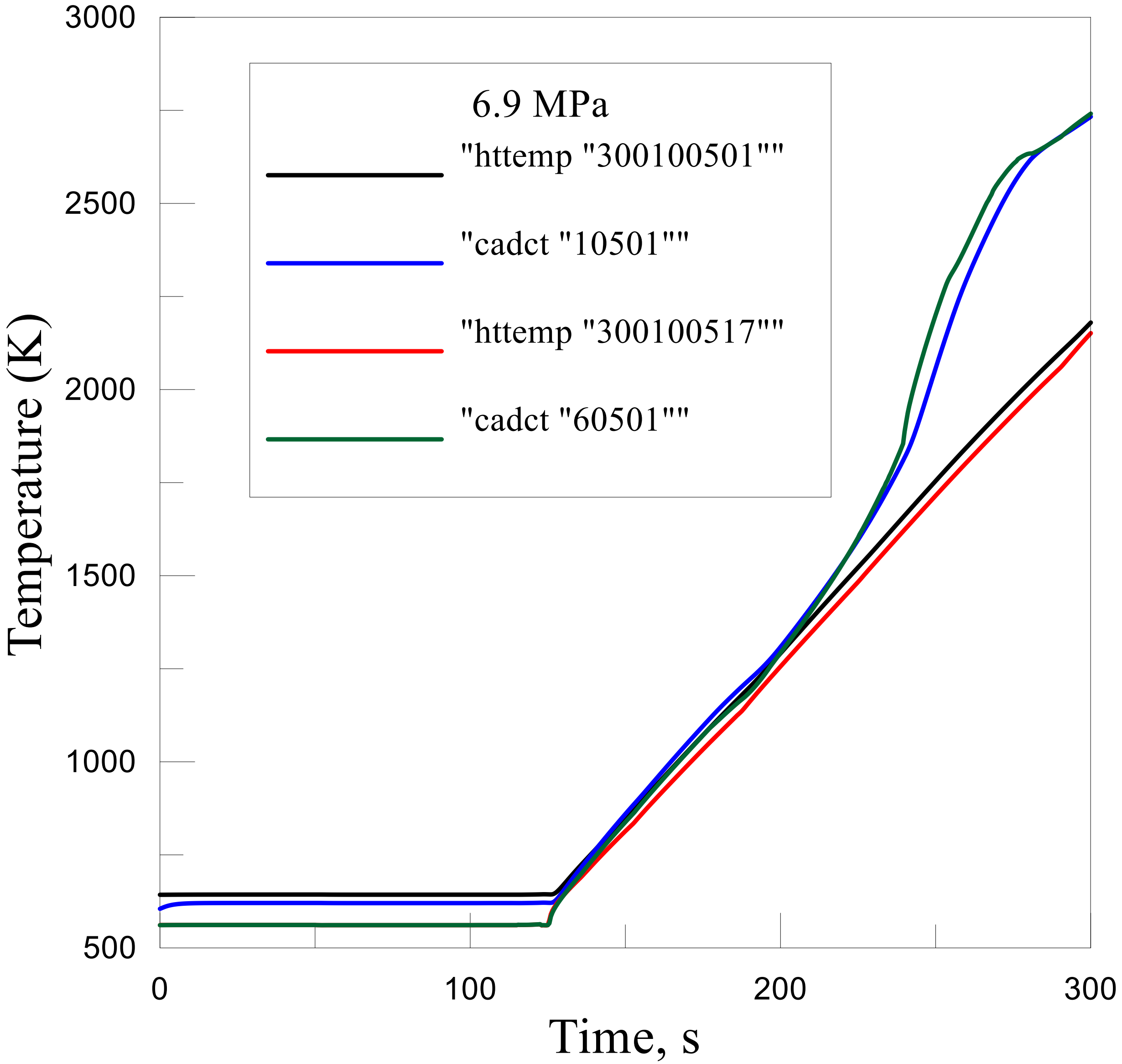
SCDAP Describtion

- ❑SCDAP is a package of new models developed to support the severe accident phenomena calculation, which is not available in RELAP5.

- ❑Two-dimensional heat conduction governing equation
- ❑Radiation model.
- ❑Fuel rod cladding deformation model.
- ❑Zircaloy oxidation model.
- ❑Fuel rod liquefaction and relocation model.

RESULTS and Discussions(cont.)

- ❑ Temperature distribution within the bundle cooling channels
- ❑The plateau in values of core maximum temperature (bgmct) at simulation times greater than 250 seconds is attributed to the melting that start to occur in the zirconium cladding of the bundle and its latent heat for melting. As hydrogen production and its associated heat is generated after simulation time of 200 seconds as depicted in, the bgmct values increase sharply at this time.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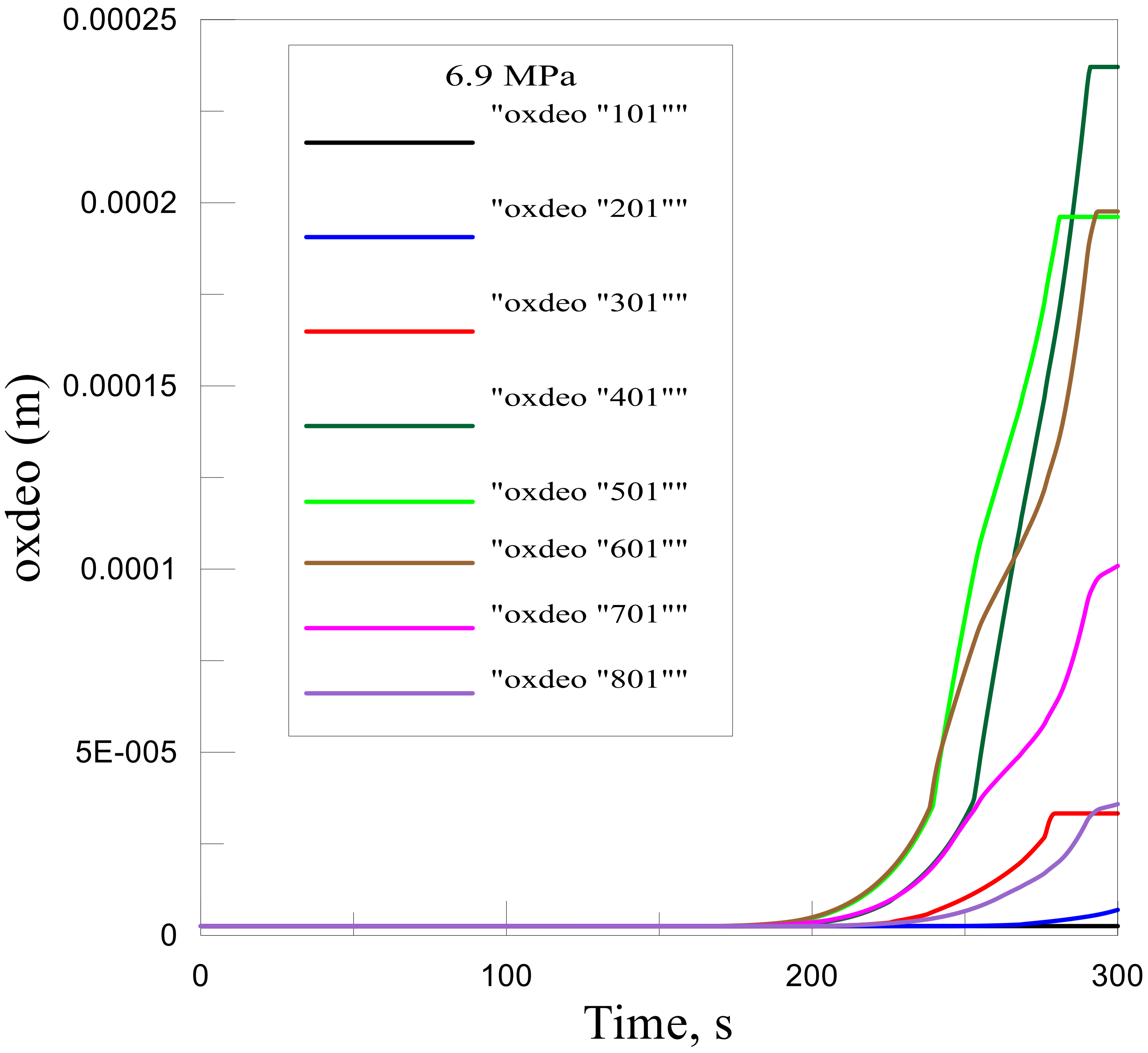
2500
2000
1500
1000
500
0
100
200
300
Temperature (K)
Time, s


