NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

FARO TEST L-14 ON FUEL COOLANT INTERACTION AND QUENCHING

Comparison Report, Volume II:
Participants Appendices

OECD/CSNI International Standard Problem 39
OECD/CSNI International Standard Problem 39
on FARO Test L-14 on Fuel Coolant Interaction and Quenching

Comparison Report, Volume II:
Participants Appendices

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Commission of the European Communities
Joint Research Centre
Ispra Site
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meetings.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article I of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all OECD Member countries except New Zealand and Poland. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of the NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;
- assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;
- developing exchanges of scientific and technical information particularly through participation in common services;
- setting up international research and development programmes and joint undertakings.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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A. - COMETA-IKEJET Calculations

A.1 - Participant Identification

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<td>Contact Person(s):</td>
<td>A. Schatz, M. Burger, E. von Berg</td>
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<td>Germany</td>
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<tr>
<td>Fax:</td>
<td>0049-711-685-2010</td>
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<td></td>
<td><a href="mailto:berg@ike.uni-stuttgart.de">berg@ike.uni-stuttgart.de</a></td>
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A.2 - Initial and boundary conditions

Two calculations have been performed with COMETA code:

a) Mandatory calculation with secondary fragmentation of primary drops produced at the jet surface taken into account (break-up criterion: Weber number We=80)

b) Comparison calculation without secondary fragmentation (We=100000)

The initial and boundary conditions valid for both calculations are reported in the following table.

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<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
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</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
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<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
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</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>0.75 *</td>
<td>-0.29</td>
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<tr>
<td><strong>Water in test vessel</strong></td>
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<td>Mass, Kg</td>
<td>623</td>
<td>616</td>
<td>-7</td>
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<td>Depth, m</td>
<td>2.05</td>
<td>2</td>
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<td>Temperature (average), K</td>
<td>536.8</td>
<td>537</td>
<td>+0.2</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>1.09</td>
<td>-0.11</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.792</td>
<td>-0.06</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>100 steam</td>
<td>no Ar</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.254</td>
<td>-0.006</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>537</td>
<td>+1</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

* The reported value was 1 m, but the input deck was initialised with 0.75 m

COMETA IKE-Stuttgart
A.3 - *Code nodalization*

One-dimensional calculations have been performed using the COMETA code developed at JRC Ispra with the IKE fragmentation models included.

The TERMOS vessel and the connected communication line to the separator as well as the separator itself have been divided into 13 slabs with a uniform height of 0.25 cm each. The diameter of slabs 1 to 12 with slab 1 starting at the bottom of the TERMOS vessel has been chosen as 0.71 m. The uppermost 13th slab contains the volumes of the dome, the communication line and the separator. Therefore its diameter has been chosen as 2.09 m.

<table>
<thead>
<tr>
<th></th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
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<td>10</td>
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<tr>
<td></td>
<td>7</td>
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<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

<--- water level
A.4 - Comparison of calculations with the experiment

A.4.1 Base calculation

![Graph of Pressure vs. Time](image1)

**Quantity: 1 - Pressure**

![Graph of Temperature vs. Time](image2)

**Quantity: 2 - Temperature in the steam dome**

COMETA IKE-Stuttgart
Quantity: 3 - Water temperature at 400 mm
Quantities: 4, 5, not present due to 1d calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantities: 7, 8, not present due to 1d calculation
Quantity: 9 - Water temperature at 1200 mm
Quantities: 10,11 not present due to 1d calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>COMETA IKE-Stuttgart (calc. a)</td>
<td>0.363 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>COMETA IKE-Stuttgart (calc. a)</td>
<td>0.825 s</td>
</tr>
</tbody>
</table>
A.4.2 Additional calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

COMETA IKE-Stuttgart
Quantity: 3 - Water temperature at 400 mm

Quantity: 6 - Water temperature at 800 mm, average position

COMETA IKE-Stuttgart
Quantity: 9 - Water temperature at 1200 mm

Quantity: 12 - Mixture level

COMETA IKE-Stuttgart
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: $33.2 \text{ m}^2$
Quantity: 19 - Jet leading edge position versus time
A.5 - Code description or code models/options

The COMETA code developed at JRC Ispra by A. Annuziato and co-workers with additionally included fragmentation models developed at IKE Stuttgart has been used for the calculations.

The standard models for heat transfer and vapor generation implemented in the original version of the code have been used. These are chosen corresponding to the boiling mode established from the heat-transfer-correlation package contained in the code. Under film boiling conditions most relevant to the situation in test L14 radiative heat transfer to the mixture and after sufficient cooling of the fragments also convective heat transfer are decisive. Here the correlation of Bromely-Pommeranz is used for convective heat transfer from the fragments to the mixture.

Fragmentation has been assumed to take place at the jet surface (primary fragmentation). Also the drops produced at the jet surface may further disintegrate while settling to the TERMOS vessel bottom (secondary fragmentation). It is the main objective of the two calculations submitted to reveal the relative importance of these fragmentation mechanisms.

For jet fragmentation wave growth and wave crest stripping along the jet surface has been assumed as decisive mechanism. In contrast to the classical treatment of this instability with the assumption of a jumping condition for the velocities of the jet and its surrounding (Kelvin-Helmholtz instability) the IKE model takes into account effects of the near surface velocity profile (logarithmic profile in turbulent boundary layer, Conte-Miles instability) as well as the surface roughness which is caused by the surface undulation itself (feedback contained). The wavelengths which are able to grow under the respective local conditions along the jet surface are determined. From these the wavelength with maximum growth rate is taken as representative.

This wave is tracked travelling along the surface and growing in amplitude until a stripping criterion for the wave crest is fulfilled. Stripping is assumed to occur when the kinetic energy of wave growth plus the work of friction forces from the ambient flow acting on the crest overcomes the additional surface energy necessary to be provided for the detachment process. The idealised wave crest stripping mechanism produces toroidal fragments, which are assumed to decay into drops of about double the diameter of the toroidal ligaments due to Rayleigh's criterion for varicose break-up. These are regarded as primary fragments.

After crest stripping wave growth starts again. From repeated stripping processes an erosion rate (stripped mass per jet surface and time) is determined. This causes subsequent reduction of the jet diameter finally leading to the formation of a coherent core of molten material surrounded by a cloud of fragments. More details on the model can be found in the papers of M. Buerger et al., e.g., in NE&D 155 (1995) 215-251 and in the proceedings of the 'Multidisciplinary International Seminar on Intense Multiphase Interactions', St. Barbara, CA, June 9-13, 1995.

In this model under the conditions of test L14 vapor film boiling should occur around the penetrating jet. Then the relative velocity between the falling jet and the rising vapor (including boundary layer effects) as well as the density of the ambient medium surrounding the jet are decisive for the fragmentation process. With this respect the following problems occurred when applying the IKE fragmentation model in the frame of the 1d-version of the COMETA code used here:

1) In COMETA averaged properties over the radial co-ordinate are provided instead properties of the vapor film at the jet surface. Thus a simple estimation for the vapor velocity near the jet has been calculated from a balance of kinetic energy and hydrostatic head (see. E. v. Berg et al. in NE&D 149 (1994) 419-429).

2) The effects of particle loading of the vapor film calculated in the IKEJET jet break-up model are not directly applicable at the present state of coupling of IKEJET and COMETA. Therefore
a parametric increase of the vapor density with reference to IKEJET calculations has been used to take into account the effects of particle loading on the instability mechanism.

3) Instead of a continuous jet as in the IKEJET model in COMETA distinct parcels or segments of the jet are released, which are tracked separately until they reach the TERMOG vessel bottom. This in principle allows interpenetration or overtaking of parcels. In the Conte-Miles fragmentation model the length of boundary layer development to be measured from the leading edge also enters the calculation. Therefore the parcel with the lowest height above the bottom has been taken for the leading edge position. Thus the sequence of parcels is treated as a representation of the coherent jet.

For drop fragmentation the original Weber number criterion used in COMETA has been modified. In calculation a) the critical Weber number has been chosen as 80 to match the results of the code with the experimental data. The second calculation b) has been performed with a very high Weber number of 100000 thus suppressing drop fragmentation to reveal the capacity of primary fragmentation alone for explanation of the experimental findings.
A.6 - Code input deck

Input deck for calculation a

ieps<--Identification string for actual calculation (4 characters)----------
0<--ibatch: =1: trigger for batch calculation (online graphics disabled)-
FARO FACILITY 114 input deck
<BASIS>
* tin tfin
-0.1 6.0
*nvol njun nvalues nsla dt frag iplo irestart igraf
5 2 1 1 4 1 1 0 1
* dati deltat
-.1 .105 1.e-8 0.1
.0 .105 1.e-8 0.1
1.00 .105 1.e-8 0.1
6.0 .205 1.e-8 0.1
<VOLUME>
* dati volumi
1 1 0.098975 0.25 0.71 0. 0. 0.25 5.E6 537.0 0.0001 0. 0
2 2 0.098975 0.25 0.71 0. 0. 0.25 5.E6 537.0 0.0001 0. 0
3 8 0.098975 0.25 0.71 0. 0. 0.25 5.E6 537.0 0.0001 0. 0
9 12 0.098975 0.25 0.71 0. 0. 0.25 5.E6 0.0 0.9999 0. 0
13 13 0.860000 0.25 2.09 0. 0. 0.25 5.E6 0.0 0.9999 0. 0
*
<JUNCTIONS>
* dati giunzioni
1 1 101 200 2.E-6 2.E-4 0.3959 0.03
2 12 201 1300 2.E-6 2.E-4 0.3959 0.03
*
<SLABS>
* dati slabs
* a vol vol ds igeom h nzone coefan tsink sn coef ds tsink ds

(sup)
1 13 0 0 1 0.25 2 0. 0. 20. 273.
0.39 0.44 1 5 0 0.
0.44 0.54 3 5 0 0.
*
<VALEVES>
1 1 12 0 0.0012566 24. 200. 1 1.65 1.65 1.0 0.5 1.
1 1 13 0 0.00251 24. 200. 1 1.65 1.65 1.0 0.5 1.
<FRACTION>
* dati frammentazione wo2
* modfrag: 1=COMETA and IKE models, I modtype: 0=L(D)-Correlation
2=Texas model I 1=Kelvin-Heilmholtz
* istrip: 0=Bradley-model I 2=Corona-Miles
* i=IKE-model I 3=fixed values
* ncatch=detajet*akjet*cortot*cormasst*0.40corr*1mtrp*tmeit*nectov* numbjets
4 0.92 1. 125. 125.
*modfrag*modtype*istrip*web+df*frag*mdmst*tpae=tmdo*ef*cline*frile
1 2 1 80. 0.005 10000. 2.9 0 1. 25. 1
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2 4. 0.005 25. 0.1 0.1 0.1 0.05 1.0 1 1 1 0.4
*items*indices*dens0*visc*visc0*icp0*ic0*mpcor*ffrag*fkpr0*xlauf0*vq0
1 0.45 1 7960. 1 5.3d-07 1 565. 1. 1. -0.250 -15.
*frp0*epsf0*p0np*p0*gabul*fch*uig*lbp0*fr0*igfr0*frp0
2 0.8 5. 25d+06 1 1. 0.1 0.1 5.4 5.0 0 0
1 2 3 4 5 6 7 8 9 10 11
*
* texas model data
* 0=discrete particles (all of them will break)
* 1=jet model nbreak
*
0 5 3.e-2
0.15 0.0104
0.136 0.013235
0.043 0.03302
0.093 0.0615
*
< PLOT>
* dati plot on line
*
1 pf108.dat
<
Input deck for calculation b

```plaintext
ispl<---Identification string for actual calculation (4 characters)--------
0  <---ibatch: -1: trigger for batch calculation (online graphics disabled)--
FARO FACILITY 114 input deck
<BASIS>
* tin tfin
-0.1 6.0
*nvol njun nvalves nala dt frag iplo irestart igraf
5 2 1 1 4 1 1 0 1
* dati deltat
-1 .105 1.e-8 0.1
0 . .105 1.e-8 0.1
1.00 . .105 1.e-8 0.1
6.0 . .205 1.e-8 0.1
<VOLUME>
* dati volumi
1 1 0.098975 0.25 0.71 0.0 0.0 0.25 5.e6 537.0 0.00001 0.0
2 2 0.098975 0.25 0.71 0.0 0.0 0.25 5.e6 537.0 0.00001 0.0
3 3 0.098975 0.25 0.71 0.0 0.0 0.25 5.e6 537.0 0.00001 0.0
9 12 0.098975 0.25 0.71 0.0 0.0 0.25 5.e6 537.0 0.00001 0.0
13 13 0.860000 0.25 2.09 0.0 0.0 0.25 5.e6 537.0 0.00001 0.0

<JUNCTIONS>
* dati giunzioni
1 1 101 200 2.5e-6 2.5e-4 0.3959 0.03
2 12 201 1300 2.5e-6 2.5e-4 0.3959 0.03
*
<SLABS>
* dati slabs
* a vol vol ds igeom h nzone coesen tsink sm coef ds tsink ds
(sup)
1 13 0 0 1 0.25 2 0.0 0.0 20. 273.
0.39 0.44 1 5 0 0.
0.44 0.54 3 5 0 0.

<VALUES>
1 12 0 0.0012566 24. 200. 1 1.e5 1.e5 1 0.5 1.
1 13 0 0.00251 24. 200. 1 1.e5 1.e5 1 0.5 1.

<FRAG>
* dati frammentazione uo2
* modfrag: 1=COMETA and IKE models, I =modotype: 0=L(D)-Correlation
2=TEXAS model
* 1=Kelvin-Helmholtz
* istrip: 0=Bradley-model
* 1=IKE-model
* ncatch=djettakjet cutot<cormas*t0cor=tintpc*tmeilt+njetv*numbjets
1 4 0.092 1 1 125. 125. 3073. 0.2850. 11 1
*modfrag=modotype=istrip=webb=dfrag0=dmte0=tpause=imb=fvel=fden=ffilm
1 2 1 10000. .005 10000. 2.9 0 1 25. 1
*vel1j+vel1j+eta0+refix=cdstr+djettakjet=meta=fnonli*ftint=icdsc0=ccddc0
2 4. 0.005 25. 0.1 0.1 0.05 1.0 1 1 0.4
*items=tena=den0=diviso=visc=icpco=ccpco=ffrag=fkpr=xlauff0=vg0
0.45 1 7960. 1 5.3d-07 1 565. 1. 1. -0.250 -15.
*ldf=ib=epsf=polnp=igabul=fcnh=fpil=cigf=fcf0=lflob=lfpio
2 1 0.8 5.d+06 1 0.1 0.1 5.4d 5.d5 0 0
1 2 3 4 5 6 7 8 9 10 11
* texas model data
* 0=discrete particles [all of them will break]
* 1=jet model nhbreak
* 0 5 3.e-2
0.15 0.0104
0.136 0.013235
0.043 0.03302
0.093 0.0615
*

<PLOT>
* dati plot on line
*
1
pf108.dat
<F>
```

COMETE IKE-Stuttgart
A.7 - Participants comments

1) Calculations a) and b) as well as others not presented show that the Weber number criterion for secondary (drop) fragmentation together with the choice of the jet fragmentation model is a very important parameter for matching the code results with experimental data. This indicates that the questions related to fragmentation
   - where it takes place (jet, drops, locus)?
   - by what mechanism?
   - to what extent?
are decisive, but still not answered sufficiently. Here at least partly still rough or parametric models are used questioning the capability for extrapolation of the results to other conditions.