0.00025
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0.00015
0.0001
5E-005
0
oxdeo (m)
0
100
200
300
Time, s
6.9 MPa
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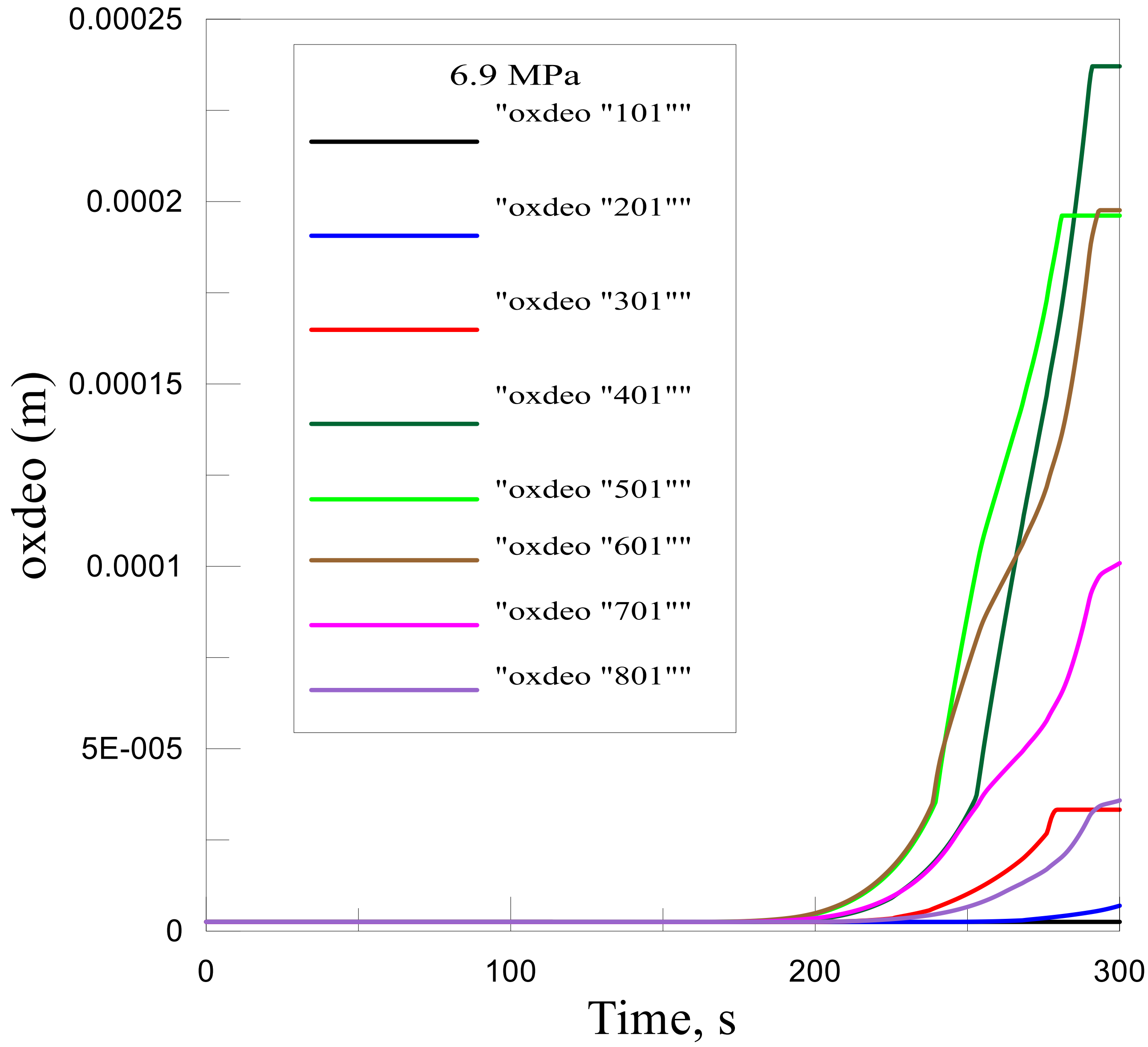
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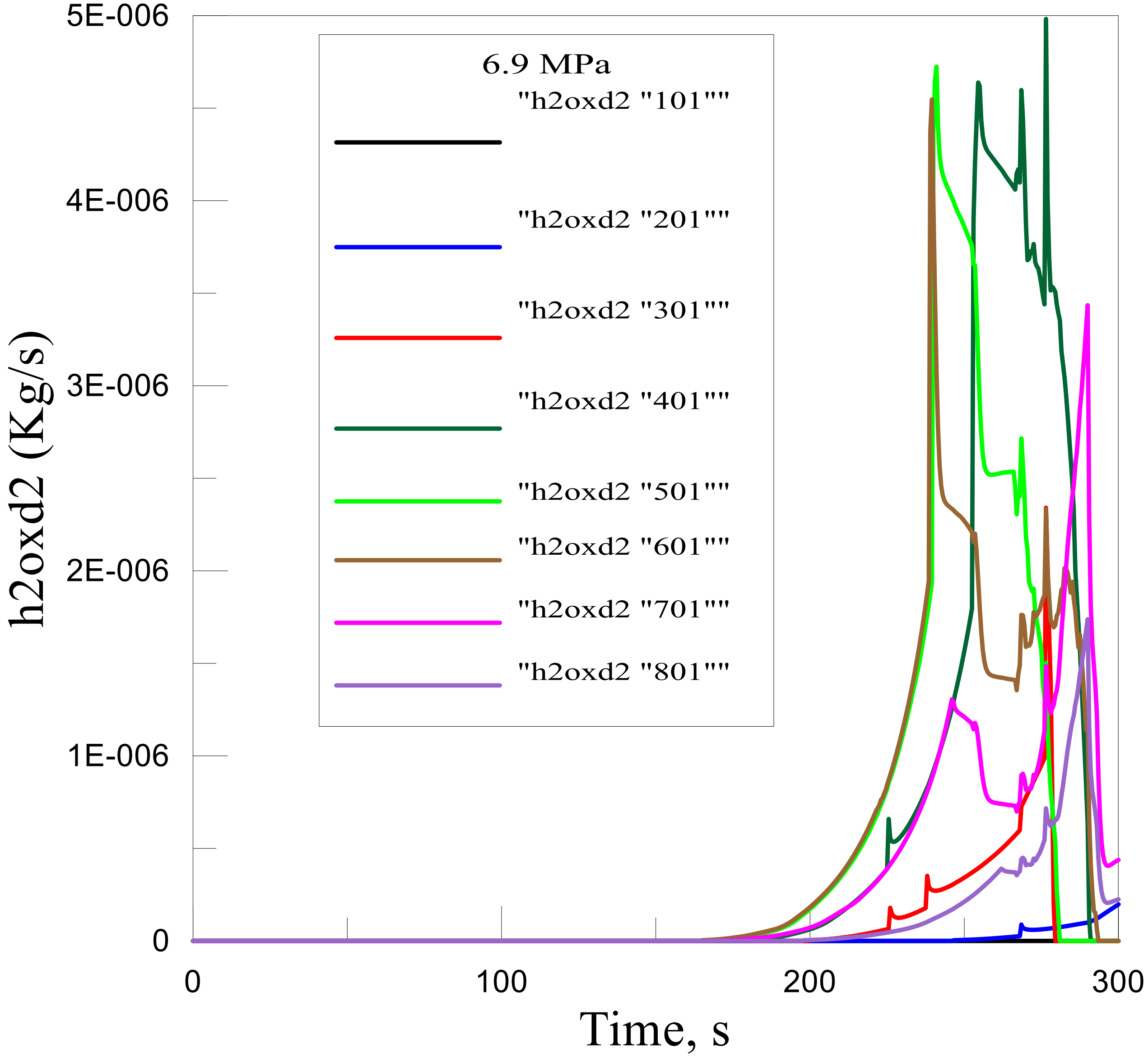
oxdeo (m)
0.00025
0.0002
0.00015
0.0001
5E-005
0
0
100
200
300
Time, s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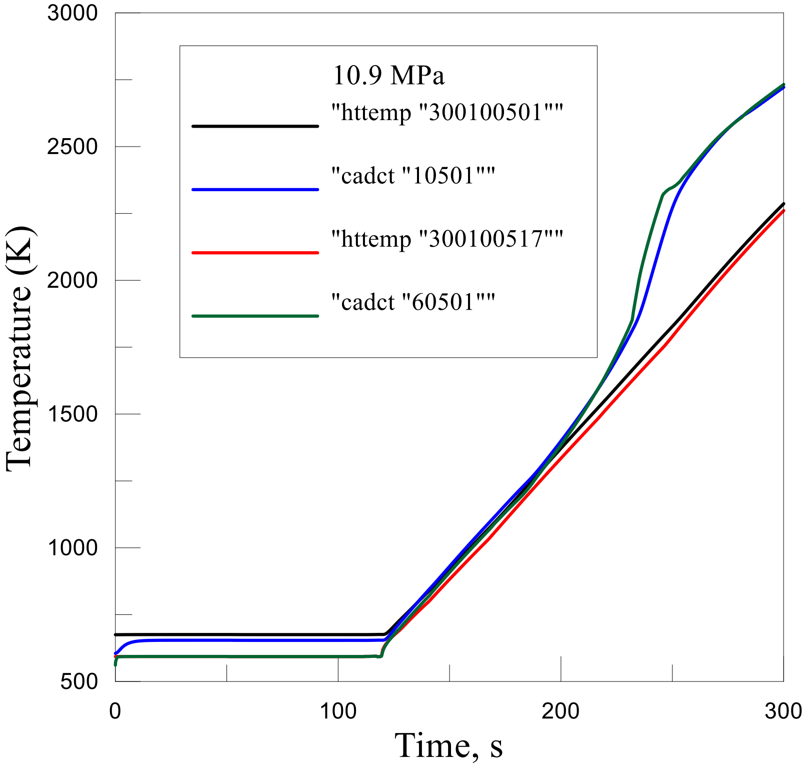
h2oxd2 (Kg/s)
5E-006
4E-006
3E-006
2E-006
1E-006
0
0
100
200
300
Time, s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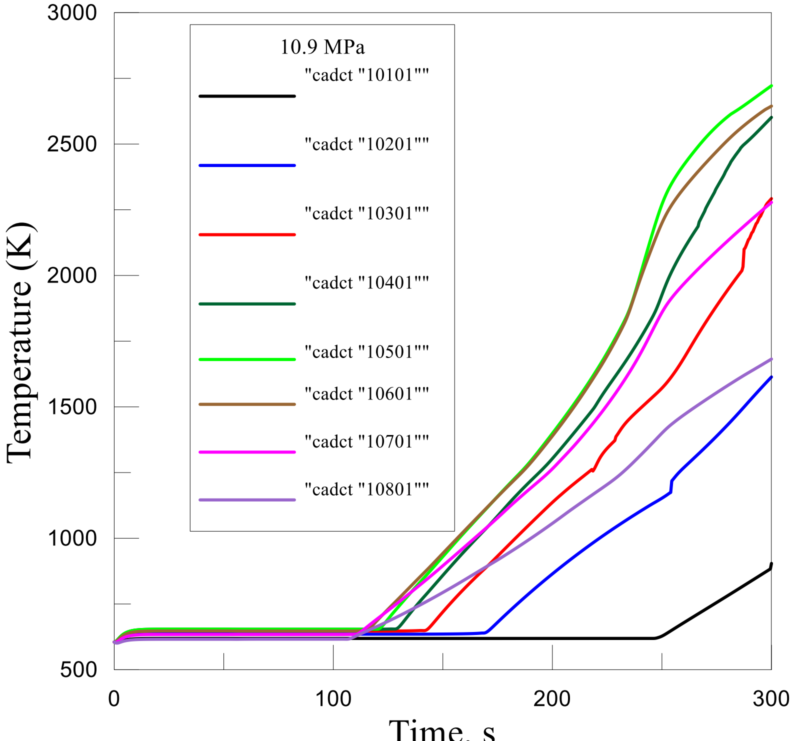
1500
1000
500
0
100
200
300
Time, s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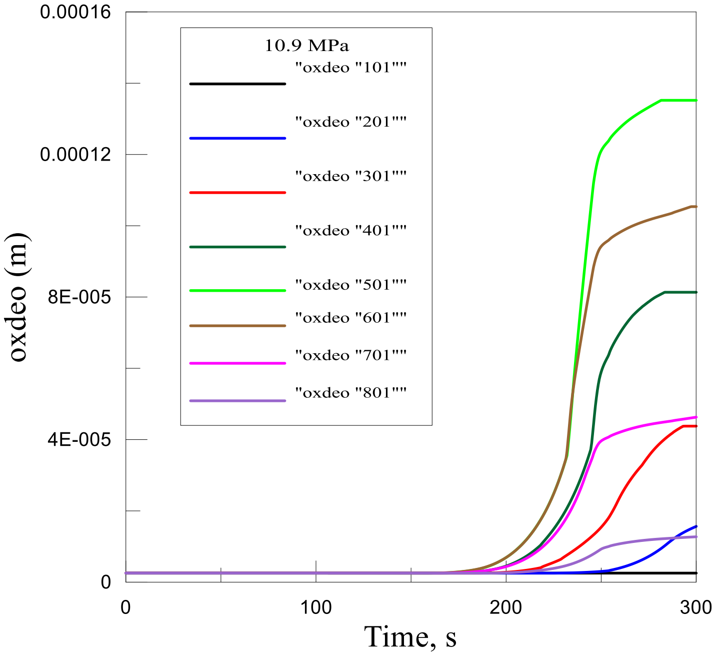
Temperature (K)
3000
2500
2000
1500
1000
500
0
100
200
300
Time, s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oxdeo (m)
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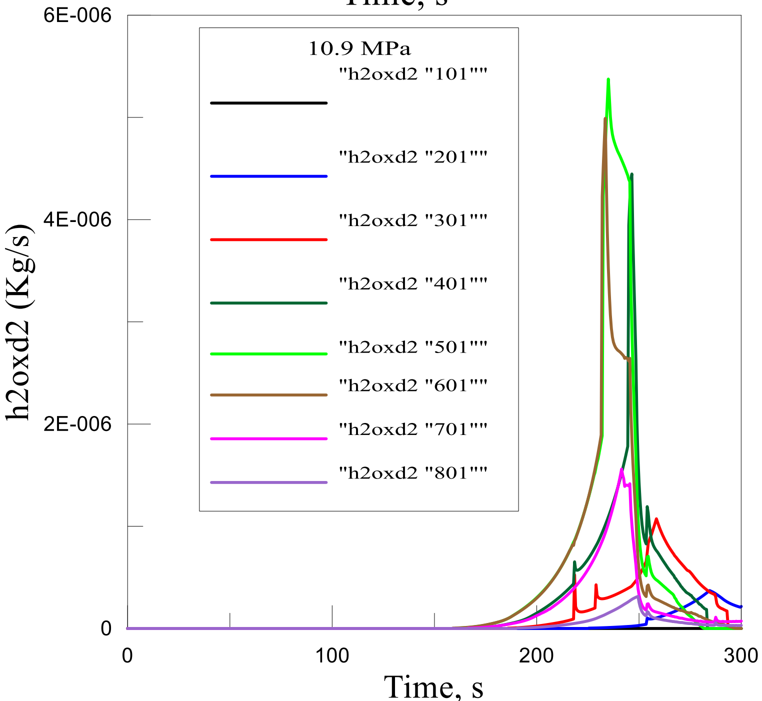
8E-005
4E-005
0
0
100
200
300
Time, s


10.9 MPa
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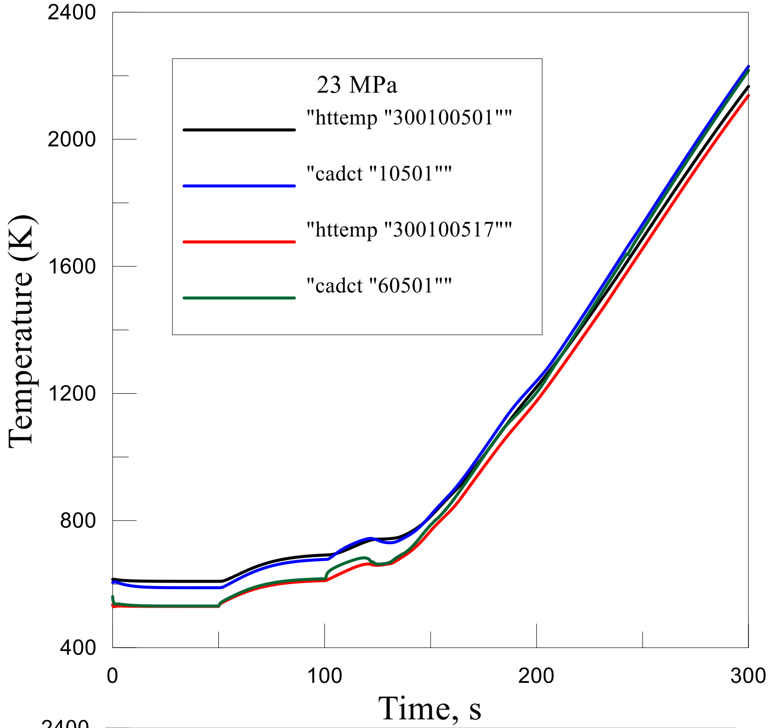
"h2oxd2 "201""
"h2oxd2 "301""
"h2oxd2 "401""
"h2oxd2 "501""
"h2oxd2 "601""
"h2oxd2 "701""
"h2oxd2 "801""
h2oxd2 (Kg/s)
6E-006
4E-006
2E-006
0
0
100
200
300
Time, s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Temperature (K)
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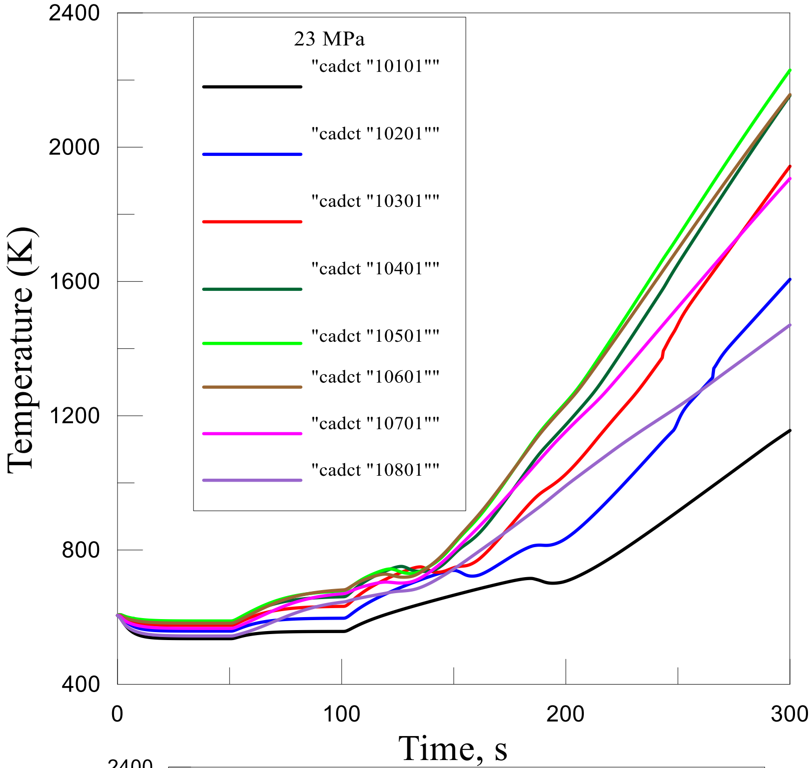
2000
1600
1200
800
400
0
100
200
300
Time, s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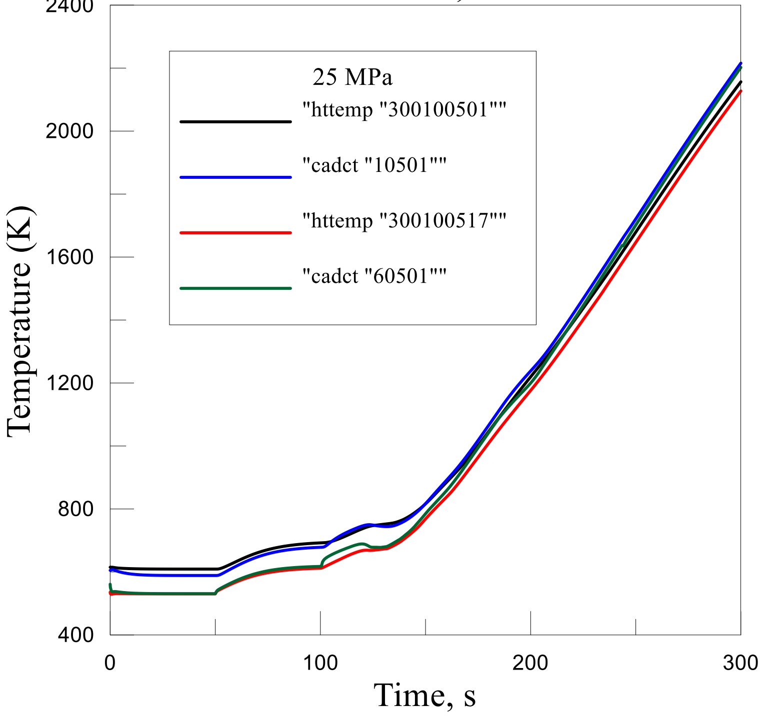
400
0
100
200
300
Time, s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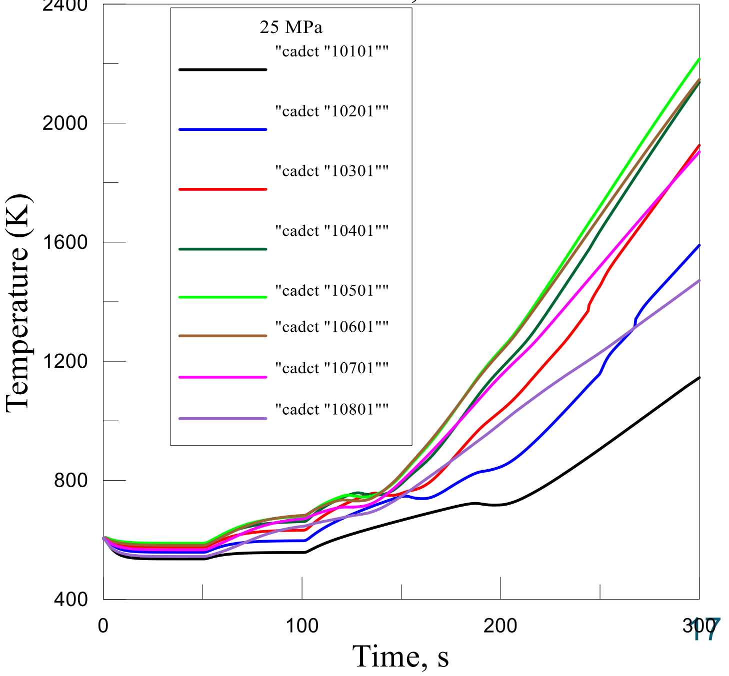
2000
1600
1200
800
400
0
100
200
300
Time, s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Temperature (K)
2400
2000
1600
1200
800
400
0
100
200
300
Time, s

RESULTS and Discussions(cont.)

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Bundle Quenching During Loss of Cooling

☐ **Effect of water addition on mitigating loss of bundle cooling.**

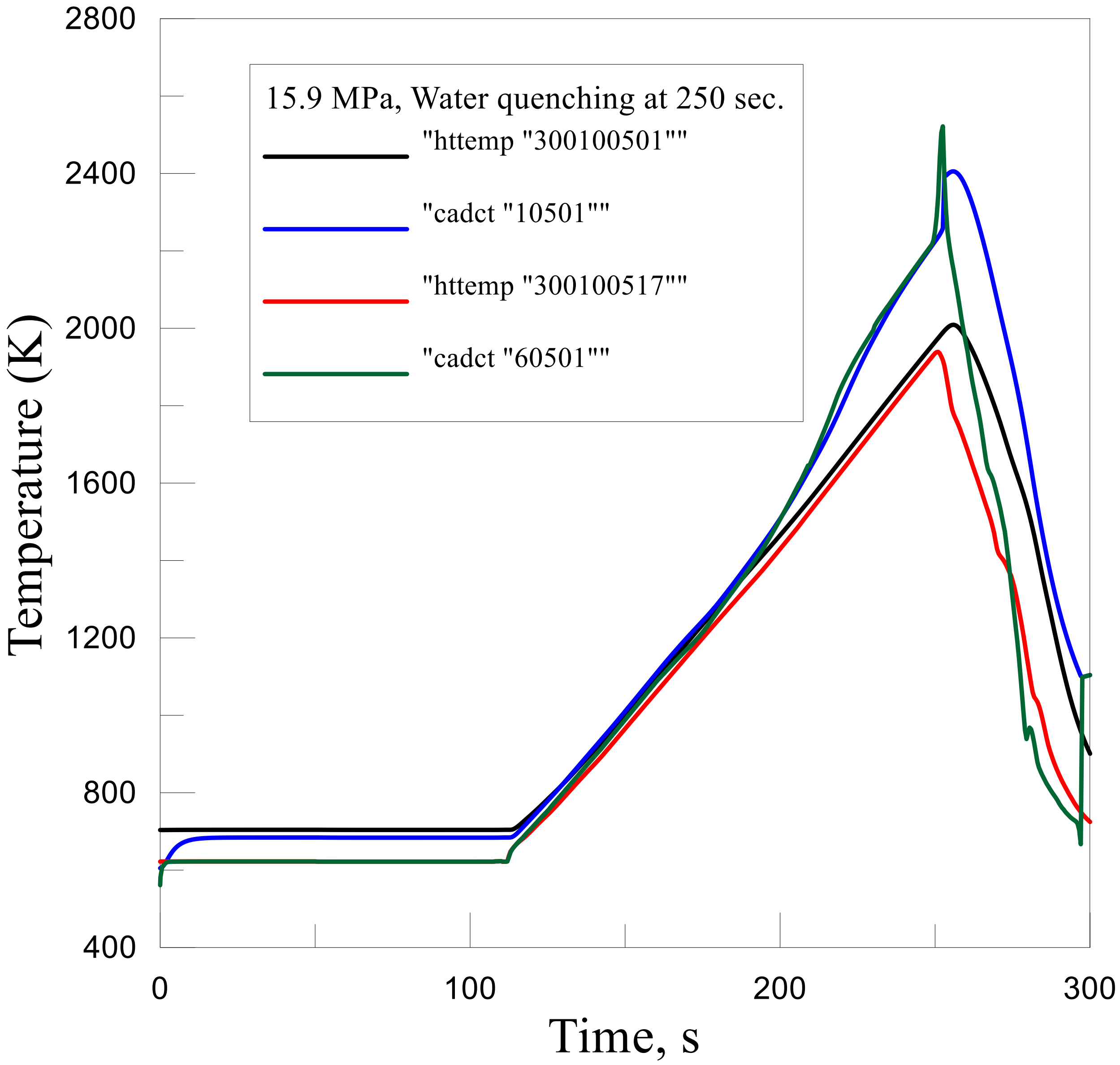
☐ **Injection of water to cool the degrading fuel bundle is the main measure used to control and mitigate the severe accidents in light water reactors like in supercritical reactors. The bundle quenching with water is associated with zirconium oxidation and immense amount of hydrogen generation. Adding water to cool the bundle can result in bundle temperature increase as will be shown in following results.**

RESULTS and Discussions(cont.)

Bundle Quenching During Loss of Cooling

- The addition of water for the purpose of mitigating accident and maintaining fuel bundle integrity at the wrong timing during the accident progression can lead to increasing the fuel temperature. This explain the reason of why the maximum cladding temperature increases with increasing the quenching time over 250 s which is the time at which zirconium start to attain its melting temperature .

- Addition of water after zirconium cladding melting increases the rate at which hydrogen production generates inside the bundle and consequently the associated heat generation increases from the exothermic chemical reaction between water and zirconium.