2) In calculation a) drop fragmentation has been adjusted by assuming a critical Weber number determining the stable drop diameter which is finally established. The value of We=80 in connection with the Conte-Miles fragmentation model has been found to give a most reasonable matching to many of the experimental data given for test L14.

In detail this choice causes a good prediction of pressure increase, but an underprediction of the final pressure level (possibly due to neglect of hydrogen?). The temperatures of steam and water (only one calculation for each height due to 1d-modelling) are overpredicted in the time range of temperature rise, but met sufficiently afterwards. The mixture level development is also roughly met, however, with a too steep increase in the transient phase between 0.5 and 2s. The energy released to the mixture reproduces basically the curve derived from experimental data. However, the increase is somewhat too steep and the values reached at the end of the calculation are lower than these from the experiment. Correspondingly the quenching rate is also predicted somewhat too high with its peak occurring too early. The corium fragmented mass is predicted sufficiently, however, the particle sizes are obviously too low. This could be explained by effects of drop coalescence not contained in the model. But it also refers to the large uncertainties still contained in the fragmentation modelling.

3) The effects of neglecting drop fragmentation (also indicating capability of jet fragmentation solely) can be detected from calculation b) as follows:

   - larger underprediction of final pressure level (at 6s)
   - now also underprediction of final temperature levels
   - mixture level development met better (steps in theoretical curve due to high void used as mixture level criterion also reached below)
   - corresponding to temperature development increase of energy release to mixture predicted better, but even stronger underprediction in the final state of the calculation than with drop fragmentation
   - corium fragmented mass not changed
   - higher but still underpredicted particle sizes which now are calculated from jet fragmentation only.

Nevertheless calculation b) indicates that the observed phenomena, e.g., pressure build up, temperature increase, fragmented mass and resulting particle sizes to a considerable amount seem to be determined by the primary jet fragmentation process.
B. - COMETA1D-JRC Calculations

B.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Joint Research Centre, Commission of the European Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>A. Annunziato, C. Addabbo</td>
</tr>
<tr>
<td>Address:</td>
<td>JRC Ispra</td>
</tr>
<tr>
<td></td>
<td>21020 Ispra (VA)</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
</tr>
<tr>
<td>Tel:</td>
<td>+39 (332) 789519 (Annunziato)</td>
</tr>
<tr>
<td></td>
<td>+39 (332) 789812 (Addabbo)</td>
</tr>
<tr>
<td>Fax:</td>
<td>+39 (332) 785584</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:alessandro.annunziato@jrc.it">alessandro.annunziato@jrc.it</a></td>
</tr>
<tr>
<td></td>
<td><a href="mailto:carmelo.addabbo@jrc.it">carmelo.addabbo@jrc.it</a></td>
</tr>
</tbody>
</table>

B.2 - Initial and boundary conditions

One calculation has been performed with the COMETA-1D code.

<table>
<thead>
<tr>
<th>Melt</th>
<th>EXPERIMENT</th>
<th>COMETA-1D</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water in test vessel</th>
<th>EXPERIMENT</th>
<th>COMETA-1D</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>618.7</td>
<td>-4.2</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2</td>
<td>-0.05</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>537.6</td>
<td>-0.8</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>0.8</td>
<td>-0.04</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.792</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas Phase</th>
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<th>COMETA-1D</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>88 steam + 12 Argon</td>
<td>less Argon</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.254</td>
<td>-0.006</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536.6</td>
<td>+0.6</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.04</td>
<td>-0.1</td>
</tr>
</tbody>
</table>
B.3 - Code nodalization

One-dimensional calculations have been performed using the COMETA code.
B.4 - Comparison of calculations with the experiment

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

COMETA-1D JRC
Quantity: 3 - Water temperature at 400 mm
Quantities: 4, 5, not present due to 1d calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantities: 7, 8, not present due to 1d calculation

COMETA-1D JRC
Quantity: 9 - Water temperature at 1200 mm
Quantity: 10,11 not present due to 1d calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m³
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th>Type</th>
<th>COMETA-1D</th>
<th>JRC</th>
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</thead>
<tbody>
<tr>
<td>Experimental</td>
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</tr>
<tr>
<td>COMETA-1D JRC</td>
<td>0.42 s</td>
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</table>

Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th>Type</th>
<th>COMETA-1D</th>
<th>JRC</th>
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</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
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</tr>
<tr>
<td>COMETA-1D JRC</td>
<td>0.92 s</td>
<td></td>
</tr>
</tbody>
</table>
B.5 - Code description or code models/options

The COMETA (Core Melt Thermal-Hydraulic Analysis) [1] code is a coupled thermal-hydraulic and fuel fragmentation code conceived for the simulation of fuel coolant interaction and quenching as represented in the FARO test facility; it has been specifically developed to provide a computational tool for test design and specification, definition of operational procedures and test results analysis. COMETA is composed of a two-phase flow field, which is described by 6+n equations (mass, momentum and energy for each phase and n mass conservation equations for n non-condensable gases) and a corium field with 3 phases: the jet, the droplets and the debris. The two-phase field is described in Eulerian while the corium field in Lagrangian co-ordinates.

The two-phase flow field is organised in a number of lumped volumes connected with junctions. A 2D nodalization can be built connecting a number of macro-volumes (containing an arbitrary number of radial and axial volumes) with macro-junctions. In addition valves, separators, pumps, accumulators and other thermal-hydraulic components can be defined in order to fully represent the FARO test facility.

In the melt field three phases are assumed: the jet, the drops and the fused debris bed. The fuel is released in the form of a coherent jet which is conical shaped with a wavy and rough surface. Three models for jet fragmentation and fragments creation are included: the original COMETA model, based on the Jet Break-up Length concept (L/D evaluated at each position at each time step, giving the local erosion rate); the Corradini-Tang model, similar to the model present in the TEXAS code [2]; the IKEJET model [3], developed by the University of Stuttgart. The calculations presented here are all performed with the original COMETA jet fragmentation model, which has been validated against the available FARO tests.

The use of COMETA code at JRC suggested the importance of the modelling of H₂ generation. In order to correctly represent the energy, temperature and pressure behaviour the generation of non-condensable gases has to be accounted for.

Particular coefficients and correlations adopted for the COMETA calculations are here listed:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drops diameter coefficient</td>
<td>8 (Web crit=96)</td>
</tr>
<tr>
<td>Jet Break-up length coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Maximum allowed H₂ mass generation</td>
<td>2.10³ kg of H₂ per kg of fragmented corium</td>
</tr>
<tr>
<td>Kinetic model for H₂ generation</td>
<td>SCDAP model [4]</td>
</tr>
</tbody>
</table>


COMETA-1D JRC
### B.6 - Code input deck

FARO FACILITY Post Test of L-14 Test

```plaintext
<BASIS>
-1 10.
*nv nj nval nsla 6 dt frag plo rest
 9 10 0 6 4 1 1 0 1
*
* dati deltat
*
0.4 .1 1.e-8 0.05
1.0 .1 1.e-9 0.05
10. 0.1 1.e-8 0.05
132. 0.1 1.e-8 0.25
*

<VOLUME>
* dati volumi
*
1 1 0.098975 0.25 .71 0. 0. +0.25 50.4e5 0. 0.0 0. 0.
1 2 8 0.098975 0.25 .71 0. 0. +0.25 50.4e5 0. 0.0 0. 0.
1 9 12 0.098975 0.25 .71 0. 0. +0.25 50.4e5 0. 1.0 0 2.e5
1 13 14 0.12508 0.41 .623 0. 0. +0.41 50.4e5 0. 1.0 0 2.e5
1 15 15 0.252692 0.304 .623 0. 0. +0.304 50.4e5 0. 1.0 0 2.e5
1 16 16 0.0553 3.38 .144 0. 0. 0. 50.4e5 0. 1.0 0 2.e5
1 17 17 0.0429 2.62 .144 0. 0. -2.62 50.4e5 0. 1.0 0 2.e5
1 18 20 0.08591 0.475 .4798 0. 0. +0.475 50.4e5 0. 1.0 0 2.e5
1 19 21 0.08591 0.475 .4798 0. 0. +0.475 50.4e5 0. 1.0 0 2.e5
1
*

<JUNCTIONS>
* dati giunzioni
*
1 11 101 1200 0.E-6 0.E-4 0.3959 0.0
12 12 1201 1300 0.E-6 0.E-4 0.3051 0.5
13 13 1301 1400 0.E-6 0.E-4 0.3051 0.0
14 14 1401 1500 0.E-6 0.E-4 0.3051 0.0
15 15 1401 1600 0.E-6 0.E-4 0.01637 0.0
16 16 1601 1700 0.E-6 0.E-4 0.01637 0.0
17 17 1701 1901 0.E-6 0.E-4 0.01637 0.0
18 18 1801 1900 0.E-6 0.E-4 0.1874 0.0
*
* separator junction *
* - qui sotto *
*19 19 1901 2000 0.E-6 0.E-4 -0.1874 0.0
19 19 1901 2000 0.E-6 0.E-4 0.1874 0.0
20 20 2001 2100 0.E-6 0.E-4 0.1874 0.0
*20 20 2001 2100 0.E-6 0.E-4 -0.1874 0.0
*
*21 21 2101 2200 0.E-6 0.E-4 1.44e-3 1.5
*22 22 2201 2300 0.E-6 0.E-4 1.44e-3 0.0
*
*23 23 2101 2400 0.E-6 0.E-4 1.44e-3 1.5
*24 24 2401 2500 0.E-6 0.E-4 1.44e-3 0.0
*
*25 25 2101 2600 0.E-6 0.E-4 1.44e-3 1.5
*26 26 2601 2700 0.E-6 0.E-4 1.44e-3 0.0
*
*27 27 2101 2800 0.E-6 0.E-4 1.44e-3 1.5
*28 28 2801 2900 0.E-6 0.E-4 1.44e-3 0.0
*
```

COMETA-1D JRC
<SLABS>
* dati slabs
  1 12 0 0 1 0.25 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0. 0.44 0.54 3 5 0 0.
  13 14 0 0 1 0.41 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0. 0.44 0.54 3 5 0 0.
  15 16 0 0 1 0.304 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0. 0.44 0.54 3 5 0 0.
* disch line heat structure isolated
  16 16 0 0 1 3.38 1 0. 0. 0. 0.
  0.0721 0.091 1 5 0 0. 0.0721 0.091 1 5 0 0.
* separator structures
  18 21 0 0 1 0.475 1 0. 0. 0. 0.
  0.25 0.29 1 5 0 0.
*

<FRAGM>
* dati framentazione uo2
*nv catch  djet  kjet  muo2  tuo2  vl  vf  tinj
  4  0.092  1.  125.  125.  3073.  0.  2830.  2860.  12 1 -7 0.0 0.
  1 1. 1 2.e-3 0. 0. 200.e5
  1 2 3 4 5 6 7 8 9 10 11 12
  0.17 0.0019163
  0.16 0.00958
  0.09 0.009425
  0.45 0.08295
* nuovo melt catcher

<PLOT>
*
* dati plot on line
*

1
pt05114.dat

<F>

QT2 in 2D

<RESTART>
  0 0 -.50 100. 3 0 1
  1.0 .05 1.e-4 0.05
  2.5 .1 1.e-8 0.05
  5555. .05 5.e-8 0.2

<PLOT>
* dati plot on line
*

1
pbct.dat
*

<F>
B.7 - Participants comments

The pressure is slightly overpredicted and the rising ramp starts earlier than in the experiment, but the overall trend is well predicted.

The temperature in the steam dome is underpredicted in the COMETA calculation, probably due to \( \text{H}_2 \) distribution not correctly predicted. At least in the location where the temperature is measured the concentration is smaller. The saturation temperature in the experiment is shown in the same figure. In the calculation the saturation temperature is higher than in the experiment (the pressure is higher) and this means that in the calculation the non-condensable concentration is higher than in the experiment.

The water temperature can only be compared with the average of the experimental data. The rising time and the rising gradient is well predicted but the final temperature is overpredicted in the calculations.

The mixture level is overpredicted. But it should be noted that this is measured on the side of the section. This means that the average water level could be higher than the value measured.

The total energy agrees quite well with the calculated value. In the vapor energy the evaporation is included. The quenching rate is also well predicted by the calculation.

The experimental value for this quantity is 105 kg. The value found at the end of the calculation is 95 kg, which is not very different from the actual value.

The 50% fragment diameter is 4.4 mm, that is quite close to the experimental value (4.8 mm). The form of the curve is however very different. In particular in the calculation the distribution is much narrower than in the experiment.

The maximum value of the heat transfer area is 17.5 m\(^2\) while the final value is 7.5 m\(^2\). The final value is not to be compared with the experiment since it is an ‘effective’ surface area. It takes into account the fact that more particles close one each other do not exchange as the whole surface is exposed to the water.
C. - COMETA2D-JRC Calculations

C.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Joint Research Centre, Commission of the European Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>A. Annunziato, C. Addabbo</td>
</tr>
<tr>
<td>Address:</td>
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<td>Italy</td>
</tr>
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<td>+39 (332) 789519 (Annunziato)</td>
</tr>
<tr>
<td></td>
<td>+39 (332) 789812 (Addabbo)</td>
</tr>
<tr>
<td>Fax:</td>
<td>+39 (332) 785584</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:alessandro.annunziato@jrc.it">alessandro.annunziato@jrc.it</a></td>
</tr>
<tr>
<td></td>
<td><a href="mailto:carmelo.addabbo@jrc.it">carmelo.addabbo@jrc.it</a></td>
</tr>
</tbody>
</table>

C.2 - Initial and boundary conditions

One calculation has been performed with the COMETA-2D code.

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>COMETA-2d</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1</td>
</tr>
</tbody>
</table>

**Water in test vessel**

| Mass, Kg   | 623       | 619.5      | -3.5 |
| Depth, m   | 2.05      | 2          | -0.05 |
| Temperature (average), K | 536.8 | 537.6 | -0.8 |
| Subcooling at melt contact, °C | 1.2 | 0.8 | -0.04 |
| Fuel to coolant mass ratio | 0.20 | 0.20 | - |
| Total water volume, m³ | 0.798 | 0.792 | -0.06 |

**Gas Phase**

| Composition, w% | 77 steam + 23 Argon | 88 steam + 12 Argon | less Argon |
| Volume, m³ | 1.26 | 1.254 | -0.006 |
| Temperature, K | 536 | 536.6 | +0.6 |
| Pressure, MPa | 5.1 | 5.04 | -0.1 |
C.3 - Code nodalization

Two-dimensional calculations have been performed using the COMETA code.

5 radial rings and 15 axial rings were modelled for the main vessel. The connecting line and the separator were modelled separately.

It should be noted that the radial ring size is reducing going to the external section in order to keep the flow area constant.
C.4 - Comparison of calculations with the experiment

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

COMETA-2D JRC
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position

COMETA-2D JRC
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level

COMETA-2D JRC
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

Experimental: 0.45 s
COMETA-2D JRC: 0.41 s

Quantity: 21 - Melt/Bottom contact

Experimental: 0.87 s
COMETA-2D JRC: 0.90 s
C.5 - Code description or code models/options

The COMETA (Core Melt Thermal-Hydraulic Analysis) [1] code is a coupled thermalhydraulic and fuel fragmentation code conceived for the simulation of fuel coolant interaction and quenching as represented in the FARO test facility; it has been specifically developed to provide a computational tool for test design and specification, definition of operational procedures and test results analysis. COMETA is composed of a two-phase flow field, which is described by 6+n equations (mass, momentum and energy for each phase and n mass conservation equations for n non-condensable gases) and a corium field with 3 phases: the jet, the droplets and the debris. The two-phase field is described in Eulerian while the corium field in Lagrangian co-ordinates.