15.9 MPa, Water quenching at 250 sec.
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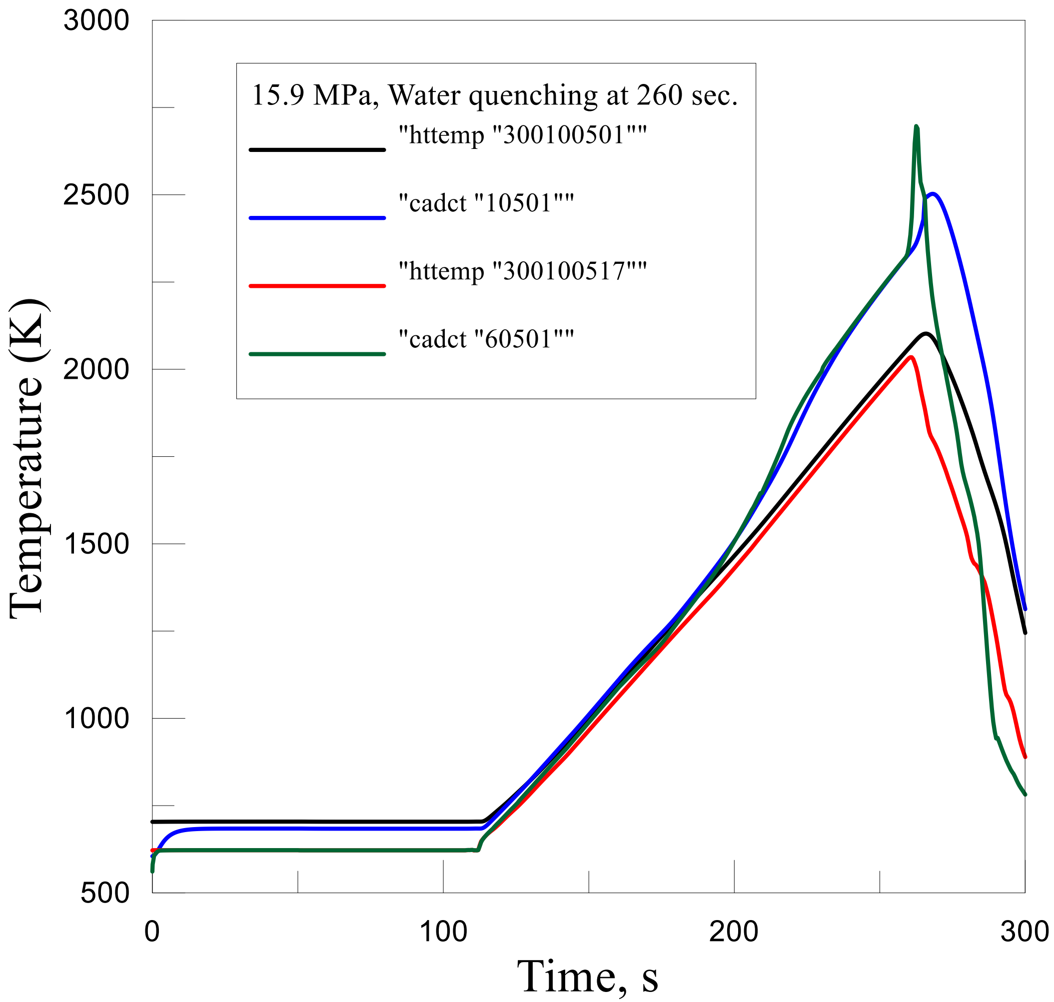
2400
2000
1600
1200
800
400
0
100
200
300
Temperature (K)
Time, s


15.9 MPa, Water quenching at 260 sec.
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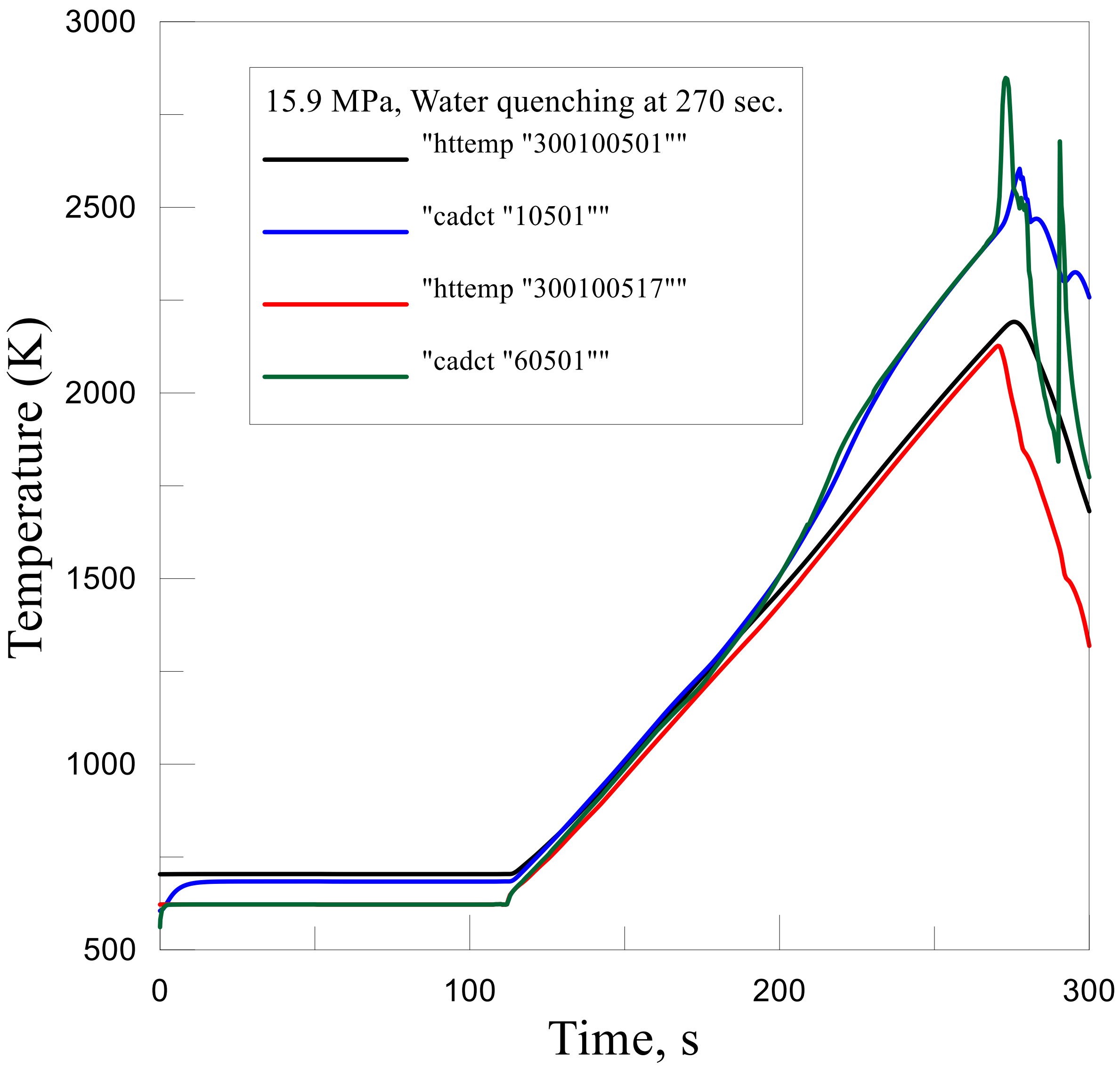
Temperature (K)
3000
2500
2000
1500
1000
500
0
100
200
300
Time, s


15.9 MPa, Water quenching at 270 sec.
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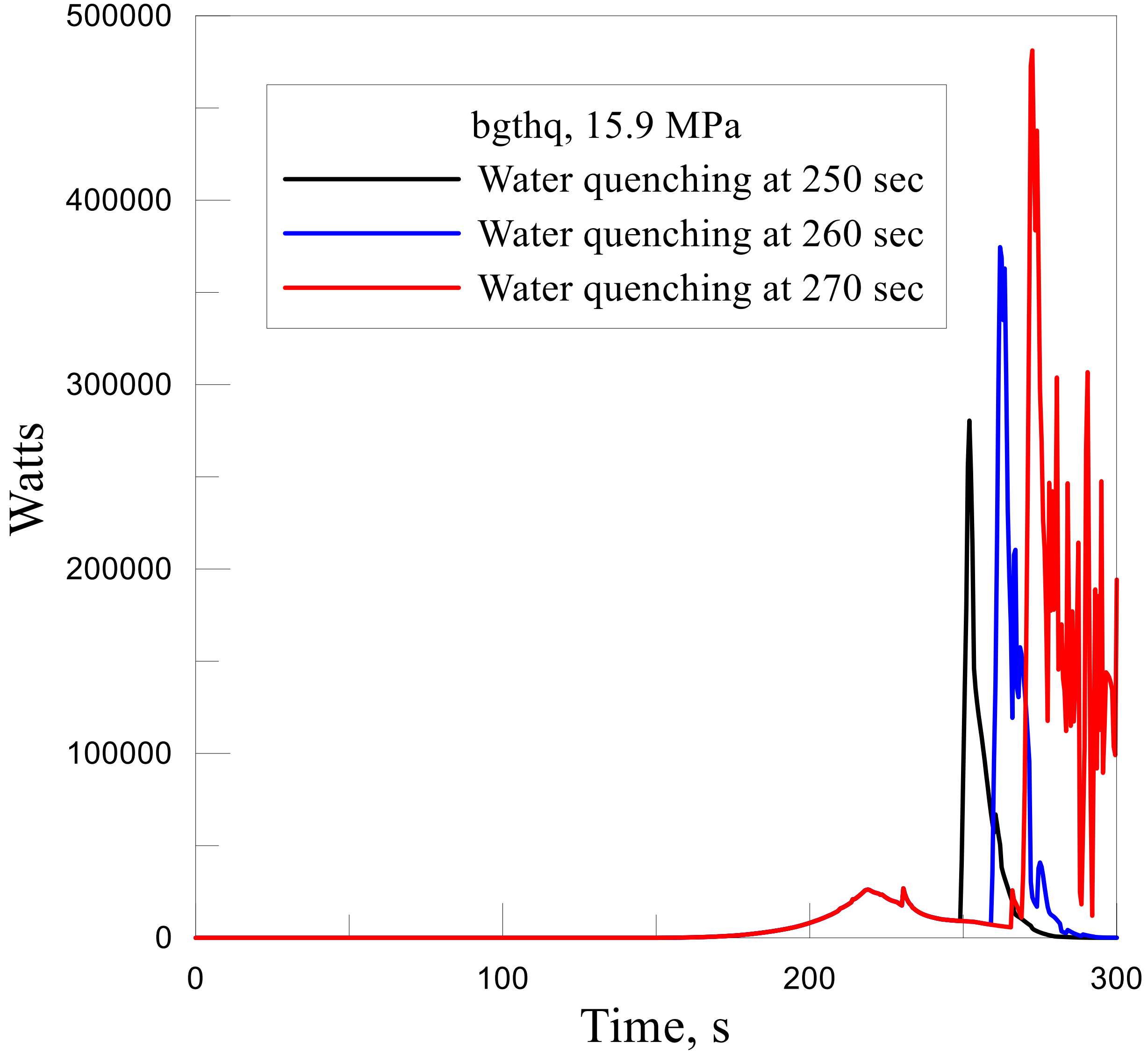
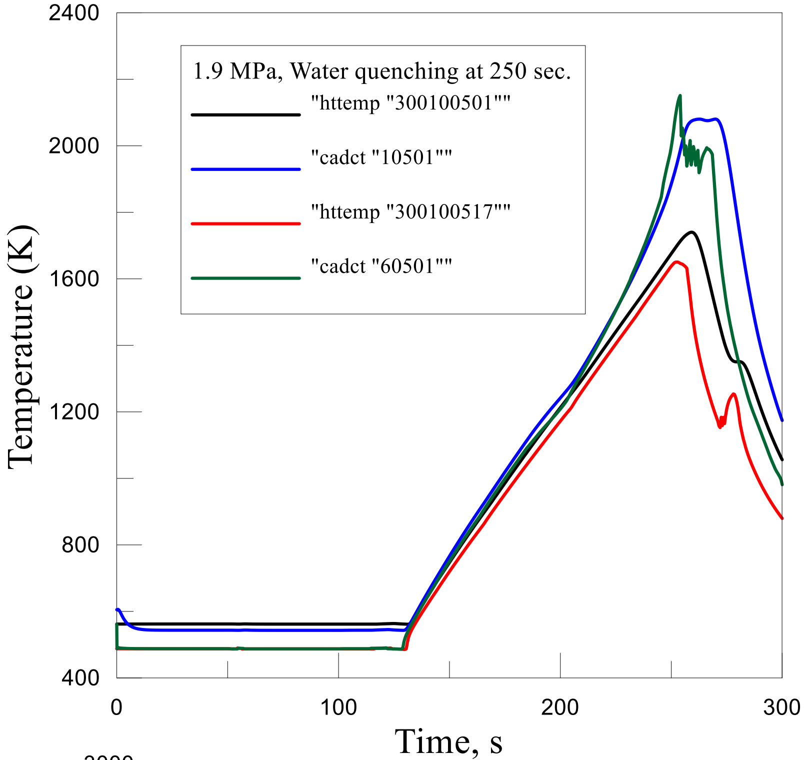
Temperature (K)
3000
2500
2000
1500
1000
500
0
100
200
300
Time, s


bgthq, 15.9 MPa
Water quenching at 250 sec
Water quenching at 260 sec
Water quenching at 270 sec
Watts
500000
400000
300000
200000
100000
0
0
100
200
300
Time, s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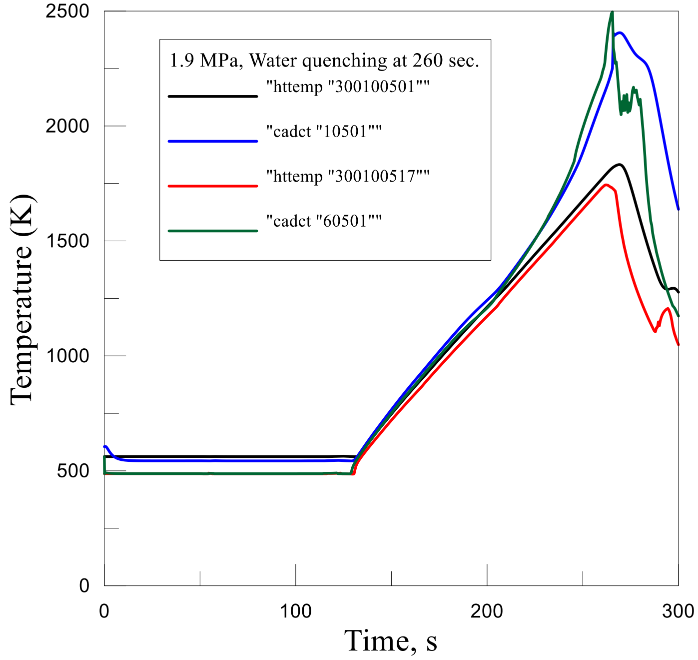
Temperature (K)
Time, s
2400
2000
1600
1200
800
400
0
100
200
300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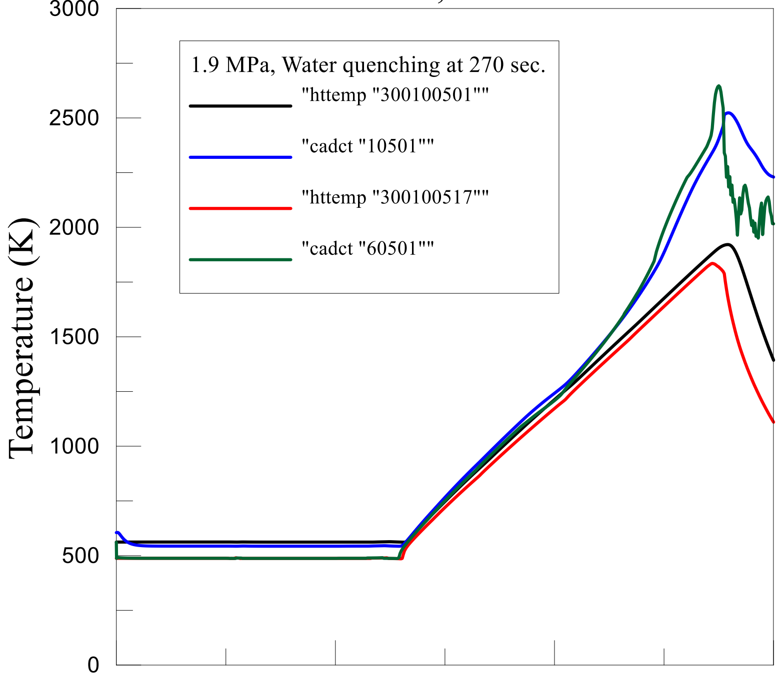
Temperature (K)
Time, s
2500
2000
1500
1000
500
0
0
100
200
300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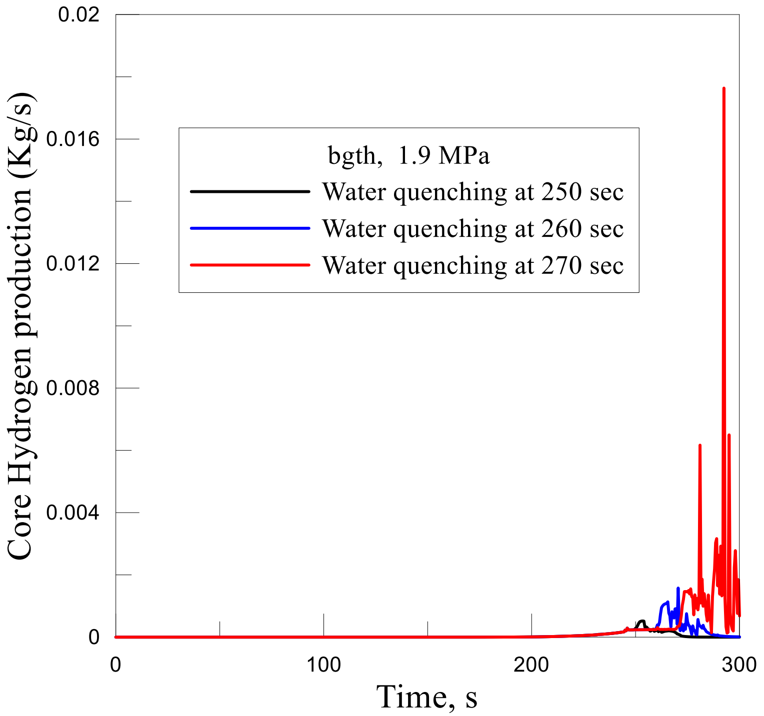
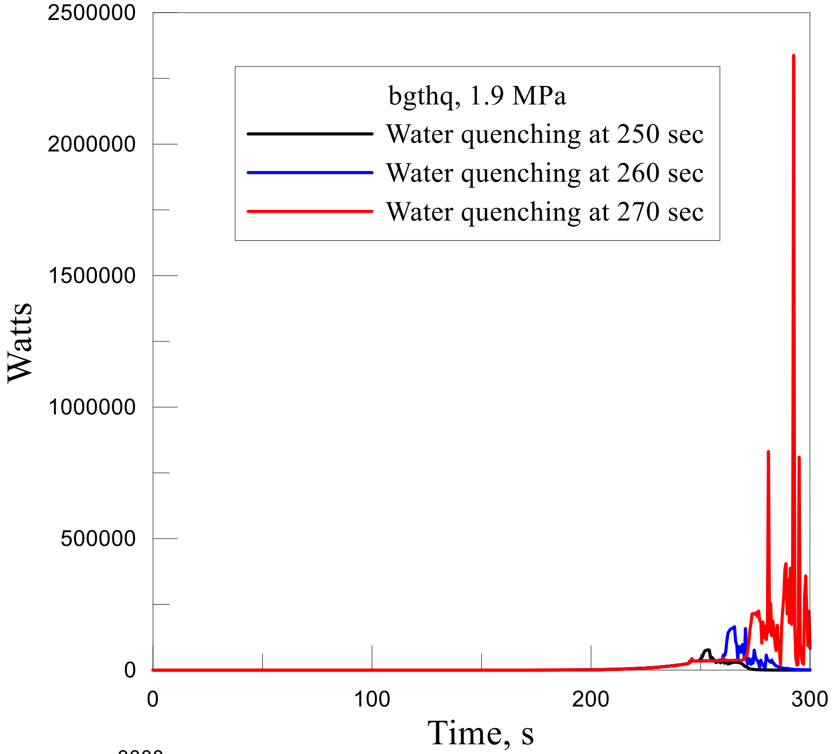
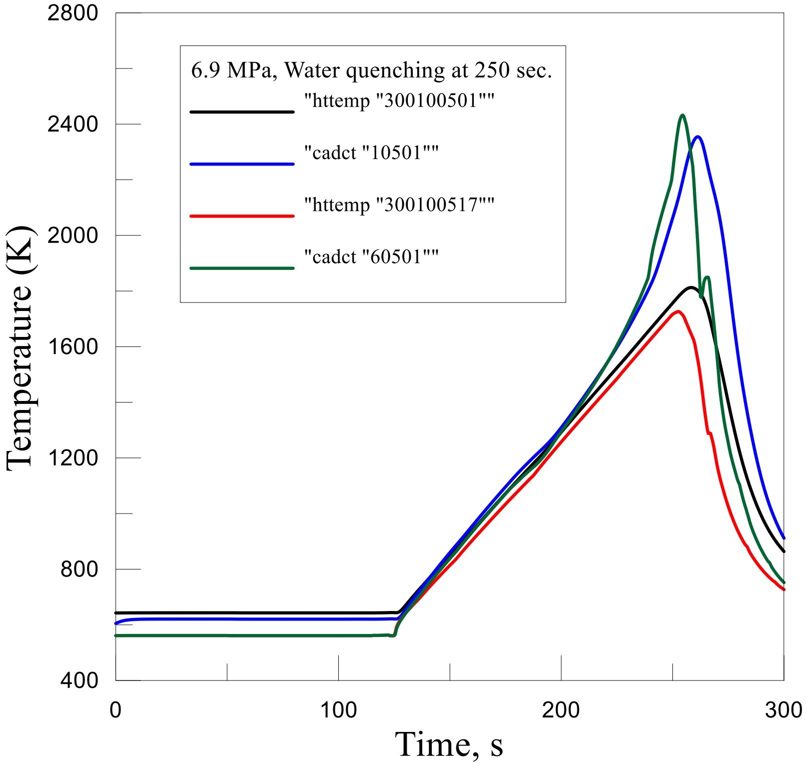
Temperature (K)
3000
2500
2000
1500
1000
500
0


bgth, 1.9 MPa
Water quenching at 250 sec
Water quenching at 260 sec
Water quenching at 270 sec
Core Hydrogen production (Kg/s)
Time, s
0.02
0.016
0.012
0.008
0.004
0
0
100
200
300