The two-phase flow field is organised in a number of lumped volumes connected with junctions. A 2d nodalization can be built connecting a number of macro-volumes (containing an arbitrary number of radial and axial volumes) with macro-junctions. In addition valves, separators, pumps, accumulators and other thermal-hydraulic components can be defined in order to fully represent the FARO test facility.

In the melt field three phases are assumed: the jet, the drops and the fused debris bed. The fuel is released in the form of a coherent jet which is conical shaped with a wavy and rough surface. Three models for jet fragmentation and fragments creation are included: the original COMETA model, based on the Jet Break-up Length concept (L/D evaluated at each position at each time step, giving the local erosion rate); the Corradini-Tang model, similar to the model present in the TEXAS code [2]; the IKEJET model [3], developed by the University of Stuttgart. The calculations presented here are all performed with the original COMETA jet fragmentation model, which has been validated against the available FARO tests.

The use of COMETA code at JRC suggested the importance of the modelling of H₂ generation. In order to correctly represent the energy, temperature and pressure behaviour the generation of non-condensable gases has to be accounted for.

Particular coefficients and correlations adopted for the COMETA calculations are here listed:

- Drops diameter coefficient: 8 (Web crit=96)
- Jet Break-up length coefficient: 1
- Maximum allowed H₂ mass generation: 2.10⁻³ kg of H₂ per kg of fragmented corium
- Kinetic model for H₂ generation: SCDAP model [4]


COMETA-2D JRC
### C.6 - Code input deck

```
FARO FACILITY  Base Case test 150 kg - 2D nodalization
<BASIS>
  -.0  6.
  *nv   nj   nval  nsla  dt  frag  plo  rest
  5      5       4     3     6    1    1     0     0
  *
  * dati deltat
  *
  -1.0  0.001  1.e-8  0.0002
  .01  0.01  1.e-8  0.02
  0.9  .01  1.e-8  0.05
  0.99  .01  1.e-8  0.05
  1.1  0.001  1.e-8  0.0002
  4.  0.01  1.e-8  0.05
  *
<VOLUME>
  *
  * dati volumi
  *
  * Top volume (ex 15)
  1  1  0.092692  0.304 .623  0.  0.3115  +0.304  50.4e5  0 .99999  0  2.0e5  1
  * line volumes (ex 16 17)
  2  2  0.0553  3.38 .144  0.  0.072  0.  50.4e5  0 .1.  0  2.0e5  1
  3  3  0.0429  2.62 .144  0.  0.072  -2.62  50.4e5  0  1.0  0  2.0e5  1
  * separator volumes (ex 18-21)
  4  6  0.08591  0.475 .4798  0.  0.2399  +0.475  50.4e5  0  1.  0  2.0e5  1
  7  7  0.08591  0.475 .4798  0.  0.2399  +0.475  50.4e5  0  1.  0  2.0e5  1
  *
<JUNCTIONS>
  *
  * dati giunzioni
  *
  1  1  7701  200  0.E-6  0.E-4  0.01637  0.0
  2  2  201  300  0.E-6  0.E-4  0.01637  0.0
  3  3  301  501  0.E-6  0.E-4  0.01637  0.0
  4  6  401  700  0.E-6  0.E-4  0.1874  0.0
  7  7  7501  100  0.E-6  0.E-4  0.01637  0.0
  *
<MACROVOLUME> - TERMS Vessel Lower part
  12  5  1.1877  3.  0.71  3.  50.4e5  0.  0.  0.2  2  1  1.  8.
  0.  0.1  0.05
  *
  1  50.4e5  0.  0.  0  1
  2  50.4e5  0.  0.  0  1
  3  50.4e5  0.  0.  0  1
  4  50.4e5  0.  0.  0  1
  5  50.4e5  0.  0.  0  1
  6  50.4e5  0.  0.  0  1
  7  50.4e5  0.  0.  0  1
  8  50.4e5  0.  0.  0  1
  9  50.4e5  0.  1.  2.e5 1
  10 50.4e5  0.  1.  2.e5 1
  11 50.4e5  0.  1.  2.e5 1
  12 50.4e5  0.  1.  2.e5 1
  *
<MACROVOLUME> - TERMS Vessel Upper part
  2  5  0.25016  0.82  0.623  0.82  50.4e5  0.  1.  0  2.0e5  2  1  1
  0.  0.1  0.05
  *
<MACROJUN>
-101  -200  0.  0.1  0.05
<VALVES>
  *
  * dati valvole
  *
  * jv  ivol  iout  aval  trip  isetval  setopen  setclose
  *
  l= sempre  xout=1
  0= sempre  xout=ivol
  * l=pressure  1=pressione
  2=temper.
  1=7  0  8.04e-4  0.  200.  4  88.e5  78.e5  2  6.  20.
  2  7  0  8.04e-4  0.  200.  4  89.e5  71.e5  2  6.  20.
  3  7  0  8.04e-4  0.  200.  4  97.e5  73.e5  2  4.  20.
  4  7  0  8.04e-4  100. 200.  4  198.e5  73.e5  2  5.  90.
```