bgthq, 1.9 MPa
Water quenching at 250 sec
Water quenching at 260 sec
Water quenching at 270 sec
Watts
2500000
2000000
1500000
1000000
500000
0
0
100
200
300
Time, s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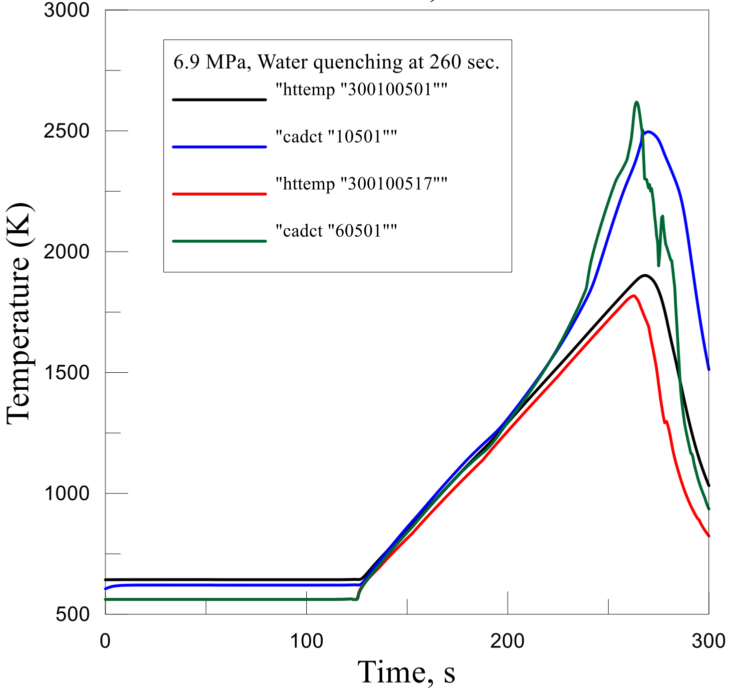
Temperature (K)
2800
2400
2000
1600
1200
800
400
0
100
200
300
Time, s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Temperature (K)
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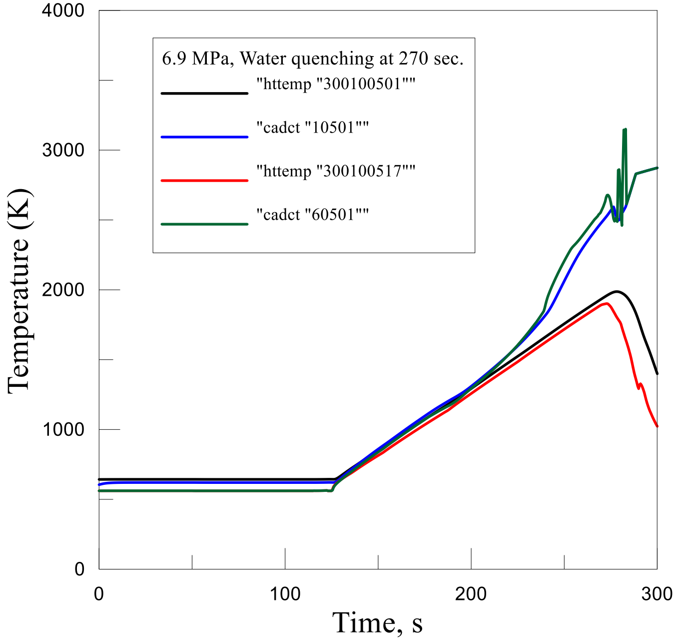
2500
2000
1500
1000
500
0
100
200
300
Time, s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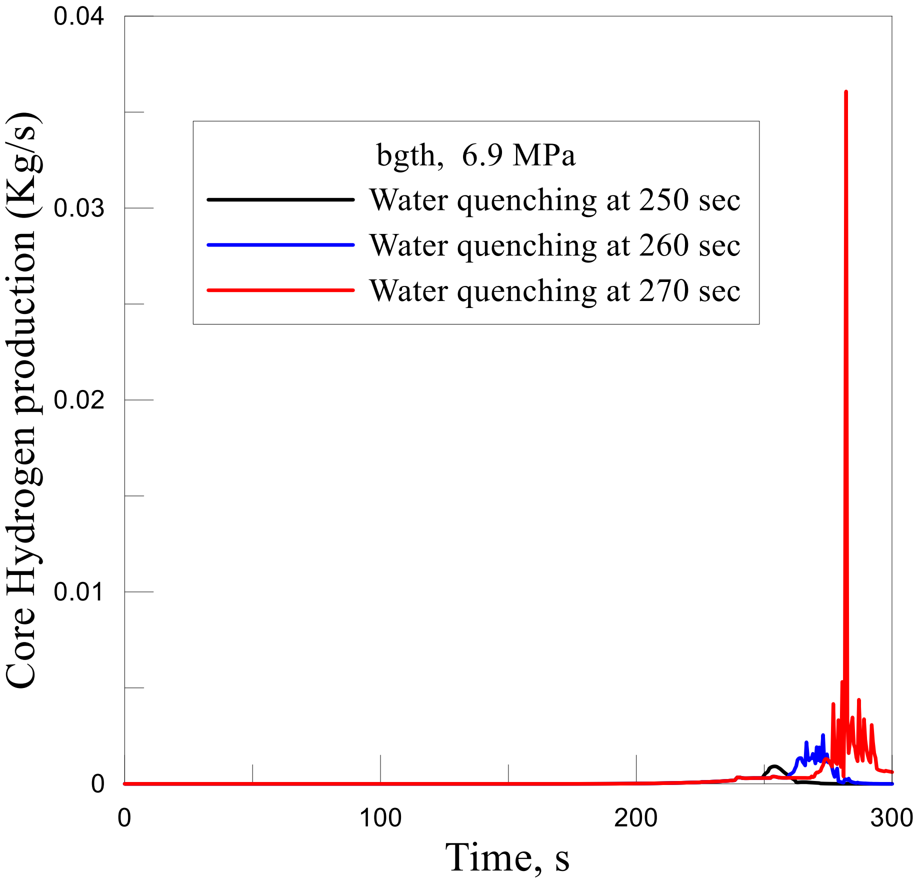
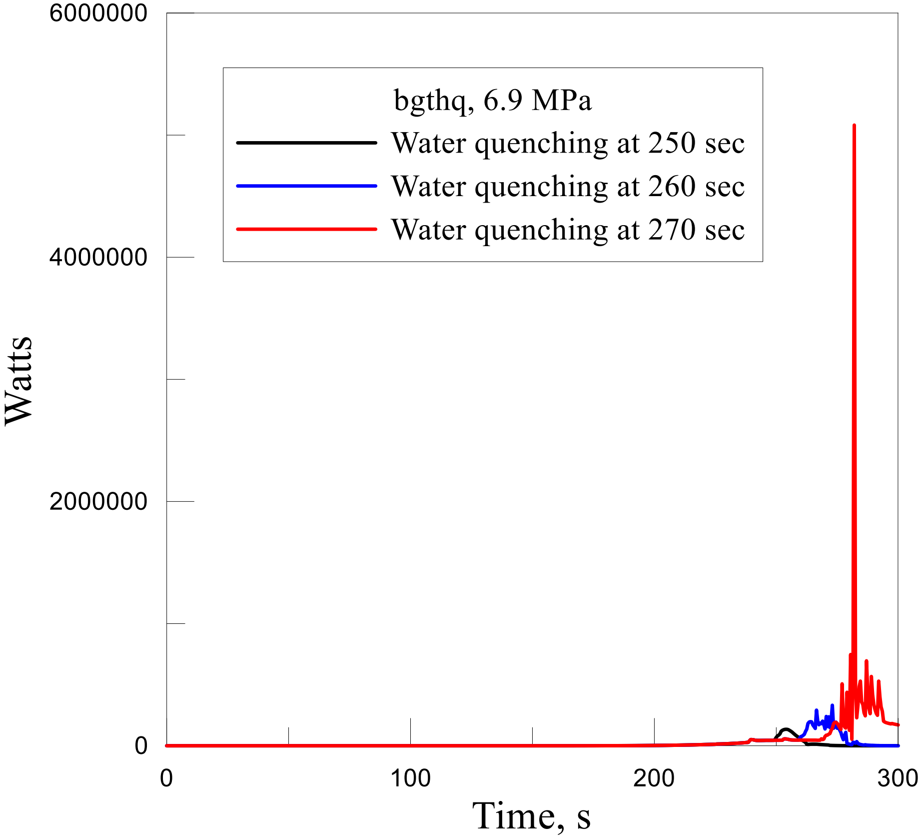
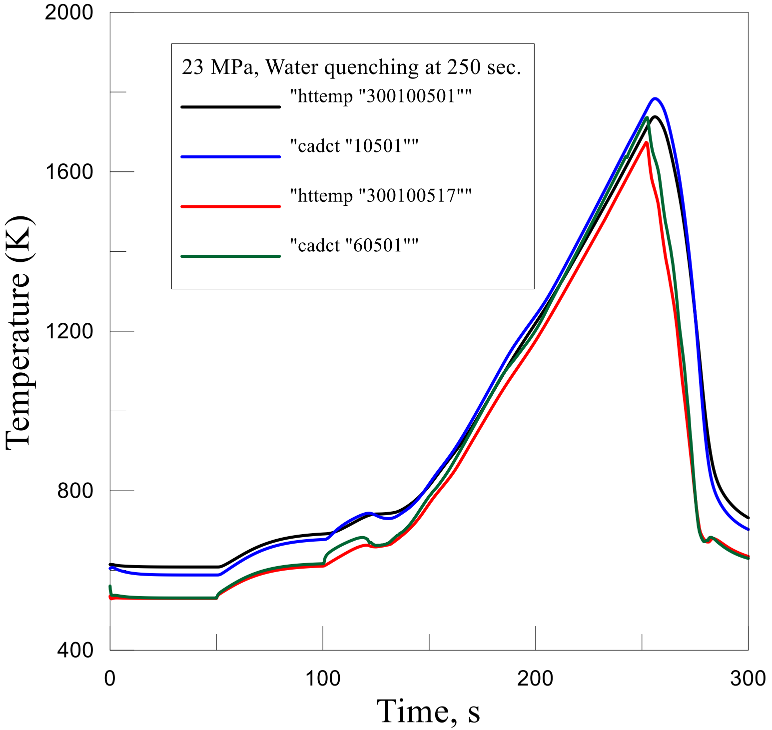
Temperature (K)
4000
3000
2000
1000
0
0
100
200
300
Time, s


bgth, 6.9 MPa
Water quenching at 250 sec
Water quenching at 260 sec
Water quenching at 270 sec
Core Hydrogen production (Kg/s)
0.04
0.03
0.02
0.01
0
0
100
200
300
Time, s


bgthq, 6.9 MPa
Water quenching at 250 sec
Water quenching at 260 sec
Water quenching at 270 sec
Watts
6000000
4000000
2000000
0
0
100
200
300
Time, s


23 MPa, Water quenching at 250 sec.
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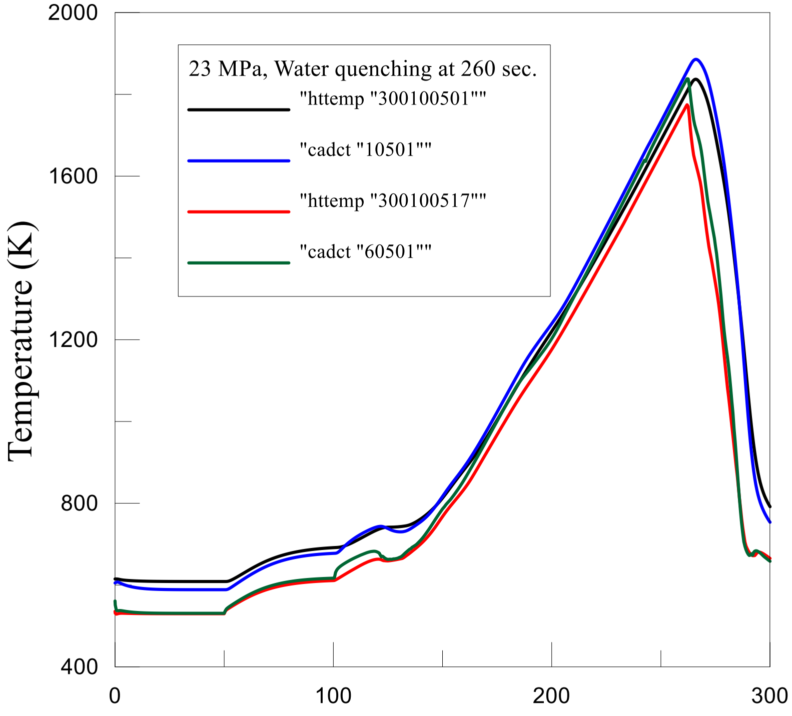
Temperature (K)
Time, s
2000
1600
1200
800
400
0
100
200
300


23 MPa, Water quenching at 260 sec.
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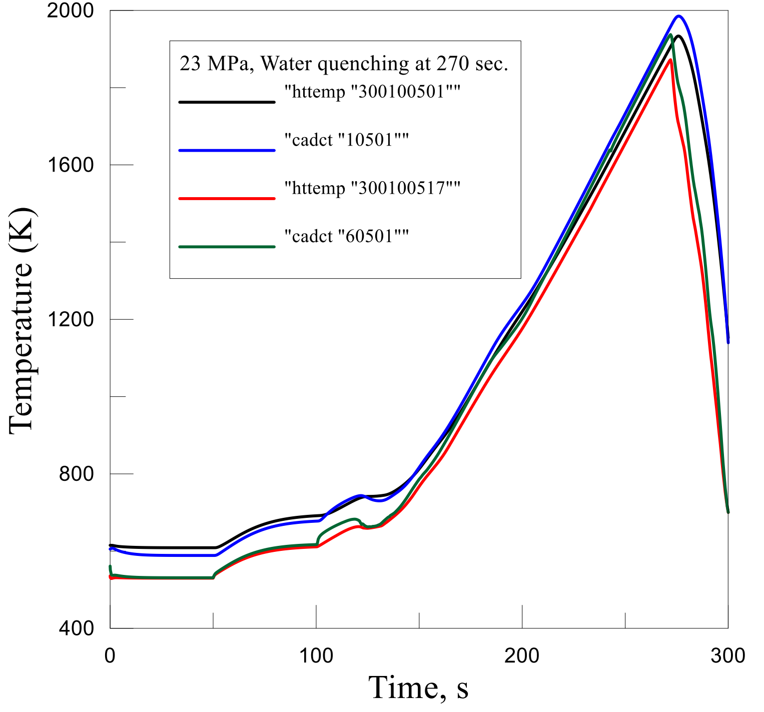
Temperature (K)
Time, s
2000
1600
1200
800
400
0
100
200
300