COMETA-2D JRC
```
* dati slabs
  -1 -1 0 0 1 0.25 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0.
  0.44 0.54 3 5 0 0.
  -2 -2 0 0 1 0.41 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0.
  0.44 0.54 3 5 0 0.
  01 01 0 0 1 0.304 2 0. 0. 20. 273.
  0.39 0.44 1 5 0 0.
  0.44 0.54 3 5 0 0.

* disch line heat structure isolated
  2 2 0 0 1 3.38 1 0. 0. 0. 0.
  0.0721 0.091 1 5 0 0.
  3 3 0 0 1 2.62 1 0. 0. 0. 0.
  0.0721 0.091 1 5 0 0.

* separator structures
  4 7 0 0 1 0.475 1 0. 0. 0. 0.
  0.25 0.29 1 5 0 0.

* vol type triptime-on triptime-off npoints
  8 1 1 1.0 100. 5 1
  0. 0. 1.e5 293. 1. 1.e5
  1.0000 0. 1.e5 293. 1. 1.e5
  1.0001 50. 1.e5 293. 1. 1.e5
  1.0005 0. 1.e5 293. 1. 1.e5
  100. 0. 1.e5 293. 1. 1.e5

* dati frammentazione uo2
  *nv catch djet kjet muo2 tuo2 v1 vf tinj vol jet Zr coef imod dia jet
  4 0.092 1. 125. 125. 3073. 0. 2830. 2860. 12 1 -7 .0 0.

1
8. 1. 1 2.e-3 0. 0. 150.e5
9 9 10 11 12 13 14 15 16 17 18 19
0.17 0.0019163
0.16 0.00958
0.09 0.009425
0.45 0.089295

* nuovo melt catcher

* dati plot on line

1
pt05114.dat

COMETA-2D JRC
C.7 - *Participants comments*

The pressure is slightly higher than the experiment in the interaction phase. The form of the curve is however well reproducing the experimental one.

The steam temperature is well reproduced in the calculation. It is also possible to note the water arrival with fast temperature decrease as in the experiment.

Very good prediction of the water temperature at all levels and radial positions.

The mixture level is very close to the experimental value. It is also possible to note after 2.8 s the level reductions present also in the experiment.

The energy is very close to the experiment. At some locations it is even superimposed.

Since the energy is well reproduced also the quenching rate is particularly good.

The experimental value for this quantity is 105 kg. The value found at the end of the calculation is 108 kg, which is very close to the experiment.

The 50% fragment diameter is 4.5 mm, that is quite close to the experimental value (4.8 mm). The form of the curve is however very different. In particular in the calculation the distribution is much narrower than in the experiment.

The heat transfer surface is here indicated. The maximum value is 16 m$^2$ while the final value is 7 m$^2$. The final value is not to be compared with the experiment since it is an ‘effective’ surface area. It takes into account the fact that more particles close one each other do not exchange as the whole surface is exposed to the water.
D. - IFCI-ENEA Calculations

D.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>ENEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>G. Colombo</td>
</tr>
<tr>
<td>Address:</td>
<td>ENEA</td>
</tr>
<tr>
<td></td>
<td>ERG-FISS-TASCO</td>
</tr>
<tr>
<td></td>
<td>Via E. Fermi</td>
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<tr>
<td></td>
<td>21020 Ispra (VA)</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
</tr>
<tr>
<td>Tel:</td>
<td>0039-332-788252</td>
</tr>
<tr>
<td>Fax:</td>
<td>0039-332-788207</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:colombo@eis410.ispra.enea.it">colombo@eis410.ispra.enea.it</a></td>
</tr>
</tbody>
</table>

D.2 - Initial and boundary conditions

A total number of two calculations performed with IFCI code version 6.0a have been submitted: calculation n. 1 with the corium physical properties as required and calculation n. 2 with the corium physical properties from MATPRO.

The initial and boundary conditions valid for both calculations are reported in the following table.

Initial and boundary conditions valid for calculation 1

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>124</td>
<td>-1</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1</td>
<td>+0.008</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.035</td>
<td>-0.005</td>
</tr>
</tbody>
</table>

**Water in test vessel**

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>635</td>
<td>+12</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536.8</td>
<td>-</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>3.45</td>
<td>+1.25</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.812</td>
<td>+0.014</td>
</tr>
</tbody>
</table>

**Gas Phase**

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>98.3 steam + 1.7 H₂ *</td>
<td>H₂ instead of Ar</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.243</td>
<td></td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536</td>
<td>-</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>

IFCI ENEA
Initial and boundary conditions valid for calculation 2

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td></td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1</td>
<td>+0.008</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.035</td>
<td>-0.005</td>
</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>635</td>
<td>+12</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536.8</td>
<td>-</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.812</td>
<td>+0.014</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>98.3 steam + 1.7 H₂ *</td>
<td></td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.243</td>
<td>-0.017</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536</td>
<td>-</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>

* corresponding to 7 bar H₂ partial pressure
D.3 - Code nodalization

The nodalization chosen has 7 radial rings and 25 axial meshes. The dimension of the bottom mesh is determined to be nearly filled by the melt in order to have the decreasing of the corium-water thermal exchange when the melt is on the bottom of the vessel.

The release vessel is simulated by very high friction factors on the surfaces of the corresponding cells and it has a cylindrical shape with 0.2 m of diameter, a delivery diameter of 0.1 m and a height of 0.7 m.

The melt height is 0.58 m, corresponding to 145 kg because during the releasing about 20 kg of melt are not released.

With this configuration the maximum released melt velocity (2.7 m/s) is lower than the required one (3.1), but it is determined by the code.

The separator is considered dividing the total volume in two parts using the friction factors.
D.4 - Comparison of calculations with the experiment

D.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

IFCI ENEA
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position

IFCI ENEA
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level

IFCI ENEA
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate

Quantity: 16, not present due to fragmentation model with initial melt diameter of 0.01 m
Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

Quantity: 19 - Jet leading edge position versus time
Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>IFCI ENEA (calc. 1)</td>
<td>0.21 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>IFCI ENEA (calc. 1)</td>
<td>0.83 s</td>
</tr>
</tbody>
</table>
D.4.2 Additional calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

IFCI ENEA
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position

IFCI ENEA
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level

IFCI ENEA
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate

IFCI ENEA
Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

Quantity: 19 - Jet leading edge position versus time
### Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45</td>
</tr>
<tr>
<td>IFCI ENEA (calc. 2)</td>
<td>s</td>
</tr>
</tbody>
</table>

### Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87</td>
</tr>
<tr>
<td>IFCI ENEA (calc. 2)</td>
<td>s</td>
</tr>
</tbody>
</table>
D.5 - Code description or code models/options

The calculations presented are made with IFCI code (Integrated Fuel Coolant Interaction) version 6.0a.

The code has a radial symmetry and are defined three fields:
- field 1 vapor
- field 2 water
- field 3 corium

It is possible to add Hydrogen as non-condensable gas, and in the present calculations Hydrogen is used, instead of Argon, with partial pressure of 7 bar.

It is also possible to model external and internal structures, then the external vessel is included in the calculations.

Module structures activated for the simulation of external vessel.
Release vessel simulated with the friction factors between cells.
Fragmentation model activated but with initial melt diameter of 0.01 m.
Oxidation model not activated.
The corium properties are defined in the subroutine MATPRO; in the standard version the code does not use the real solidus liquidus temperatures, then was necessary to modify the subroutine to insert for the first run the properties required and for the second run to insert the liquidus solidus temperatures from the phase diagram found on the library MATPRO.

<table>
<thead>
<tr>
<th>MELT PHYSICAL PROPERTIES</th>
<th>run 1</th>
<th>run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat J/kg K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>565</td>
<td>565</td>
</tr>
<tr>
<td>solid</td>
<td>445</td>
<td></td>
</tr>
<tr>
<td>Fusion heat J/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>0.362 $10^6$</td>
<td></td>
</tr>
<tr>
<td>solid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density kg/m$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>7960</td>
<td>7497</td>
</tr>
<tr>
<td>solid</td>
<td>9430</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity W/m K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>2.88</td>
<td>2.91</td>
</tr>
<tr>
<td>solid</td>
<td>2.88</td>
<td></td>
</tr>
<tr>
<td>Viscosity Pa s</td>
<td>4.23 $10^3$</td>
<td>2.97 $10^3$</td>
</tr>
<tr>
<td>Surface tension N/m</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Liquid/Solid temperature K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>2850</td>
<td>2845</td>
</tr>
<tr>
<td>solid</td>
<td>2830</td>
<td>2815</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.79</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The melt is treated as drops with initial diameter of 0.01 m, then is not possible to have a fragmented fraction value.

The values of melt-water time contact, melt-bottom vessel time contact, water swelling, leading edges, are determined by considering the presence of a fraction less then 0.05 for the related field.

IFCI ENEA
D.6 - Code input deck

Input deck for calculation 1

IFICI Tests - 7 rings - 25 axial zones - Test L-14 for ISP39 - Ver. 6.0a
$ 0.01 m of initial melt diameter, default inv. sound speed squared
$ Regioni inizializzate con corium fuso
$ Utilizzati Friction factors per simulare il contenimento del corium
$
$ 28/11/1996 G.C. Colombo
$ TEST WITH UO2(80%) + ZrO2(20%)
$ Modificate le caratteristiche fisiche UO2-ZrO2 per ISP39
$ HP9000 data set
$
$ begin general input section
$
$ restart file (1=yes, 0=no)
0
$
$ dumping time interval
5.0
$ plot interval
5.0
$ edit interval
0.05
$ number of steps for main print (iprint>0)
10
$ print flags (3)
3 1 1
$
$ number of axial mesh cells
25
$ number of radial rings
7
$ radiation time step control (gascoef)
.02
$ start time in sec
0.0
$ problem end time
6.0
$ initial time step
1.0e-4
$ number of entries (ntim) in table of maximum timestep versus time
4
$ entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-4 0.1 1.00e-5 1.0 1.0e-2 10.0 1.0e-2
$
$****end general input section
$
$ begin fluids input
$
$ time step increase factor (if no other time step limitations present)
1.05
$ minimum time step
1.e-1
$ courant number to limit time step
0.25
$ minimum iterations to allow timestep increase
3
$ maximum iterations before failure
20
$ convergence error in pressure iteration (error1)
1.e-7
$ maximum allowable relative change in volume fraction per time step
0.2
$ maximum allowable relative change in temperature per time step
.05
$ initial field 3 diameter door1
$ removed from calculation
0.005
$ initial field 4 diameter door2
$
$ 0.01
$ material id's (8 #s)

IFICI ENEA
**UO2 + ZrO2**

1 4 6*0

***following are additions to standard v52 melprog input***

**reference mass fractions for fields 3 and 4 (6 #s)**

<table>
<thead>
<tr>
<th>Field 3</th>
<th>Field 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>6*0</td>
<td></td>
</tr>
</tbody>
</table>

**reference pressure**

1.6

**reference temperatures for fields 3 and 4 (2 #s)**

3073.0 3073.0

**inverse sound speed squared for fields 3 and 4 (2 #s)**

2*1.0e-4

**detonation flag and model selector - Ver. 6.0A**

<table>
<thead>
<tr>
<th>Flag 0</th>
<th>Flag 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**type 2 flag**

<table>
<thead>
<tr>
<th>Flag 0</th>
<th>Flag 0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**fragmentation data (to be input only if det. model used)**

**explosion calculations with 0.1 mm particle**

**using the pressure threshold flag model (type 1)**

<table>
<thead>
<tr>
<th>Threshold</th>
<th>0.0001</th>
<th>0.00001</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

**end of Ver. 6.0A**

***end of IFCl additions***

**number of time steps for minor print to ntty (1 line)**

50

**IOUT, info print control (0 cycles thru)**

8

***additive friction factors***

**number of additive regions**

1

**boundary of region #1**

<table>
<thead>
<tr>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

**axial friction factors region #1 field 1**

<table>
<thead>
<tr>
<th>25*0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>5*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
</tbody>
</table>

**axial friction factors region #1 field 2**

<table>
<thead>
<tr>
<th>25*0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>14*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>5*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
</tbody>
</table>

**axial friction factors region #1 field 3**

<table>
<thead>
<tr>
<th>25*0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>14*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>5*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
</tbody>
</table>

**axial friction factors region #1 field 4**

<table>
<thead>
<tr>
<th>25*0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>14*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>5*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
<tr>
<td>20*0.0</td>
</tr>
<tr>
<td>1.0e25</td>
</tr>
<tr>
<td>4*0.0</td>
</tr>
</tbody>
</table>

**radial friction factors region #1 field 1**

| 25*0.0 |
| 15*0.0 |
| 3703.0 |
| 25*0.0 |
| 25*0.0 |

**IFCl ENEA**
25*0.0
25*0.0
$ radial friction factors region #1 field 2
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0
$ radial friction factors region #1 field 3
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0
$ radial friction factors region #1 field 4
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0
$ *** end additive friction
$*** inflow boundaries
$
$ number of locations of inflow boundary conditions (ninbc)
0
$*** end of inlet bc section *****
$*** outflow boundary conditions ********
$
$ Flow areas are areas of each annulus at top of problem domain.
$ Top areas of rings 1 and 2 (inflow BCs) not included.
$ HDr are delta-r's of each ring.
$
$ number of locations for outlet pressure boundaries (npbc)
0
$ no outflow in scoping tests !!!! - other data left
$*** end outlet bc section
$ the following cards [to the end of fluids in] not included in restart
$*** fluid region input
$ number of fluid regions
$ 1 region for the water temperature, saturated at 51 bar
$ temperature 536.8 K
$
$ fluid region 1 (water)
$ 1 1 1 10
$ initial system pressure (spatially uniform)
$ 5.1e6
$ initial hydrogen partial pressure
$ 7.00e5
$ initial fluid volume fractions (1 to nf)
$ 0.0001 0.9999 0.0 0.0001
$ field 4 mass fractions
$ 0.2 0.0
$ initial temperatures (4 fluids)
$ 536.8 536.8 536.8 536.8
$ initial fluid axial velocities (1 to nf)
$ 0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
$ 4*0.0
$ fluid region 2 (water)
$ 2 1 1 10
$ initial system pressure (spatially uniform)
$ 5.1e6
$ initial hydrogen partial pressure
$ 7.00e5
$ initial fluid volume fractions (1 to nf)
$ 0.0001 0.9999 0.0 0.0001
$ field 4 mass fractions
$ 0.2 0.0
$ initial temperatures (4 fluids)
$ 536.8 536.8 536.8 536.8
$ initial fluid axial velocities (1 to nf)
$ initial fluid radial velocities (1 to nf)
 0.0 2*0.0 0.0
$ fluid region 3 (vapor)
 1 11 7 15
$ initial system pressure (spatially uniform)
 5.1e6
$ initial hydrogen partial pressure
 7.00e5
$ initial fluid volume fractions (1 to nf)
 0.9996 0.0001 0.0 0.0001
$ field 4 mass fractions
 .8 .2 6*0.0
$ initial temperatures (4 fluids)
 536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)
 0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
 4*0.0
$ fluid region 4 (vapor)
 3 16 7 25
$ initial system pressure (spatially uniform)
 5.1e6
$ initial hydrogen partial pressure
 7.00e5
$ initial fluid volume fractions (1 to nf)
 0.9996 0.0001 0.0 0.0001
$ field 4 mass fractions
 .8 .2 6*0.0
$ initial temperatures (4 fluids)
 536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)
 0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
 4*0.0
$ fluid region 5 (corium)
 1 16 2 16
$ initial system pressure (spatially uniform)
 5.1e6
$ initial hydrogen partial pressure
 7.00e5
$ initial fluid volume fractions (1 to nf)
 0.0001 0.0001 0.0 0.9999
$ field 4 mass fractions
 .8 .2 6*0.0
$ initial temperatures (4 fluids)
 536. 536. 536. 3073.
$ initial fluid axial velocities (1 to nf)
 0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
 4*0.0
$ fluid region 6 (corium)
 1 17 2 17
$ initial system pressure (spatially uniform)
 5.1e6
$ initial hydrogen partial pressure
 7.00e5
$ initial fluid volume fractions (1 to nf)
 0.2999 0.0001 0.0 0.7
$ field 4 mass fractions
 .8 .2 6*0.0
$ initial temperatures (4 fluids)
 536. 536. 536. 3073.
$ initial fluid axial velocities (1 to nf)
 0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
 4*0.0
$ fluid region 7 (vapor)
 1 18 2 25
$ initial system pressure (spatially uniform)
 5.1e6
$ initial hydrogen partial pressure
 7.00e5
$ initial fluid volume fractions (1 to nf)
 0.9996 0.0001 0.0 0.0001
$ field 4 mass fractions
 .8 .2 6*0.0
$ initial temperatures (4 fluids)
 536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ volume fraction equivalent to zero
1.e-7
$*** end fluid ic section
$*** vessel geometry
$ axial length of cell (m)
0.045 0.245 4*0.22 0.235 4*0.08 0.055 0.135 3*0.34
$ location of radial nodes, 1 to nrnl (l = 0.0)
0.0 0.05 0.1 0.15 0.2 0.25 0.33 0.4
$ additional embedded interface cell connections
0
$*** structures input
$ structure input table size, convergence criteria, iterations
$ this has maxmod=0 to turn off structures input
$ 1 1.0e-6 1.0e-6 10 10
$ TERMOS external vessel
12 1 0 0 2 0 1 5 1 900 536.0
300.0 20.0
7.5 0.355 0.4 5.235
$ $*** end structures
$ $*** radiation input
$ $ number of radiation groups
1
$ max number of iterations
100
$ convergence criteria
1.0e-4
$ tbound
300.
$ emissivities
0.3 0.3 0.3 0.3 0.3 0.79
$ mass absorption coefficient
4*0.1
$ $*** end radiation
$ $*** debris data
0
40 1 2
0.8 0.70 0.08 0.004 0.0
$ $*** end debris
$*** end input deck ***

Input deck for calculation 2
IFCI Tests - 7 rings - 25 axial zones - Test L-14 for ISP39 - Ver. 6.0a
$ 0.01 m of initial melt diameter, default inv. sound speed squared
$ Regioni inizializzate con corium fuso
$ Utilizzati Friction factors per simulare il contenimento del corium
$ $ 29/11/1996 G.C. Colombo
$ TEST WITH UO2(80%) + ZrO2(20%)
$ Utilizzate le caratteristiche fisiche UO2-ZrO2 come da NAPRO
$ HP9000 data set
$ $ begin general input section
$ $ $ restart file (1=yes,0=no)
0
$ $ dumping time interval
5.0
$ plot interval
5.0
$ edit interval
0.05
$ number of steps for main print (iprint>0)

IFCI ENEA
$ print flags (3)
$ 1 1

$ number of axial mesh cells
25
$ number of radial rings
7
$ radiation time step control (gascoef)
.02
$ start time in sec
0.0
$ problem end time
6.0
$ initial time step
1.0e-6
$ number of entries (ntim) in table of maximum timestep versus time
4
$ entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-4 0.1 100.0e-5 1.0 1.0e-2 100. 1.0e-2

$*** end general input section

$ begin fluids input

$ time step increase factor (if no other time step limitations present)
1.05
$ minimum time step
1.e-7
$ courant number to limit time step
0.25
$ minimum iterations to allow timestep increase
3
$ maximum iterations before failure
20
$ convergence error in pressure iteration (errorl)
1.e-7
$ maximum allowable relative change in volume fraction per time step
0.2
$ maximum allowable relative change in temperature per time step
0.05
$ initial field 3 diameter dcorl
$ removed from calculation
0.005
$ initial field 4 diameter dcor2
$
0.01
$ material id's (8 #s)
$ 1002 + 2002
4 6*0
$
$*** following are additions to standard v52 melproq input
$
$ reference mass fractions for fields 3 and 4 (8 #s)
0.8 0.2 6*0.0
$ reference pressure
5.1e6
$ reference temperatures for fields 3 and 4 (2 #s)
3073.0 3073.0
$ inverse sound speed squared for fields 3 and 4 (2 #s)
same as default
2*1.0e-4
$ $ detonation flag and model selector - Ver. 6.0A
0 0
$ type 0 flag
16 1 0.01
$ type 1 flag
1.0e5
$ type 2 flag
0.01 0.001
$ fragmentation data (to be input only if det. model used)
$ explosion calculations with 0.1 mm particle
$ using the pressure threshold flag model (type 1)
$ 0.0001 0.00001 0 10.
$ end of Ver. 6.0A
$
$*** end of IFCl additions

$ number of time steps for minor print to ntty (1 line)
$ IIOUT, info print control (0 cycles thru)
8

$*** additive friction factors

$ number of additive regions
1

$ boundary of region #1
1 1 7 25

$ axial friction factors region #1 field 1
25*0.0
14*0.0 1.0e25 5*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0

$ axial friction factors region #1 field 2
25*0.0
14*0.0 1.0e25 5*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0

$ axial friction factors region #1 field 3
25*0.0
14*0.0 1.0e25 5*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0

$ axial friction factors region #1 field 4
25*0.0
14*0.0 1.0e25 5*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0
20*0.0 1.0e25 4*0.0

$ radial friction factors region #1 field 1
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0

$ radial friction factors region #1 field 2
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0

$ radial friction factors region #1 field 3
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0

$ radial friction factors region #1 field 4
25*0.0
15*0.0 3*1.0e25 7*0.0
25*0.0
25*0.0
25*0.0
25*0.0

$*** end additive friction

$*** inflow boundaries

$ number of locations of inflow boundary conditions (ninbc)

IFCI ENEA
$*** end of inlet bc section *****

$*** outflow boundary conditions **********

$ Flow areas are areas of each annulus at top of problem domain.
$ Top areas of rings 1 and 2 (inflow BCs) not included.
$ HDs are delta-r's of each ring.
$ number of locations for outlet pressure boundaries (npbc)
$ no outflow in scoping tests !!!! - other data left
0

$*** end outlet bc section
$ the following cards (to the end of fluids in) not included in restart

$*** fluid region input
$ number of fluid regions
$ 1 region for the water temperature, saturated at 51 bar
$ temperature 536.8 K

$ fluid region 1 (water)
  1 1 10
$ initial system pressure (spatially uniform)
  5.16e6
$ initial hydrogen partial pressure
  7.00e5
$ initial fluid volume fractions (1 to nf)
  0.0001 0.9998 0.0 0.0001
$ field 4 mass fractions
  0.8 0.2 0.0
$ initial temperatures (4 fluids)
  536.8 536.8 536.8 536.8
$ initial fluid axial velocities (1 to nf)
  0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
  4*0.0
$ fluid region 2 (water)
  2 1 7 10
$ initial system pressure (spatially uniform)
  5.16e6
$ initial hydrogen partial pressure
  7.00e5
$ initial fluid volume fractions (1 to nf)
  0.0001 0.9998 0.0 0.0001
$ field 4 mass fractions
  0.8 0.2 0.0
$ initial temperatures (4 fluids)
  536.8 536.8 536.8 536.8
$ initial fluid axial velocities (1 to nf)
  0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
  4*0.0
$ fluid region 3 (vapor)
  1 11 7 15
$ initial system pressure (spatially uniform)
  5.16e6
$ initial hydrogen partial pressure
  7.00e5
$ initial fluid volume fractions (1 to nf)
  0.9998 0.0001 0.0 0.0001
$ field 4 mass fractions
  0.8 0.2 0.0
$ initial temperatures (4 fluids)
  536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)
  0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
  4*0.0
$ fluid region 4 (vapor)
  3 16 7 25
$ initial system pressure (spatially uniform)
  5.16e6
$ initial hydrogen partial pressure
  7.00e5
$ initial fluid volume fractions (1 to nf)
  0.9998 0.0001 0.0 0.0001
$ field 4 mass fractions
  0.8 0.2 0.0
$ initial temperatures (4 fluids)
  536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)

IFCI ENEA
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ fluid region 5 (corium)
1 16 2 16
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
7.00e5
$ initial fluid volume fractions (1 to nf)
0.0001 0.0001 0.0 0.9998
$ field 4 mass fractions
.8 .2 6*0.0
$ initial temperatures (4 fluids)
536. 536. 536. 3073.
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ fluid region 6 (corium)
1 17 2 17
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
7.00e5
$ initial fluid volume fractions (1 to nf)
0.2099 0.0001 0.0 0.79
$ field 4 mass fractions
.8 .2 6*0.0
$ initial temperatures (4 fluids)
536. 536. 536. 3073.
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ fluid region 7 (vapor)
1 18 2 25
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
7.00e5
$ initial fluid volume fractions (1 to nf)
0.9998 0.0001 0.0 0.0001
$ field 4 mass fractions
.8 .2 6*0.0
$ initial temperatures (4 fluids)
536. 536. 536. 536.
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ volume fraction equivalent to zero
1.e-7
$*** end fluid ic section
$*** vessel geometry
$ axial length of cell (m)
0.045 0.245 8*0.22 0.235 4*0.2 0.3 0.4 3*0.08 0.055 0.135 3*0.34
$ location of radial nodes, 1 to nrpl (1 = 0.0)
0.0 0.05 0.1 0.15 0.2 0.25 0.33 0.4
$ additional embedded interface cell connections
0
$*** structures input
$ structure input table size, convergence criteria, iterations
$ this has maxmode=0 to turn off structures input
$ 1 1.0e-6 1.0e-6 10 10
$ TERMOS external vessel
12 1 0 0 0 2 0 1 5 1 900 536.0
300.0 20.0
0.0
7 5 0.355 0.4 5.235
$*** end structures
$*** radiation input
$ $ number of radiation groups

IFCI ENEA
1
max number of iterations 100
convergence criteria 1.0e-4
tbound 300.
emissivities 0.3 0.3 0.3 0.3 0.3 0.8
mass absorption coefficient 4=0.1
end radiation
end debris data
4 1 2
0.8 0.70 0.08 0.004 0.0
end debris
end

IFCI ENEA
E. IFCI-ENEL Calculations

E.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>ENEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>M. Valisi, G. Sandrelli</td>
</tr>
<tr>
<td>Address:</td>
<td>ENEL</td>
</tr>
<tr>
<td></td>
<td>Nuclear Energy Division</td>
</tr>
<tr>
<td></td>
<td>Via Monfalcone 15</td>
</tr>
<tr>
<td></td>
<td>20132 Milano</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
</tr>
<tr>
<td>Tel:</td>
<td>0039-2-7224 3440</td>
</tr>
<tr>
<td>Fax:</td>
<td>0039-2-7224 3497</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:valisi@cram.enel.it">valisi@cram.enel.it</a></td>
</tr>
</tbody>
</table>

E.2 - Initial and boundary conditions

A total number of 4 calculations with IFCI code version 6.0a have been submitted. The first calculation, termed SPG, is the reference calculation. The melt was injected from inside the problem domain with the exit velocity calculated by the code itself.

In the second calculation, termed SP, the melt was injected from outside the problem domain with the exit velocity calculated by JRC but with higher melt free fall.

In the third calculation, termed SB, the melt was injected from outside the problem domain with the correct melt free fall and the exit velocity calculated by JRC but with distorted vessel diameter.

The fourth calculation, termed SG, is a best estimate case with the same hypothesis of case SPG but with the corium physical properties calculated by the code.

Initial and boundary conditions valid for calculation 1 (reference)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EXPERIMENT</th>
<th>ENEL (calc. 1) (SPG)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125.4</td>
<td>+0.4</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
<td>-</td>
</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>622.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.054 *</td>
<td>+0.004</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>low 536.3 high 538.3</td>
<td>+0.97</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>2.17</td>
<td>-</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.8</td>
<td>+0.002</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>99.23steam+0.77H₂**</td>
<td>H₂ instead of Ar</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.24</td>
<td>-0.02</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>538.3</td>
<td>+2.3</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>

IFCI ENEL
### Initial and boundary conditions valid for calculation 2

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEL (calc. 2) (SP)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>3.115</td>
<td>+2.075</td>
</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>621.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.054 *</td>
<td>+0.004</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>low 536.3</td>
<td>high 538.3</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.799</td>
<td>+0.001</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>99.23steam+0.77H₂**</td>
<td>H₂ instead of Ar</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.264</td>
<td>+0.004</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>538.3</td>
<td>+2.3</td>
</tr>
<tr>
<td>Pressure, Mpa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>

### Initial and boundary conditions valid for calculation 3

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>ENEL (calc. 3) (SB)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
<td>-</td>
</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>621.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.054 *</td>
<td>+0.004</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>low 536.3</td>
<td>high 538.3</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.799</td>
<td>+0.001</td>
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Initial and boundary conditions valid for calculation 4

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* value deduced from the nodalization drawing
** corresponding to 3 bar H₂ partial pressure
### E.3 - Code nodalization

**Code nodalization for calculation 1**

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*Figure A - IFCI (r,z) Nodalization for the FARO L-14 Test (25 Axial Mesh Cells & 7 Radial Mesh Cells). All Dimensions are meters. Case SPG.*
## Code Nodalization for Calculation 2

![Diagram Image]

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*Figure B - IFCI (r,z) Nodalization for the FARO L-14 Test (25 Axial Mesh Cells & 7 Radial Mesh Cells). All dimensions are meters. Case SP.*
**Code nodalization for calculation 3**

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**Figure C** - IFCI (r,z) Nodalization for the FARO L-14 Test (21 Axial Mesh Cells & 7 Radial Mesh Cells). All dimensions are meters. Case SB.
**Figure D** - IFCI (r,z) Nodalization for the FARO - L-14 Test (25 Axial Mesh Cells & 7 Radial Mesh Cells). All Dimensions are meters. Case SG.
E.4 - Comparison of calculations with the experiment

E.4.1 Base calculation (case SPG)

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

IFCI ENEL
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate

Quantity: 16 not present due to fragmentation model with initial melt diameter of 0.01 m
Quantity: 18 - Heat transfer surface versus time, compared with the final estimate:
33.2 m³

Quantity: 19 - Jet leading edge position versus time
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<th>Quantity: 20 - Melt/Water contact</th>
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<table>
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<th>Quantity: 21 - Melt/Bottom contact</th>
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<tbody>
<tr>
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<td>IFCI ENEL</td>
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</table>
E.4.2 Additional calculations

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position

IFCI ENEL
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level

IFCI ENEL
Quantity: 13, 14 - Total energy

Quantity: 15 - Quenching rate
Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

Quantity: 19 - Jet leading edge position versus time
E.5 - Code description or code models/options

The USNRC Integrated Fuel-Coolant Interaction (IFCI) computer code is being developed to investigate Fuel-Coolant Interactions (FCIs) in as mechanicistic as possible manner. The code is intended to address all aspects of FCI phenomena, including coarse fragmentation and mixing of molten material with water, triggering, shock wave propagation and fine fragmentation, and expansion of the melt-water system [1].

The ultimate objective of the code is to predict rates of steam and hydrogen formation, melt fragmentation and dispersion, fission product release, shock wave generation and propagation, and system loading for explosive and non-explosive FCIs in a reactor system.

IFCI is based on the MELPROG/MOD.1 implementation of the SETS (Stability Enhancing Two-Steps) hydrodynamic method [2]. This model provides a two-dimensional, r-z geometry, four-field model, whose fields consist of vapor (steam + hydrogen), water, solid debris (not used by IFCI), and molten material.

A "field" in this context is represented by separate mass-continuity, momentum and energy equations; each component of the fuel-coolant mixture is described by a different field. Use of a multifield method allows slip between the various materials and a different temperature for each material. IFCI uses the TRAC equation of state for water and steam, and a stiff-gas equation of state for the melt.

The constitutive relations required for the interfied coupling terms (heat transfer, momentum exchange, and phase change) include a bulk boiling model, a sub-cooled surface boiling model (Dhir and Purohit), a three-field flow regime map, and adaptation of standard heat transfer and momentum transfer correlation.

Additional models are included, which are necessary to calculate phenomena that occurs in FCIs. These are: the Pilch melt fragmentation model, coupled with a convection equation for melt surface per unit volume, a surface tracking model, a trigger model, and a melt oxidation/hydrogen production model [1].

The fragmentation model in IFCI is a version of a dynamic fragmentation model developed by Pilch, based on Rayleigh-Taylor instability theory and experimental data on drop break-up in gases and liquids [1].

Common to all calculations were the following hypotheses:

1. Argon was simulated in the code with hydrogen, that is the only non-condensable modelled in the IFCI Code.

2. Melt was injected as droplets, and the initial melt drop diameter was taken 1.0 cm, on the basis of the Kutateladze droplet stability principle, as in all previous FARO-TERMOS IFCI calculations.

3. Gas volumes due to the communication line between TERMOS and separator, the separator and the line connecting the separator with the exhaust valves were simulated as directly added to the TERMOS gas volume. No connecting line is modelled. The hypothesis was based on the consideration that TERMOS pressure and separator pressure were experimentally found always identical both as value and as timing.

4. Water volume was simulated in two regions, one for the bottom slightly sub-cooled, and the rest at saturation temperature.
5. Time zero of the simulation was set at the start of melt injection.

6. Two metal structures were modelled:
   - debris catcher:
   - vessel walls.


E.6 - Code input deck

Input deck for calculation 1

FARO L14 TEST - ISP39 CASE SPG - MELT SUSPENDED

L-14 - L-14 - L-14 - L-14 - L-14 - L-14 - L-14 - L-14

0.01 m of initial melt diameter, default inv. sound speed squared

This is set up for ifci v60a, 10/28/94 mava

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Data from:
D. Magallon, G. Leva : FARO LWR Programme
Test L-14 Data Report
Technical Note No. 1.96.25

A. Annunziato, C. Addabbo, G. Leva:
OECD/CSNI International Standard Problem
No. 39 on FARO Test L14
Reference Specification

Start general input section

Restart file (1=yes,0=no)
0

Dumping time interval
2e-1

Plot interval
2.5e-2

Edit interval
2.5e-1

Number of steps for main print (iprint=0)
2000

Print flags (3)
1 0 0

Number of axial mesh cells
25

Number of radial rings
7

Radiation time step control (gascoef)
.02

Start time in sec
0.0

Problem end time
5.0

Initial time step
1.0e-5

Number of entries (ntim) in table of maximum timestep versus time
4

Entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-5 0.1 1.0e-4 1.0 1.0e-3 100. 1.0e-2

End general input section

Begin fluids input

Time step increase factor (if no other time step limitations present)
1.05

Minimum time step
1.0e-10

Courant number to limit time step
0.25

Minimum iterations to allow timestep increase
$ maximum iterations before failure
10
$ convergence error in pressure iteration (error1)
1.e-7
$ maximum allowable relative change in volume fraction per time step
0.3
$ maximum allowable relative change in temperature per time step
0.02
$ initial field 3 diameter dcor1
$ removed from calculations
0.000
$ initial field 4 diameter dcor2
$ Jet Entry diameter of 0.1 m - Particle Diameter of 0.01 m
0.01
$ material id's (8 #s)
$ IMAT = 2, as 80% UO2 and 20% ZrO2
2 7 0
$
$ *** following are additions to standard v52 melprog input
$
$ reference mass fractions for fields 3 and 4 (8 #s)
1.0 7.0 0.0
$ reference pressure 5.1MPa
5.1e6
$ reference temperatures for fields 3 and 4 (2 #s)
3073.15 3073.15
$ inverse sound speed squared for fields 3 and 4 (2 #s)
2*1.0e-4
$
$ ### Ver. 6.0A additions
$ detonation flag and model selector - Ver. 6.0A
0 0
$ type 0 flag
16 1 0.01
$ type 1 flag
1.0e5
$ type 2 flag
0.01 0.001
$ fragmentation data (to be input only if det. model used)
$ explosion calculations with 0.1 mm particle
$ using the pressure threshold flag model (type 1)
0.0001 0.00001 0 10.
$ ### end of Ver. 6.0A
$ ### end of IFC1 additions
$
$ number of time steps for minor print to mnty (1 line)
50
$ I1OUT, info print control (0 cycles thru)
0
$
$ *** additive friction factors
$
$ *** number of additive regions
$
1
1
7
25
$ field 1 - axial
$ ring 1
25*0.0
$ ring 2
14*0.0 1.255*0.0 1.254*0.0
$ ring 3
20*0.0 1*1.255 4*0.0
$ ring 4
20*0.0 1*1.255 4*0.0
$ ring 5
20*0.0 1*1.255 4*0.0
$ ring 6
20*0.0 1*1.255 4*0.0
$ ring 7
20*0.0 1*1.255 4*0.0
$ field 2 - axial
$ ring 1
25*0.0
$ ring 2
14*0.0 1.4*0.0 1.4*0.0
$ ring 3
20*0.0 1*1.4 4*0.0

IFCI ENEL
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 3 - axial
25*0.0
$ ring 2
14*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 4 - axial
25*0.0
$ ring 2
14*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 1 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$ field 2 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$ field 3 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
IFCI ENEL
$ ring 7
25*0.0
$ field 4 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$
$*** end additive friction$
$
$*** inflow boundaries .
$
$ number of locations of inflow boundary conditions (ninbc)
0$
$
$*** end of inlet bc section *****
$
$*** outflow boundary conditions ***********$
$
$ Flow areas are areas of each annulus at top of problem domain.
$ Top areas of rings 1 and 2 (inflow BCs) not included.
$ HDS are delta-r's of each ring.
$
$ number of locations for outlet pressure boundaries (npbc)
$ no outflow in quenching tests !!!! - other data left
0$
$
$*** end outlet bc section$
$ the following cards (to the end of fluids in) not included in restart
$*** fluid region input
$ number of fluid regions
$ 5 regions for the water temperature, data from Ispra Pax
$ Constant Temperature of 263 deg.C (538.3 deg.K)
$ the variation is the same as for the first Base Case with Metallic Zr
$
$ fluid region 1 (water)
1 1 7 2
$ initial system pressure (spatially uniform)
5.16e5
$ initial hydrogen partial pressure
0.00e5
$ initial fluid volume fractions (1 to nf)
0.0 1.0 0.0 0.0
$ initial temperatures (4 fluids) - try 2 deg. of undersat. near the melt catche
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ fluid region 2 (water)
1 3 7 10
$ initial system pressure (spatially uniform)
5.16e5
$ initial hydrogen partial pressure
0.00e5
$ initial fluid volume fractions (1 to nf)
0.6 1.0 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 3 - cover gas, modeled as water vapor
3 11 7 25
$ initial system pressure (spatially uniform)
5.16e5
$ initial (argon as hydrogen) partial pressure
0.36e5
$ initial fluid volume fractions (1 to nf)
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)  
4*0.0