23 MPa, Water quenching at 270 sec.
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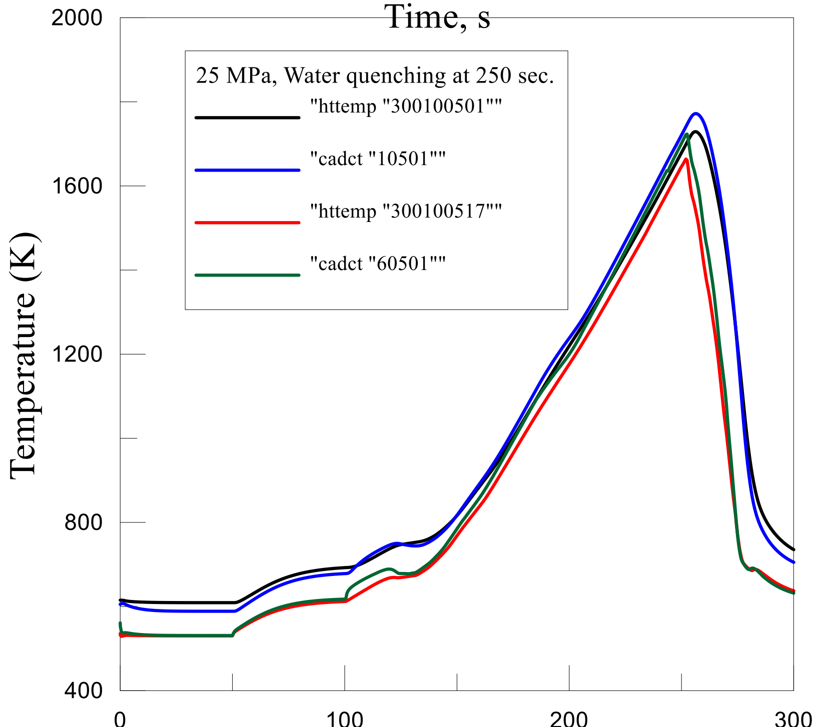
Temperature (K)
Time, s
2000
1600
1200
800
400
0
100
200
300


25 MPa, Water quenching at 250 sec.
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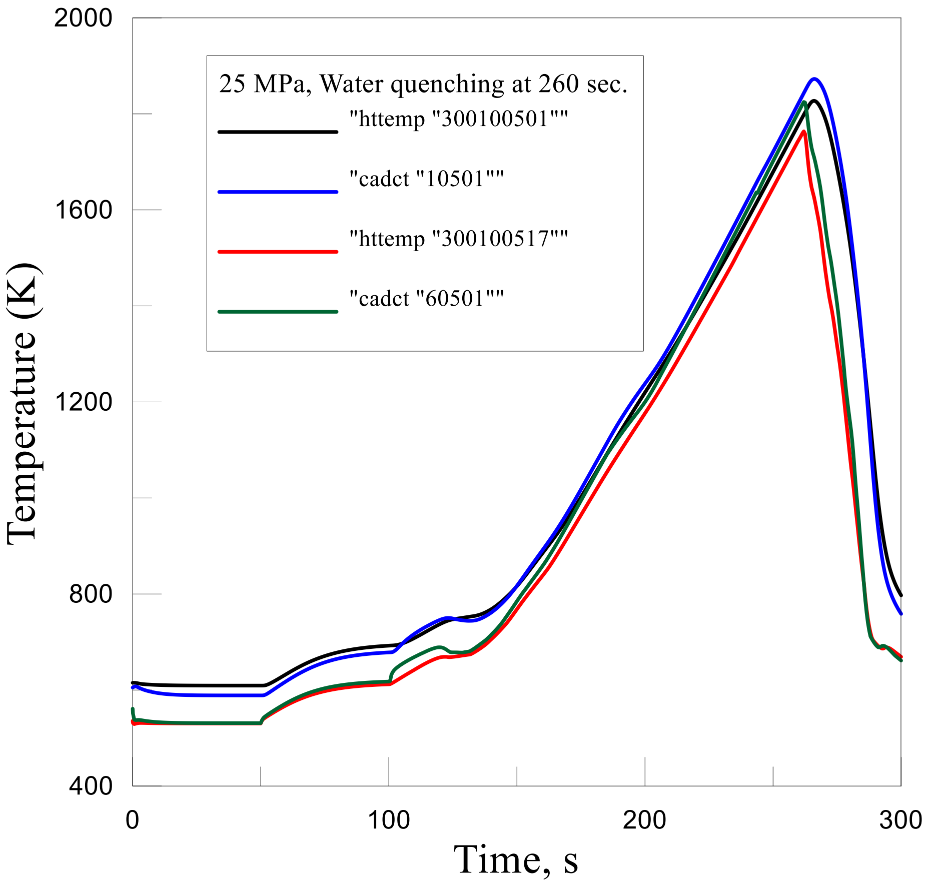
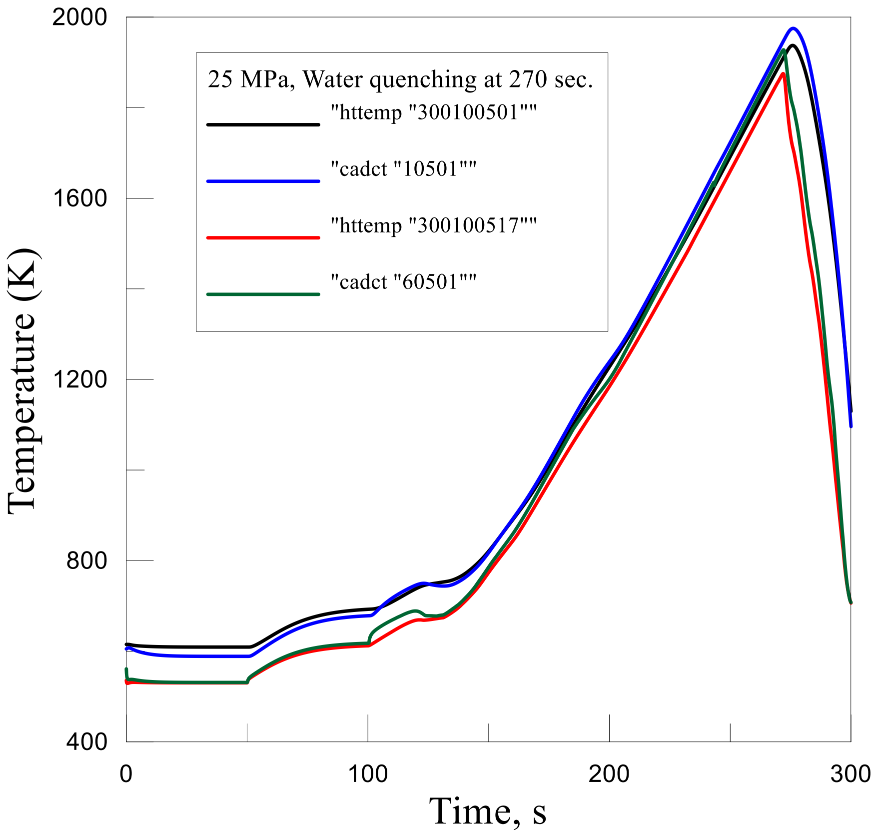
Temperature (K)
2000
1600
1200
800
400
0
100
200
300


25 MPa, Water quenching at 260 sec.
"httemp "300100501""
"cadct "10501""
"httemp "300100517""
"cadct "60501""
Temperature (K)
2000
1600
1200
800
400
0
100
200
300
Time, s


25 MPa, Water quenching at 270 sec.
"httemp "300100501""
"cadct "10501""
"httemp "300100517""
"cadct "60501""
Temperature (K)
2000
1600
1200
800
400
0
100
200
300
Time, s

Fuel bundle maximum temperature as function of quenching time, operating pressure and time of maximum temperature.

Quenching time (sec)	Pressure (MPa)	bgmct (^{0}C)	Time of max. temperature
250	1.9	2151.35	254
260	1.9	2507.49	265.5
270	1.9	2849.02	295
250	3.9	2235.81	255.5
260	3.9	2528	265.5
270	3.9	2762.06	278.5
250	6.9	2459.46	255.5
260	6.9	2625.95	265
270	6.9	3150.38	283
250	15.9	2521.7	252.5
260	15.9	2696.75	262.5

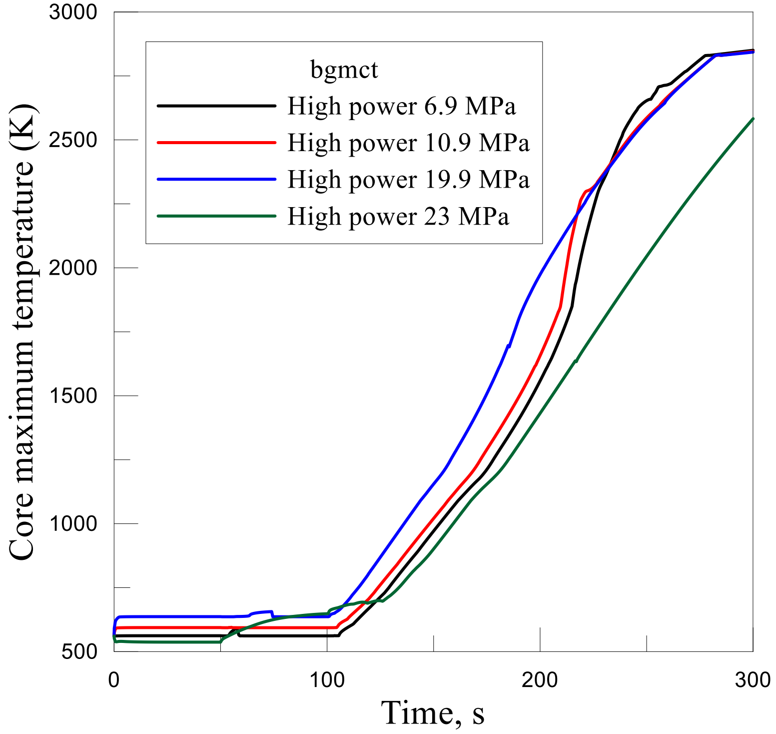
270	15.9	2848.65	273
250	19.9	2607.16	252
260	19.9	2765.65	262
270	19.9	3177.68	287.5
250	23	1735.93	252.5
260	23	1838.17	262
270	23	1937.48	272
250	25	1723.31	252.5
260	25	1824.81	262
270	25	1927.62	272.05

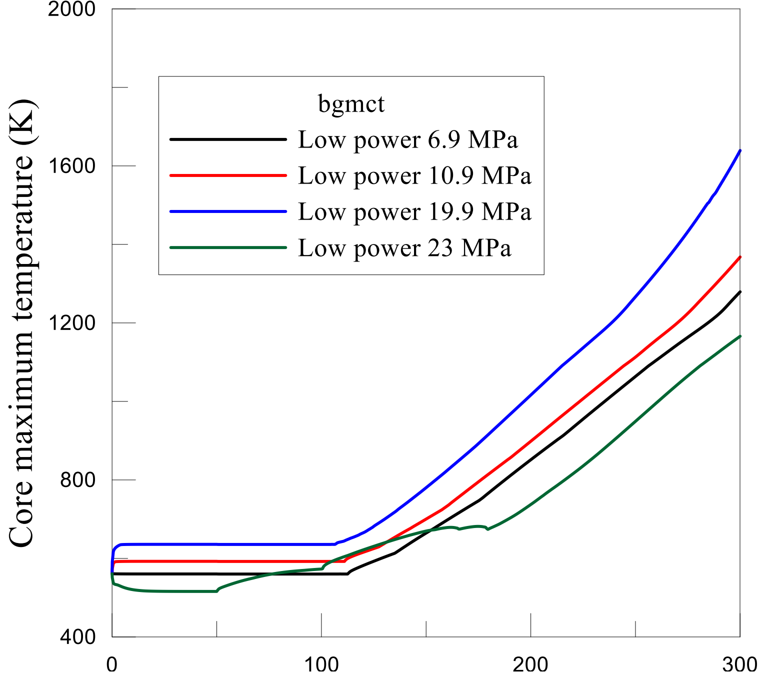
RESULTS and Discussions(cont.)