$ initial fluid radial velocities (1 to nf)  
4*0.0
$ region 4 - 125 kg of melt in two central cells  
1 16 1.17
$ initial system pressure (spatially uniform)  
5.1e6
$ initial hydrogen partial pressure  
0.3e6
$ initial fluid volume fractions (1 to nf)  
0.1 0.0 0.0 0.9
$ field 4 mass fractions (same as inflow BC)  
1.0 7*0.0
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)  
4*0.0
$ initial fluid radial velocities (1 to nf)  
4*0.0
$ region 5 - 125 kg of melt in two central cells  
2 16 2.17
$ initial system pressure (spatially uniform)  
5.1e6
$ initial hydrogen partial pressure  
0.3e6
$ initial fluid volume fractions (1 to nf)  
0.1 0.0 0.0 0.9
$ field 4 mass fractions (same as inflow BC)  
1.0 7*0.0
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)  
3*0.0 0.0
$ initial fluid radial velocities (1 to nf)  
3*0.0 -1.0
$ region 6 - cover gas, modeled as water vapor  
1 11 1.15
$ initial system pressure (spatially uniform)  
5.1e6
$ initial hydrogen partial pressure  
0.3e6
$ initial fluid volume fractions (1 to nf)  
1.000 0.0 0.0 0.000
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)  
4*0.0
$ initial fluid radial velocities (1 to nf)  
4*0.0
$ region 7 - cover gas, modeled as water vapor  
2 11 2.15
$ initial system pressure (spatially uniform)  
5.1e6
$ initial hydrogen partial pressure  
0.3e6
$ initial fluid volume fractions (1 to nf)  
1.000 0.0 0.0 0.000
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)  
4*0.0
$ initial fluid radial velocities (1 to nf)  
4*0.0
$ region 8 - cover gas, modeled as water vapor  
1 18 1.25
$ initial system pressure (spatially uniform)  
5.1e6
$ initial hydrogen partial pressure  
0.3e6
$ initial fluid volume fractions (1 to nf)  
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)  
538.3 538.3 538.3 3077.15
$ initial fluid axial velocities (1 to nf)  
4*0.0
$ initial fluid radial velocities (1 to nf)  
4*0.0

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Data from:
D. Magallon, G. Leva: FANO LWR Programme
Test L-14 Data Report
Technical Note No. I.96.25
A. Annunziato, C. Addabbo, G. Leva:
OECD/CSNI International Standard Problem
No. 39 on FANO Test L14
Reference Specification

Input for In-Flow Melt Injection.

= = = = = = = = = = = = = = =
Full TERMOS Lenght=
= = = = = = = = = = = = = = =
Material Properties in IMAT = 2

= = = = = = = = = = = = = = =

$ begin general input section

$ restart file (1=yes, 0=no)

0
$ dumping time interval
20000.
$ plot interval
2.5e-2
$ edit interval
2.5e-1
$ number of steps for main print (iprnt>0)
2000
$ print flags (3)
1 0 0
$ number of axial mesh cells
25
$ number of radial rings
7
$ radiation time step control (gascoef)
.02
$ start time in sec
0.
$ problem end time
5.0
$ initial time step
1.0e-5
$ number of entries (ntim) in table of maximum timestep versus time
4
$ entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-5 0.1 1.0e-4 1.0 1.0e-3 100. 1.0e-2

$ end general input section

$ begin fluids input

$ time step increase factor (if no other time step limitations present)
1.05
$ minimum time step
1.e-10
$ courant number to limit time step
0.25
$ minimum iterations to allow timestep increase
10
$ maximum iterations before failure
30
$ convergence error in pressure iteration (error1)
1.e-6
$ maximum allowable relative change in volume fraction per time step
0.3
$ maximum allowable relative change in temperature per time step
.02
$ initial field 3 diameter dcor1
$ removed from calculations
  0.000
$ initial field 4 diameter dcor2
$ Jet Entry diameter of 0.1 m - Particle Diameter of 0.01 m
  0.01
$ material id's (8 #s)
$ uo2(80%), and zo2(20%) - implemented as IMAT = 2 - MaVa 6/96
  2 7*0
$
$ *** following are additions to standard v52 melprog input
$
$ $ reference mass fractions for fields 3 and 4 (8 #s)
  1.00 7*0.0
$ reference pressure 5.1MPa
  5.1e6
$ reference temperatures for fields 3 and 4 (2 #s)
  3073.15 3073.15
$ inverse sound speed squared for fields 3 and 4 (2 #s)
$ same as default
  2*1.0e-4
$
$### Ver. 6.0A additions
$ detonation flag and model selector - Ver. 6.0A
  0 0
$ type 0 flag
  16 1 0.01
$ type 1 flag
  1.0e5
$ type 2 flag
  0.01 0.001
$ fragmentation data (to be input only if det., model used)
$ explosion calculations with 0.1 mm particle
$ using the pressure threshold flag model (type 1)
  0.0001 0.00001 0 10.
$### end of Ver. 6.0A
$### end of IFCI additions
$
$ number of time steps for minor print to ntty (1 line)
  50
$ IIFOUT, info print control (0 cycles thru)
  0
$
$*** additive friction factors
$
$*** number of additive regions
$ Melt is injected from outside the simulated vessel
$ only to match inlet velocities as in Ref. Spec.
$ free fall higher than reality !!!!!!!!!!
  0
$
$*** end additive friction
$
$*** inflow boundaries
$
$ number of locations of inflow boundary conditions (ninbc)
  1
$ inflow boundary conditions (ninbc sets of cards)******
$ radial node
  1
$ axial node
  26
$ inflow area
  6.6476e-3
$ number of entries in inlet pressure boundary condition tables
  2
$ number of entries in inlet velocity boundary condition tables
  32
$ number of entries in inlet temperature boundary condition tables
  2
$ number of entries in inlet volume fraction boundary condition tables
  4
$ inflow pressures (nprin*(time,pressure))
  0.0 5.1e6 100.0 5.1e6
$ inflow hydrogen partial pressures (nprin*(time,pressure))
  0.0 0.00 100.0 0.00
$ inflow velocities, fluid 1 (nvin*(time,vel))
  0.0 -0.01

IFCI ENEL
Flow areas are areas of each annulus at top of problem domain.
Top areas of rings 1 and 2 (inflow BCs) not included.
HDs are delta-r's of each ring.
number of locations for outlet pressure boundaries (mpbc)
no outflow in quenching tests - other data left

$*** end outlet bc section
$ the following cards (to the end of fluids in) not included in restart
$*** fluid region input
$ number of fluid regions
$ 2 regions for the water temperature, data from Impra Fax
$ Constant Temperature of 538.3 deg.K
$ the variation is the same as for the first Base Case with Metallic Zr
$ fluid region 1 (water) - 0.001 steam to prevent SETS fuzzy
1 1 7 2
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.00e5
$ initial fluid volume fractions (1 to nf)
0.001 0.999 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ fluid region 2 (water) - 0.001 steam to prevent SETS fuzzy
1 3 7 10
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.00e5
$ initial fluid volume fractions (1 to nf)
0.001 0.999 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
0.0 2*0.0 0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 3 - cover gas, modeled as water vapor
3 1 1 7 25
$ initial system pressure (spatially uniform)
5.1e6
$ initial (argon as hydrogen) partial pressure
0.3e6
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 4 - steam
1 16 1 24
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.3e6
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 5 - 125 kg of melt in two central cells
2 16 2 17
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.3e6
$ initial fluid volume fractions (1 to nf)
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
3*0.0 0.0
$ initial fluid radial velocities (1 to nf)
3*0.0 0.0
$ region 6 - cover gas, modeled as water vapor
1 11 1 15
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.366
$ initial fluid volume fractions (1 to nf)
1.000 0.0 0.0 0.000
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 7 - cover gas, modeled as water vapor
2 11 2 15
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.366
$ initial fluid volume fractions (1 to nf)
1.000 0.0 0.0 0.000
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 8 - melt inlet region
1.25 1 25
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.366
$ initial fluid volume fractions (1 to nf)
0.99 0.0 0.0 0.001
$ melt - as in BC
1.0 7*0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ region 9 - cover gas, modeled as water vapor
2 18 2 25
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.366
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ volume fraction equivalent to zero
1.e-5
$*** end fluid ic section
$*** vessel geometry
$ axial length of cell (m)
0.11 9*0.215555 5*0.288 6*0.159167 4*0.280
$ location of radial nodes, 1 to nrpi (1 = 0.0)
$ TERMSO walls included
0.0 0.06 0.1 0.15 0.20 0.25 0.30 0.400
$ additional embedded interface cell connections
0
$*** structures input
$
structure input table size, convergence criteria, iterations
this has maxmode=0 to turn off structures input
2 1.0e-6 1.0e-6 10 10
TERMOS melt catcher - water temperature
31 1 0 0 0 0 1 5 1 901 538.3
0.0
7 5 0.0 0.33 0.04 0.0 1.0 0.0 1.0
TERMOS external vessel - saturated steam temperature
11 1 9 0 2 0 1 5 2 900 538.3
300. 7.5
7 5 0.355 0.400 4.621
*** end structures
*** radiation input
$ number of radiation groups
1
$ max number of iterations
50
$ convergence criteria
1.0e-4
$ tbound
300.
$ emissivities - melt data from ref. spec.
0.3 0.3 0.3 0.3 0.3 0.79
$ mass absorption coefficient
4.0 1.
$*** end radiation
*** debris data
0
50 9 2
0.6 0.55 0.05 0.0035 0.0
$ end of input deck
$

Input deck for calculation 3

TERMOS - Li4 for SP - Big vessel for real melt free fall - PowerPC
$ this is set up for ifci v60a, 06/05/96 mava
$ begin general input section
$ restart file (1=yes,0=no)
0
$ dumping time interval
2e-1
$ plot interval
5.e-2
$ edit interval
2.5e-1
$ number of steps for main print (iprnt>0)
10
$ print flags (3)
1 0 0
$ number of axial mesh cells
21
$ number of radial rings
7
$ radiation time step control (gascoef)
.02
$ start time in sec
0.0
$ problem end time
5.0
$ initial time step
1.0e-5
$ number of entries (ntim) in table of maximum timestep versus time
4
$ entries in maximum time step table (ntim = (time, max time))
0.0 1.0e-5 0.1 100.0e-6 1.0 1.0e-2 100. 1.0e-2
$***end general input section
$
$ begin fluids input
$ $ time step increase factor (if no other time step limitations present) 1.05
$ $ minimum time step 1.e-10
$ $ courant number to limit time step 0.25
$ $ minimum iterations to allow timestep increase 3
$ $ maximum iterations before failure 10
$ $ convergence error in pressure iteration (error1) 1.e-7
$ $ maximum allowable relative change in volume fraction per time step 0.2
$ $ maximum allowable relative change in temperature per time step 0.05
$ $ initial field 3 diameter (removed from the calculation) data from Magallion report
$ $ 0.0
$ $ initial field 4 diameter dcor2
$ $ jet entry diameter 0.1 m, particle diameter 0.01 m
$ $ 0.01
$ $ material Id's (8 #s)
$ $ uo2(#1), and zro2(#4)
$ $ 2 7 0
$ $ $*** following are additions to standard v52 melprog input $ $ $ reference mass fractions for fields 3 and 4 (8 #s) 1.0 7e-0.0
$ $ $ reference pressure 5.1e6
$ $ $ reference temperatures for fields 3 and 4 (2 #s) taken from jet characterization test data 2500. deg C
$ $ 3073.0 3073.0
$ $ $ inverse sound speed squared for fields 3 and 4 (2 #s) same as default
$ $ 2*1.0e-4
$ $ $ detonation flag and model selector - Ver. 6.00
$ $ 0 0
$ $ $*** end of IPCI additions $ $ $ number of time steps for minor print to ntty (1 line) 10
$ $ $ IIGOUT, info print control (0 cycles thru)
$ $ 8
$ $ $*** additive friction factors
$ $ $ number of additive regions 0
$ $ $*** end additive friction
$ $ $*** inflow boundaries
$ $ $ number of locations of inflow boundary conditions (ninbc) 1
$ $ $ inflow boundary conditions (ninbc sets of cards)*******
$ $ $ radial node 1
$ $ $ axial node 22
$ $ $ inflow area $ orifice of 9.2 cm in diameter
$ $ 6.6476e-3
$ $ $ number of entries in inlet pressure boundary condition tables 2
$ $ $ number of entries in inlet velocity boundary condition tables 31
$ $ $ number of entries in inlet temperature boundary condition tables 2

IPCI ENEL
| number of entries in inlet volume fraction boundary condition tables | 4 |
| inflow pressures (nprint(time,pressure)) | 0.0 5.16 100.0 5.16 |
| inflow hydrogen partial pressures (nprint(time,pressure)) | 0.0 0.306 100.0 0.306 |
| inflow velocities, fluid 1 (nvin(time,vel)) | 0.01 -0.182 |
| 0.0432758260698555 -0.7745358540847454 |
| 0.076551724137931 -1.31681888101513 |
| 0.109827586206897 -1.7828189507049 |
| 0.143103448275862 -2.16302174521617 |
| 0.17637910344828 -2.45559934498393 |
| 0.209655172413793 -2.67315036286311 |
| 0.2429310344827582 -2.82626480285517 |
| 0.276206896551724 -2.93104380853284 |
| 0.3094827586206955 -3.0.9723413047693 |
| 0.342758260698555 -3.01525575353962 |
| 0.376034482758621 -3.05327434713233 |
| 0.409310344827586 -0.305699360790356 |
| 0.442582606966552 -0.30884947446832 |
| 0.475862068965517 -0.30343199194078 |
| 0.50913791034483 -0.30144594692824 |
| 0.54241379103448 -2.991162927222185 |
| 0.575689655172414 -2.96440396082867 |
| 0.609865171241379 -2.930427973955196 |
| 0.64224137910345 -2.8962843095217 |
| 0.67551724137931 -2.8522743932186 |
| 0.70879310344827586 -2.803891810865224 |
| 0.742068965517241 -2.75269507252665 |
| 0.775344827586207 -2.6869288941819 |
| 0.808620689655172 -2.5570163115275 |
| 0.84186517241379 -2.34508921505844 |
| 0.875172413793103 -2.01495130065203 |
| 0.9084827586206955 -1.54118619319753 |
| 0.941724137931035 -0.887619449746355 |
| 0.975 0.0 |
| 100.0 0.0 |
| inflow temperatures, fluid 1 (nint(time,vel)) | 0.0 0.0.3073.100.0 0.3073.0 |
| inflow volume fractions, fluid 1 (nain(time,all)) | 0.0 0.0 0.9690 0.0 0.969001 0.0 100.0 0.0 |
| inflow velocities, fluid 2 (nvin(time,vel)) | 0.01 -0.182 |
| 0.0432758260698555 -0.7745358540847454 |
| 0.076551724137931 -1.31681888101513 |
| 0.109827586206897 -1.7828189507049 |
| 0.143103448275862 -2.16302174521617 |
| 0.17637910344828 -2.45559934498393 |
| 0.209655172413793 -2.67315036286311 |
| 0.2429310344827582 -2.82626480285517 |
| 0.276206896551724 -2.93104380853284 |
| 0.3094827586206955 -3.0.9723413047693 |
| 0.342758260698555 -3.01525575353962 |
| 0.376034482758621 -3.05327434713233 |
| 0.409310344827586 -0.305699360790356 |
| 0.442582606966552 -0.30884947446832 |
| 0.475862068965517 -0.30343199194078 |
| 0.50913791034483 -0.30144594692824 |
| 0.54241379103448 -2.991162927222185 |
| 0.575689655172414 -2.96440396082867 |
| 0.609865171241379 -2.930427973955196 |
| 0.64224137910345 -2.8962843095217 |
| 0.67551724137931 -2.8522743932186 |
| 0.70879310344827586 -2.803891810865224 |
| 0.742068965517241 -2.75269507252665 |
| 0.775344827586207 -2.6869288941819 |
| 0.808620689655172 -2.5570163115275 |
| 0.84186517241379 -2.34508921505844 |
| 0.875172413793103 -2.01495130065203 |
| 0.9084827586206955 -1.54118619319753 |
| 0.941724137931035 -0.887619449746355 |
| 0.975 0.0 |
| 100.0 0.0 |
| inflow temperatures, fluid 2 (nint(time,vel)) | 0.0 0.0 0.3073.100.0 0.3073.0 |
| inflow volume fractions, fluid 2 (nain(time,all)) | 0.0 0.0 0.9690 0.0 0.969001 0.0 100.0 0.0 |
$ $ inflow velocities, fluid 3 (mvin*(time,vel))
0.01 -0.182
0.0432758620689655 -0.774538540847454
0.076551724137931 -1.316818898101513
0.109827586206897 -1.792818389070049
0.143103448275862 -2.163021745216171
0.176379310344828 -2.55599344983939
0.209655172413793 -2.67315062863111
0.2429310434482798 -2.852664802865517
0.276206986551724 -2.9310498853284
0.3094827856206209 -2.97223431047693
0.342758620689655 -3.0352557638962
0.376034482758621 -3.05327434731233
0.409310434482758 -3.0506936709356
0.442586206896552 -3.04884947464832
0.475862068965517 -3.044199194078
0.509137931034483 -3.01465949692924
0.5424137931034483 -2.99136857232185
0.575686986551724 -2.96444036908287
0.608965172413793 -2.9340279355196
0.642241379310345 -2.8962843065217
0.67551724137931 -2.85227432932186
0.708793103448276 -2.80389183865224
0.742068965517241 -2.7526907252665
0.775344827586207 -2.6869869414918
0.808620689655172 -2.5570116315275
0.841896986551724 -2.3450921950844
0.875172413793103 -2.10495110065203
0.908448275862069 -1.54118619319753
0.941724137931035 -0.887619449746355
0.975 0.0
100. 0.0

$ $ inflow temperatures, fluid 3 (ntin*(time,temp))
0.0 3073. 100.0 3073.

$ $ inflow volume fractions, fluid 3 (main*(time,ali))
0.0 0.0 0.9690 0.0 0.969001 0.0 100.0 0.0

$ $ calculated with a melt density of 7960.0 kg/m**3

$ $ inflow velocities, fluid 4 (mvin*(time,vel))
0.01 -0.182
0.0432758620689655 -0.774538540847454
0.076551724137931 -1.316818898101513
0.109827586206897 -1.792818389070049
0.143103448275862 -2.163021745216171
0.176379310344828 -2.55599344983939
0.209655172413793 -2.67315062863111
0.24293104344482798 -2.852664802865517
0.276206986551724 -2.9310498853284
0.3094827856206209 -2.97223431047693
0.342758620689655 -3.0352557638962
0.3760344482758621 -3.05327434731233
0.409310434482758 -3.0506936709356
0.442586206896552 -3.04884947464832
0.475862068965517 -3.044199194078
0.509137931034483 -3.01465949692924
0.5424137931034483 -2.99136857232185
0.575686986551724 -2.96444036908287
0.608965172413793 -2.9340279355196
0.642241379310345 -2.8962843065217
0.67551724137931 -2.85227432932186
0.708793103448276 -2.80389183865224
0.742068965517241 -2.7526907252665
0.775344827586207 -2.6869869414918
0.808620689655172 -2.5570116315275
0.841896986551724 -2.3450921950844
0.875172413793103 -2.10495110065203
0.908448275862069 -1.54118619319753
0.941724137931035 -0.887619449746355
0.975 0.0
100. 0.0

$ $ inflow temperatures, fluid 4 (ntin*(time,temp))
0.0 3073. 100.0 3073.

$ $ inflow volume fractions, fluid 4 (main*(time,ali))
0.0 0.0 0.9794 1.0 0.9750 0.0 100.0 0.0

$ $ inflow mixture vf for fields 3 and 4 (2 sets of 8#s)
1.0 7*0.0
1.0 7*0.0

IFCI ENEL
*** end of inlet bc section *****

*** outflow boundary conditions ***********

Flow areas are areas of each annulus at top of problem domain.
Top areas of rings 1 and 2 (inflow BCs) not included.
MDs are delta-r's of each ring.
number of locations for outlet pressure boundaries (npbc)
no outflow in this test !!!
0

*** end outlet bc section
the following cards (to the end of fluids in) not included in restart

*** fluid region input
number of fluid regions
2 regions for the water temperature, all saturated at 51 bar

temperature 538.3 deg. K

5

fluid region 1 (water)
1 1 7 1
initial system pressure (spatially uniform)
5.1e6
initial hydrogen partial pressure
0.0e5
initial fluid volume fractions (1 to nf)
0.001 0.999 0.0 0.0
initial temperatures (4 fluids)
538.3 538.3 3073.0 3073.0
initial fluid axial velocities (1 to nf)
4*0.0
initial fluid radial velocities (1 to nf)
4*0.0

fluid region 2 (water)
1 2 7 10
initial system pressure (spatially uniform)
5.1e6
initial hydrogen partial pressure
0.0e5
initial fluid volume fractions (1 to nf)
0.001 0.999 0.0 0.0
initial temperatures (4 fluids)
538.3 538.3 3073.0 3073.0
initial fluid axial velocities (1 to nf)
4*0.0
initial fluid radial velocities (1 to nf)
4*0.0

region 3 - cover gas, modeled as water vapor
2 11 7 21
initial system pressure (spatially uniform)
5.1e6
initial hydrogen partial pressure
0.3e6
initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
initial temperatures (4 fluids)
538.3 538.3 3073.0 3073.0
initial fluid axial velocities (1 to nf)
4*0.0
initial fluid radial velocities (1 to nf)
4*0.0

region 4 - cover gas, modeled as water vapor
1 11 1 20
initial system pressure (spatially uniform)
5.1e6
initial hydrogen partial pressure
0.3e6
initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
initial temperatures (4 fluids)
538.3 538.3 3073.0 3073.0
initial fluid axial velocities (1 to nf)
4*0.0
initial fluid radial velocities (1 to nf)
4*0.0

region 5 - water vapor + melt
1 21 1 21
initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.36
$ initial fluid volume fractions (1 to nf)
0.99 0.0 0.0 0.01
$ melt
1.0 7*0.0
$ initial temperatures (4 fluids)
538.3 538.3 3073.0 3073.0
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ volume fraction equivalent to zero
1.e-5
$*** end fluid ic section
$*** vessel geometry
$ axial length of cell (m)
0.11 9*0.215556 11*0.094545
$
$ location of radial nodes, 1 to nrpl (1 = 0.0)
0.0 0.05 0.10 0.15 0.20 0.25 0.30 0.621
$
$ additional embedded interface cell connections
0
$ $*** structures input
$ structure input table size, convergence criteria, iterations
$ this has maxmod=0 to turn off structures input
2 1.0e-5 1.0e-6 1.0 10.
$ TERMOS melt catcher - water temperature
311 0 0 0 0 1 5 1 901 538.3
0.0
7 5 0.0 0.33 0.04 0.0 1.0 0.0 1.0
$ TERMOS external vessel - saturated steam temperature
2 1 0 0 0 2 0 1 5 2 900 538.3
300.7.5
0.0
4 5 0.355 0.621 2.050
$ $*** end structures
$ *** radiation input
$ number of radiation groups
1
$ max number of iterations
50
$ convergence criteria
1.0e-4
$ tbound
300.
$ emissivities
0.3 0.3 0.3 0.3 0.3 0.3 0.79
$ mass absorption coefficient
4*0.1
$
$*** end radiation
$*** debris data
0
50 1 2
0.60 0.70 0.08 0.0038 0.0
$ end of input deck
$
**Input deck for calculation 4**

```
FARO/TERMOS - 7rs - 25a zon. - L-14 - Ver. 6.0a - 0.01 m PID - ISP39

$***************************
$L-14 - L-14 - L-14 - L-14 - L-14 - L-14 - L-14 - L-14 - L-14 *
$L. 0.01 m of initial melt diameter, default inv. sound speed squared.
$***************************
$ this is set up for ifci v60a, mava

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*******************************************************************************
$data from :  
$D. Magallion, G. Leva : FARO LWR Programme
$Test L-14 Data Report
$Technical Note No. I.96.25
$A. Annunziato, C. Addabbo, G. Leva :
$OECD/CSNI International Standard Problem
$No. 39 on FARO Test L14
$Reference Specification

$begin general input section

$restart file (1=yes, 0=no)
0
$dumping time interval
2e-1
$plot interval
5.e-2
$edit interval
2.5e-1
$number of steps for main print (iprint>0)
2000
$print flags (3)
1 0 0
$number of axial mesh cells
25
$number of radial rings
7
$radiation time step control (gascoef)
.02
$start time in sec
0.0
$problem end time
5.0
$initial time step
1.0e-5
$number of entries (ntim) in table of maximum timestep versus time
4
$entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-5 0.1 1.0e-4 1.0 1.0e-3 100. 1.0e-2

$**end general input section

$begin fluids input

$ time step increase factor [if no other time step limitations present]
1.05
$ minimum time step
1.e-10
$ courant number to limit time step
0.25
$ minimum iterations to allow timestep increase
3
$ maximum iterations before failure
100
$ convergence error in pressure iteration (error)
1.e-6
$ maximum allowable relative change in volume fraction per time step
0.3