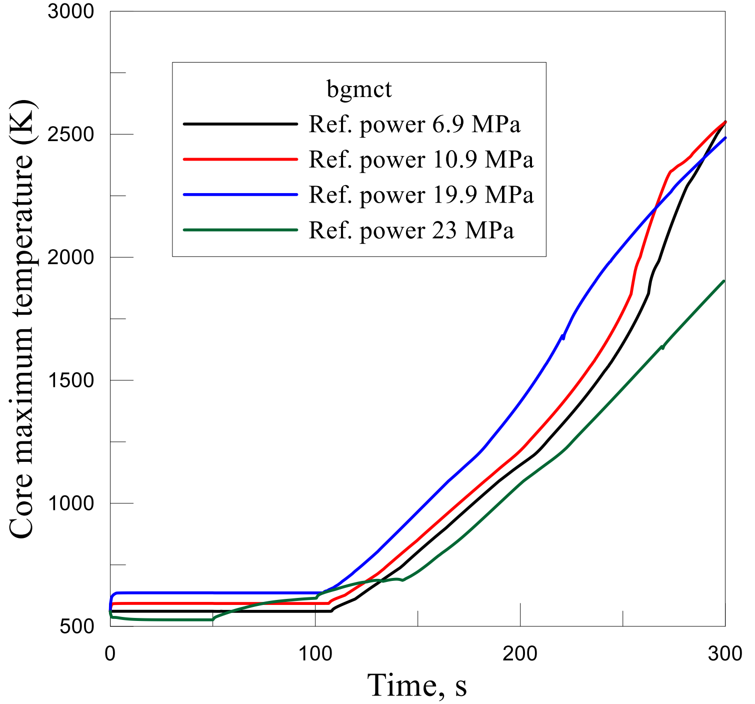
Effect of Decay Heat

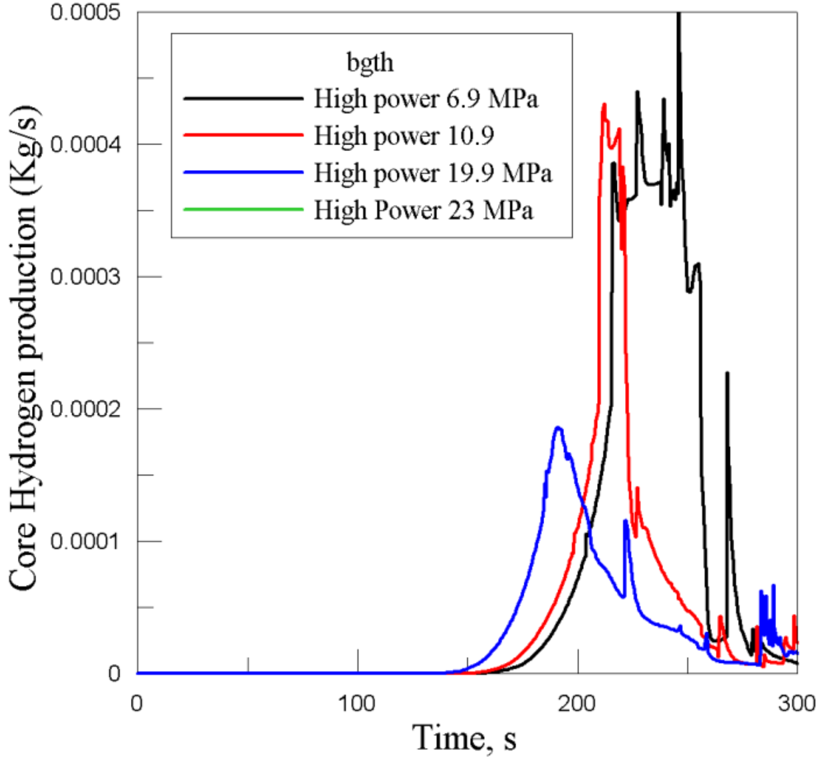
- The decay heat play an important role in nuclear reactor accident scenarios. The bundle under consideration is studied for three different values of decay heat in order to investigate the effect of decay heat values in driving the accident and on the values of hydrogen production.

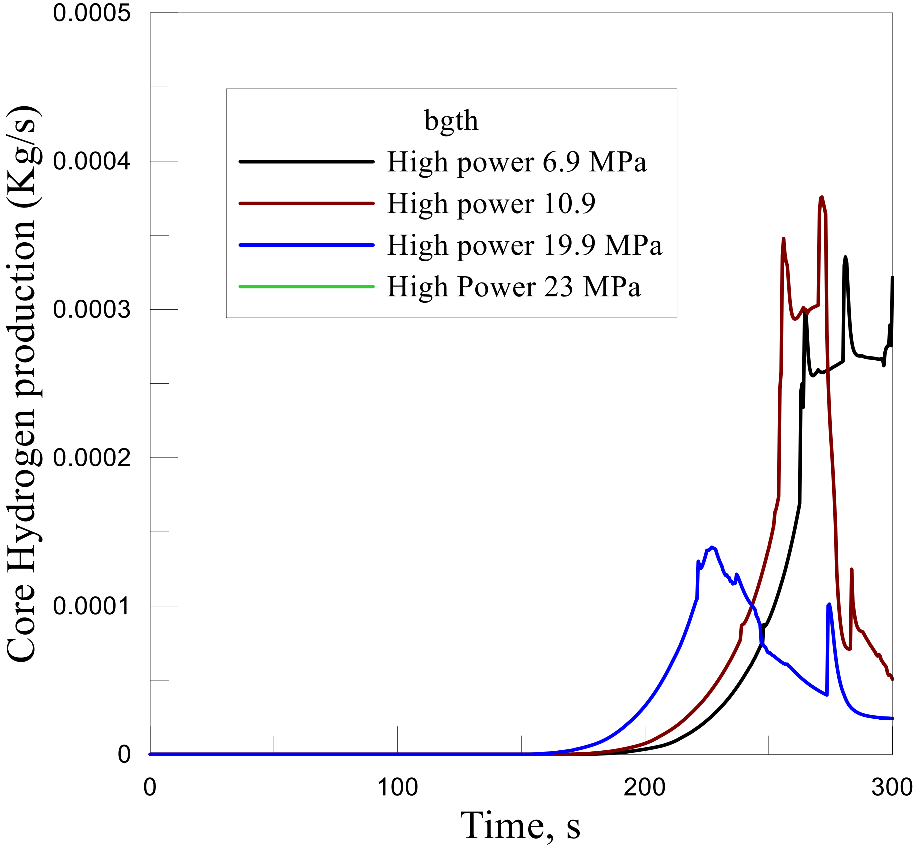
- The low, reference, and high values of heat generation per bundle are 70, 50, and 30 kw per bundle respectively.

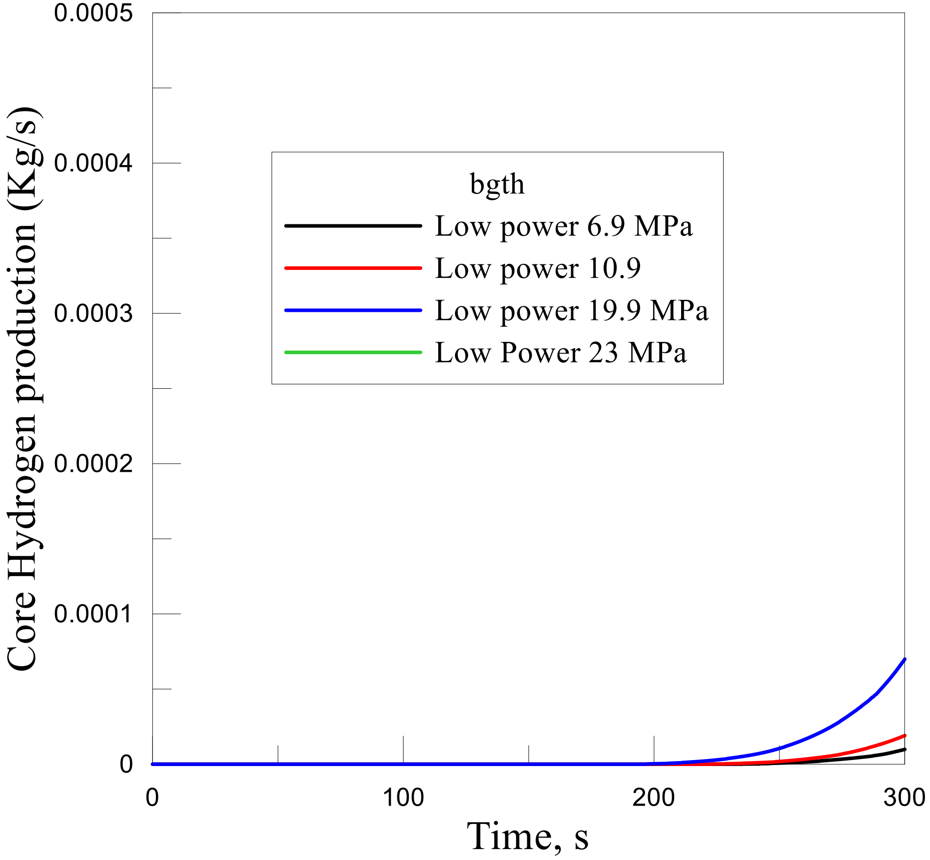

bgmct
High power 6.9 MPa
High power 10.9 MPa
High power 19.9 MPa
High power 23 MPa
Core maximum temperature (K)
3000
2500
2000
1500
1000
500
0
100
200
300
Time, s


bgmct
Low power 6.9 MPa
Low power 10.9 MPa
Low power 19.9 MPa
Low power 23 MPa
Core maximum temperature (K)
2000
1600
1200
800
400
0
100
200
300


bgmct
Ref. power 6.9 MPa
Ref. power 10.9 MPa
Ref. power 19.9 MPa
Ref. power 23 MPa
Core maximum temperature (K)
3000
2500
2000
1500
1000
500
0
100
200
300
Time, s


bgth
High power 6.9 MPa
High power 10.9
High power 19.9 MPa
High Power 23 MPa
Core Hydrogen production (Kg/s)
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
100
200
300
Time, s


0.0005
0.0004
0.0003
0.0002
0.0001
0
Core Hydrogen production (Kg/s)
0
100
200
300
Time, s
bgth
High power 6.9 MPa
High power 10.9
High power 19.9 MPa
High Power 23 MPa


0.0005
0.0004
0.0003
0.0002
0.0001
0
Core Hydrogen production (Kg/s)
0
100
200
300
Time, s
bgth
Low power 6.9 MPa
Low power 10.9
Low power 19.9 MPa
Low Power 23 MPa

Conclusions and Recommendations (cont.)

Principal findings of the present work:

1. A RELAP5 input model is developed to simulate a typical fuel bundle under wide range of operating pressure from 2 up to 25 MPa.
2. Effect of water addition on mitigating loss of bundle cooling is studied at different operating pressures and different simulation times.
3. The bundle under consideration is studied for three different values of decay heat in order to show the effect of decay heat values in driving the accident and on the values of hydrogen production.
4. Hydrogen generation is studied at all pressure ranges. Almost no hydrogen production is associated with supercritical bundle proposed cladding.

Conclusions and Recommendations (cont.)

8. The bundle is heated up and the mass flux is allowed to decrease to study the bundle at severe accident condition. A comparison between RELAP5 and SCDAP in the supercritical ranges of operating pressure shows very good agreement.
9. The present study compares the amount of hydrogen generation associated with different values of decay heat. The amount of hydrogen generation massively increases with increasing the bundle decay heat.

Thank you