IFCI ENEL
```
$ maximum allowable relative change in temperature per time step
0.02
$ initial field 3 diameter dcor1
$ removed from calculations
0.000
$ initial field 4 diameter dcor2
$ jet entry diameter of 0.1 m - Particle Diameter of 0.01 m
0.01
$ material id's (8 #s)
$ u02(#1), and zro2(#4)
1 4 e+0
$
$*** following are additions to standard v52 melprog input
$
$ reference mass fractions for fields 3 and 4 (8 #s)
0.80 0.20 6e+0
$ reference pressure 5.1MPa
5.1e6
$ reference temperatures for fields 3 and 4 (2 #s)
3073.15 3073.15
$ inverse sound speed squared for fields 3 and 4 (2 #s)
2*1.0e-4
$
$### Ver. 6.0A additions
$ detonation flag and model selector - Ver. 6.0A
0 0
$ type 0 flag
1 1 0.01
$ type 1 flag
1 0.05
$ type 2 flag
0.01 0.001
$ fragmentation data (to be input only if det. model used)
$ explosion calculations with 0.1 mm particle
$ using the pressure threshold flag model (type 1)
0.0001 0.0001 0 10.
$### end of Ver. 6.0A
$### end of IFCI additions
$
$ number of time steps for minor print to ntty (1 line)
50
$ IIOUT, info print control (0 cycles thru)
0
$
$*** additive friction factors
$
$ number of additive regions
$
$1
$ field 1 - axial
$ ring 1
25*0.0
$ ring 2
14*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 2 - axial
$ ring 1
25*0.0
$ ring 2
14*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7

IFCI ENEL
20*0.0 1*1.e25 4*0.0
$ field 3 - axial
25*0.0
$ ring 2
16*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 4 - axial
25*0.0
$ ring 2
14*0.0 1.e25 5*0.0 1.e25 4*0.0
$ ring 3
20*0.0 1*1.e25 4*0.0
$ ring 4
20*0.0 1*1.e25 4*0.0
$ ring 5
20*0.0 1*1.e25 4*0.0
$ ring 6
20*0.0 1*1.e25 4*0.0
$ ring 7
20*0.0 1*1.e25 4*0.0
$ field 1 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$ field 2 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$ field 3 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0
$ ring 3
25*0.0
$ ring 4
25*0.0
$ ring 5
25*0.0
$ ring 6
25*0.0
$ ring 7
25*0.0
$ field 4 - radial
$ ring 1
25*0.0
$ ring 2
15*0.0 4*1.e30 6*0.0

IFCI ENEL
$ ring 3
  25*0.0
$ ring 4
  25*0.0
$ ring 5
  25*0.0
$ ring 6
  25*0.0
$ ring 7
  25*0.0
$
$*** end additive friction
$
$*** inflow boundaries
$
$ number of locations of inflow boundary conditions (ninbc) 0
$
$*** end of inlet bc section *****
$
$*** outflow boundary conditions ***********
$
$ Flow areas are areas of each annulus at top of problem domain.
$ Top areas of rings 1 and 2 (inflow Ecs) not included.
$ WBs are delta-r's of each ring.
$ number of locations for outlet pressure boundaries (npbc) 0
$ no outflow in quenching tests !!!! - other data left
$
$*** end outlet bc section
$ the following cards (to the end of fluids in) not included in restart
$*** fluid region input
$ number of fluid regions 2
$ 2 regions for the water temperature, data from Ispra Fax
$ 2 Constant Temperature of 263 deg.C (538.3 deg.K)
$ the variation is the same as for the first Base Case with Metallic Zr
$ fluid region 1 (water)
  1 1 7 2
$ initial system pressure (spatially uniform) 5.1e6
$ initial hydrogen partial pressure 0.00e6
$ initial fluid volume fractions (1 to nf) 0.0 1.0 0.0 0.0
$ initial temperatures (4 fluids) 538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf) 0.0 2.0 0.0 0.0
$ initial fluid radial velocities (1 to nf) 4*0.0
$ fluid region 2 (water)
  1 3 7 10
$ initial system pressure (spatially uniform) 5.1e6
$ initial hydrogen partial pressure 0.00e6
$ initial fluid volume fractions (1 to nf) 0.0 1.0 0.0 0.0
$ initial temperatures (4 fluids) 538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf) 0.0 2.0 0.0 0.0
$ initial fluid radial velocities (1 to nf) 4*0.0
$ region 3 - cover gas, modeled as water vapor
  3 11 7 25
$ initial system pressure (spatially uniform) 5.1e6
$ initial (argon as hydrogen) partial pressure 0.3e6
$ initial fluid volume fractions (1 to nf) 1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids) 538.3 538.3 538.3 3073.15
$ initial fluid axial velocities (1 to nf) 4*0.0
$ initial fluid radial velocities (1 to nf) 4*0.0

IFCI ENEL
$\text{region 4} - 125 \text{ kg of melt in two central cells}
1 1 1 17
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6
$\text{initial fluid volume fractions (1 to nf)}
0.0 0.0 0.0 1.0
$\text{field 4 mass fractions (same as inflow BC)}
0.80 0.20 6*0.0
$\text{initial temperatures (4 fluids)}
538.3 538.3 538.3 3073.15
$\text{initial fluid axial velocities (1 to nf)}
4*0.0
$\text{initial fluid radial velocities (1 to nf)}
4*0.0
$\text{region 5} - 125 \text{ kg of melt in two central cells}
2 1 1 17
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6
$\text{initial fluid volume fractions (1 to nf)}
0.0 0.0 0.0 1.0
$\text{field 4 mass fractions (same as inflow BC)}
0.80 0.20 6*0.0
$\text{initial temperatures (4 fluids)}
538.3 538.3 538.3 3073.15
$\text{initial fluid axial velocities (1 to nf)}
3*0.0 0.0
$\text{initial fluid radial velocities (1 to nf)}
3*0.0 -1.0
$\text{region 6} - \text{cover gas, modeled as water vapor}
1 11 1 15
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6
$\text{initial fluid volume fractions (1 to nf)}
1.000 0.0 0.0 0.000
$\text{initial temperatures (4 fluids)}
538.3 538.3 538.3 3073.15
$\text{initial fluid axial velocities (1 to nf)}
4*0.0
$\text{initial fluid radial velocities (1 to nf)}
4*0.0
$\text{region 7} - \text{cover gas, modeled as water vapor}
2 11 2 15
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6
$\text{initial fluid volume fractions (1 to nf)}
1.000 0.0 0.0 0.000
$\text{initial temperatures (4 fluids)}
538.3 538.3 538.3 3073.15
$\text{initial fluid axial velocities (1 to nf)}
4*0.0
$\text{initial fluid radial velocities (1 to nf)}
4*0.0
$\text{region 8} - \text{cover gas, modeled as water vapor}
1 18 1 25
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6
$\text{initial fluid volume fractions (1 to nf)}
1.0 0.0 0.0 0.0
$\text{initial temperatures (4 fluids)}
538.3 538.3 538.3 3077.15
$\text{initial fluid axial velocities (1 to nf)}
4*0.0
$\text{initial fluid radial velocities (1 to nf)}
4*0.0
$\text{region 9} - \text{cover gas, modeled as water vapor}
2 18 2 25
$\text{initial system pressure (spatially uniform)}
5.1e6
$\text{initial hydrogen partial pressure}
0.3e6

IFCI ENEL
initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
initial temperatures (4 fluids)
530.3 530.3 538.3 3077.15
initial fluid axial velocities (1 to nf)
4*0.0
initial fluid radial velocities (1 to nf)
4*0.0
volume fraction equivalent to zero
1.e-5
end fluid ic section
vessel geometry
axial length of cell (m)
0.11 9*0.215555 5*0.298 2*0.285 4*0.09625 4*0.280
location of radial nodes, 1 to nrp1 (1 = 0.0)
0.0 0.046 0.098 0.15 0.20 0.25 0.30 0.355
additional embedded interface cell connections
0
structures input
structure input table size, convergence criteria, iterations
this has maxmod=0 to turn off structures input
2 1.0e-6 1.0e-6 10 10
TERMOS melt catcher - water temperature
31 1 0 0 0 0 1 5 1 901 538.3
7.5 0.0 0.33 0.04 0.0 1.0 0.0 1.0
TERMOS external vessel - saturated steam temperature
11 1 0 0 2 0 1 5 2 900 538.3
300. 7.5
7.5 0.355 0.400 4.621
end structures
radiation input
number of radiation groups
1
max number of iterations
50
convergence criteria
1.0e-4
tbound
300.
emissivities
0.3 0.3 0.3 0.3 0.79
mass absorption coefficient
4*0.1
end radiation
debris data
6
50 9 2
0.6 0.55 0.05 0.0035 0.0
end of input deck
E.7 - Participants comments

IFCI includes a subroutine for the calculation of the corium physical properties, with many pre-selected materials. It is also able to calculate properties for mixtures of single materials. To accommodate the physical properties recommended in the ISP39 Reference Specification, a new material was introduced in the list (IMAT = 2).

Moreover, the code assumes that fluid fields can enter (or exit) the problem domain only at the outer boundaries. It was so impossible to simulate the melt inlet velocity recommended in the ISP39 Reference Specification for the FARO situation, in which the melt ‘enters’ the problem domain inside the domain itself, because the melt catcher is located inside the TERMOS vessel.

Three alternative approaches were possible:

1. Insert all the melt inside the problem domain from the beginning, simulating the structure of the melt catcher. In this case, the code would calculate the melt exit velocity taking into account the melt inertia, the relative motion of the surrounding steam atmosphere, melt-steam heat exchange, etc. The recommended melt exit velocity is instead calculated resolving only the momentum equation of the melt exiting the melt catcher, and so cannot be properly simulated.

2. Inject the melt from the outside of the problem domain, simulating the whole length and diameter of the TERMOS vessel. The melt inlet velocity could be correctly simulated, but with a higher melt free fall, because the melt is injected from the top of the vessel dome, and not from the melt catcher exit.

3. Inject the melt from the outside of the problem domain, simulating the correct free fall, but distort the vessel diameter, in order to simulate the right total gas volume. In this case, the water volume is not correctly simulated.

Any of the previous possibilities has deficiencies as regards both the correct simulation of the test and the correct simulation of the agreed boundary conditions, even if hypothesis 1 should be the code ‘best estimate’ for melt exit velocity.

It was decided to run four calculations, as follows:

1. A case, termed SPG, in which hypothesis 1 was made, and IMAT = 2 (case proposed for the ISP39 benchmark comparison);

2. A case, termed SP, in which hypothesis 2 was made, and IMAT = 2;

3. A case, termed SB, in which hypothesis 3 was made, and IMAT = 2;

4. A ‘best estimate’ case, termed SG, in which hypothesis 1 was made, and the original subroutine of the code is used to determine the corium physical properties.

Common to all calculations were the following hypotheses:

1. Argon was simulated in the code with hydrogen, that is the only non-condensible modelled in the IFCI Code.

2. Melt was injected as droplets, and the initial melt drop diameter was taken 1.0 cm, on the basis of the Kutateladze droplet stability principal, as in all previous FARO-TERMOS IFCI calculations.
3. Gas volumes due to the communication line between TERMOS and separator, the separator and the line connecting the separator with the exhaust valves were simulated as directly added to the TERMOS gas volume. No connecting line is modelled. The hypothesis was based on the consideration that TERMOS pressure and separator pressure were experimentally found always identical both as value and as timing.

4. Water volume was simulated in two regions, one for the bottom slightly sub-cooled, and the rest at saturation temperature.

5. Time zero of the simulation was set at the start of melt injection.

Results of the IFCI code were reasonably good, when compared with the experimental results, even in the short period (up to one second from the start of melt injection), both in terms of TERMOS pressure and water and/or steam temperatures.

As already mentioned, uncertainties related to the melt fragmentation during the period of melt discharge from the melt release vessel were solved only in a parametric way, mainly for lack of information regarding the actual jet shape and behaviour, even if it is recognised that those data appear almost impossible to obtain from in-situ measurements.
F. - IFCI-KAERI Calculations

F.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Korea Atomic Energy Research Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>Moonkyu Hwang</td>
</tr>
<tr>
<td></td>
<td>KAERI</td>
</tr>
<tr>
<td>Address:</td>
<td>P.O. Box 105</td>
</tr>
<tr>
<td></td>
<td>Yusong, Taegon</td>
</tr>
<tr>
<td></td>
<td>KOREA 305-600</td>
</tr>
<tr>
<td>Tel:</td>
<td>0082-42-868 2696</td>
</tr>
<tr>
<td>Fax:</td>
<td>0082-42-861 2574</td>
</tr>
<tr>
<td>e-mail:</td>
<td><a href="mailto:mkhwang@nanum.kaeri.re.kr">mkhwang@nanum.kaeri.re.kr</a></td>
</tr>
</tbody>
</table>

F.2 - Initial and boundary conditions

Two calculations have been performed with IFCI code. Initially only the first calculation was submitted. In this calculation the particle initial diameter was set to 9 cm. The second calculation with a particle initial diameter of 3 cm was requested during the second ISP-39 workshop in April 1997. The initial and boundary conditions valid for both calculations are reported in the following Table.

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>KAERI</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>126.2</td>
<td>+1.2</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1042</td>
<td>+0.0122</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.035</td>
<td>-0.005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Water in test vessel</strong></th>
<th>EXPERIMENT</th>
<th>KAERI</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>624.4</td>
<td>+1.4</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.016</td>
<td>-0.034</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536.8</td>
<td>-</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>1.94</td>
<td>+0.74</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.79</td>
<td>-</td>
</tr>
</tbody>
</table>

| **Gas Phase**           |            |        |            |
| Composition, w%         | 77 steam + 23 Argon | 77 steam + 23 H₂ | H₂ instead of Ar +0.021 |
| Volume, m³              | 1.26       | 1.281  |            |
| Temperature, K          | 536        | 536    | -          |
| Pressure, MPa           | 5.1        | 5.1    | -          |
F.3 - Code nodalization

The total active volume (thermos vessel and connected gas volume) is nodalized as seen in Fig. 1. The configuration is a little different from the actual geometry. The total height in Fig. 1 (h₁+h₂) is that of jet nozzle height of thermos vessel. Under the current version of IFCI, which allows exact velocity control only through the inlet boundary condition, this was unavoidable to meet the melt inlet boundary condition of ISP-39. The thermos gas volume above the melt inlet nozzle is now moved to V₂' in the diagram. The gas volume inside of thermos vessel (0.76 m³) is, therefore, represented by V₂ and V₂'.

The gas volume outside of thermos vessel is now modelled as V₂''. There is only one open connection between V₂' and V₂''. Finally, water is represented by V₃. The height h₁ for region V₁ is adjusted to 2.016 m instead of 2.050 m, i.e. 1.7% lower, to maintain the same water volume with constant radius in the water zone. The radial node size for V₁ and V₂ is constant and is denoted as (Δr)₁. The axial node size for V₁ is constant as (Δh)₁, and for V₂, V₂' and V₂'' they are same value as (Δh)₂. The actual values of the parameters found in the Fig. 1 are as below.

h₁ = 2.016m  (Δh)₁ = 0.1008m  r₁ = 0.355m  (Δr)₁ =0.05071m  V₁ = 0.798m³
h₂ = 1.035m  (Δh)₂ = 0.1035m  r₂ = 0.6287m  (Δr)₂ =0.09123m  V₂ = 0.4098m³
h₃ = 0.414m  r₃ = 0.8921m  (Δr)₃ =0.1317m  V₂' = 0.3502m³  V₂'' = 0.521m³
F.4 - Comparison of calculations with the experiment

F.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position

IFCI KAERI
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m$^3$
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>IFCI KAERI</td>
<td>0.25 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>IFCI KAERI</td>
<td>0.75 s</td>
</tr>
</tbody>
</table>

IFCI KAERI
F.4.2 Additional calculation

In the additional calculation the initial diameter was set to 3 cm.

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position

IFCI KAERI
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position

IFCI KAERI
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position

IFCI KAERI
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate

IFCI KAERI
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time
F.5 - Code description

The code used was IFCI version 6.01. The fragmentation model, heat transfer, and vapor generation are internal of the code and not user selectable. The models are described in NUREG/CR-6211.
F.6 - Code input deck

PARO test L-14 using IFCl6.01
$ This is a simulation of the PARO L-14
$ begin general input section
$ restart file (1=yes, 0=no)
0
$ time intervals
$ dump plot edit
 1.0 0.025 1e-1
$ number of steps for main print (iprint>0)
1
$ print flags (3)
1 0 0
$
$ number of axial mesh cells
30
$ number of radial rings
12
$ radiation time step control (gascoef)
0.01
$ start time in sec
0.50
$ problem end time
6.0
$ initial time step
1.0e-6
$ number of entries (ntim) in table of maximum timestep versus time
4
$ entries in maximum time step table (ntim * (time, max time))
0.0 1.0e-3 2.0 1.0e-3 5.0 3.0e-3 100.0 1.0e-2
$
$***end general input section
$
$ begin fluids input
$
$ time step increase factor (if no other time step limitations present)
1.05
$ minimum time step
1.e-10
$ courant number to limit time step
0.25
$ minimum iterations to allow timestep increase
4
$ maximum iterations before failure
25
$ convergence error in pressure iteration (error1)
1.0e-7
$ maximum allowable relative change in volume fraction per time step
0.250
$ maximum allowable relative change in temperature per time step
0.050
$ condensation coefficient
1.0
$ initial field 3 diameter dcor1
$ data irrelevant (field 3 not used)
0.0024
$ initial field 4 diameter dcor2
$ data
0.09
$ material id's (8 #s)
$ uo2(#1), and zr2(#4)
 1 4 6*0
$
$*** following are additions to standard v52 melprog input
$
$ reference mass fractions for fields 3 and 4 (8 #s)
0.8 0.2 6*0.0
$ reference pressure
8.0e6
$ reference temperatures for fields 3 and 4 (2 #s)
3000.0 3099.0

IFCI KAERI
$ inverse sound speed squared for fields 3 and 4 (2 #s)
$ same as default
 2*1.0e-4
$
$ detonation flag and model selector
 0 0 1
$ type 0 flag
 16 1 0.01
$ type 1 flag
 10.0e6
$ type 2 flag
 0.01 0.001
$ fragmentation data (to be input only if det model used)$
 0.001 0.00001 0 10.
$
$ number of time steps for minor print to ntty (1 line)
 50
$ IFOOT, info print control (0 cycles thru)
 8
$
*** additive friction factors
$
$ number of additive regions
 3
$
 7 1 7 26
$
 26*0.0
$
 26*0.0
$
 26*0.0
$
 26*0.0
$
 26*1.0e21
$
 26*1.0e21
$
 26*1.0e21
$
 26*1.0e21
$
 8 26 12 26
$
 1.0e21
 1.0e21
 1.0e21
 1.0e21
$
 1.0e21
 1.0e21
 1.0e21
 1.0e21
$
 1.0e21
 1.0e21
 1.0e21
 1.0e21
$
 1.0e21
 1.0e21
 1.0e21
 1.0e21
$
 1.0e21
 1.0e21
 1.0e21
 1.0e21
$
 0.0
 0.0
 0.0
 0.0
$
 0.0
 0.0
 0.0
 0.0

IFCI KAERI
0.0
0.0
0.0
0.0
0.0
0.0
10 27 10 29
3*0.0
3*0.0
3*0.0
3*0.0
3*1.0e21
3*1.0e21
3*1.0e21
3*1.0e21
*** end additive friction
*** INFLOW BOUNDARIES
number of locations of inflow boundary conditions (ninbc) 1
ring number of inflow cell (INN) 1
axial location of inflow condition (NMAX+1) 31
flow area 8.07862e-3
number of entries in inflow pressure condition tables 2
number of entries in inflow velocity tables 22
number of entries in inflow temperature tables 2
number of entries in inflow volume fraction tables 4
inflow pressure table (time, pressure) 0.0 5.1e6 100.0 5.1e6
inflow hydrogen partial pressure table (time, pressure) 0.0 0.0 100.0 0.0
inflow velocity, temp, vol frac, and compos. table (time, *)
Field 1
velocity
0.0 0.0
0.05 0.0
0.1 0.0
0.15 0.0
0.2 0.0
0.25 0.0
0.3 0.0
0.35 0.0
0.4 0.0
0.45 0.0
0.5 0.0
0.55 0.0
0.6 0.0
0.65 0.0
0.7 0.0
0.75 0.0
0.8 0.0
0.85 0.0
0.9 0.0
0.95 0.0
0.975 0.0
1.0 0.0
<table>
<thead>
<tr>
<th>Field</th>
<th>Temperature</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0 538.4</td>
<td>0.0 100.0 538.4</td>
</tr>
<tr>
<td></td>
<td>0.0 0.17714</td>
<td>0.975 0.17714 0.9751 1.0 100.0 1.0</td>
</tr>
<tr>
<td>3</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
<tr>
<td>4</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
</tbody>
</table>

**Temperature**

<table>
<thead>
<tr>
<th>Field</th>
<th>Temperature</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0 538.4</td>
<td>0.0 100.0 538.4</td>
</tr>
<tr>
<td></td>
<td>0.0 0.17714</td>
<td>0.975 0.17714 0.9751 1.0 100.0 1.0</td>
</tr>
<tr>
<td>3</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
<tr>
<td>4</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
</tbody>
</table>

**Velocity**

<table>
<thead>
<tr>
<th>Field</th>
<th>Temperature</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0 538.4</td>
<td>0.0 100.0 538.4</td>
</tr>
<tr>
<td></td>
<td>0.0 0.17714</td>
<td>0.975 0.17714 0.9751 1.0 100.0 1.0</td>
</tr>
<tr>
<td>3</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
<tr>
<td>4</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
</tbody>
</table>

**Volume Fraction**

<table>
<thead>
<tr>
<th>Field</th>
<th>Temperature</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0 538.4</td>
<td>0.0 100.0 538.4</td>
</tr>
<tr>
<td></td>
<td>0.0 0.17714</td>
<td>0.975 0.17714 0.9751 1.0 100.0 1.0</td>
</tr>
<tr>
<td>3</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
<tr>
<td>4</td>
<td>Velocity</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td></td>
<td>0.0 0.0</td>
<td>0.0 0.975 0.0 0.9751 0.0 100.0 0.0</td>
</tr>
</tbody>
</table>
0.95 -2.277
0.9 -1.677
0.95 -0.69
0.975 0.0
100.0 0.0
$ temperature
0.0 3073. 100.0 3073.
$ volume fraction
0.0 0.92286 0.975 0.82286 0.9751 0.0 100.0 0.0
0.8 0.2 6*0.0
0.8 0.2 6*0.0
$*** end of inlet bc section *****
$
$*** outflow boundary conditions ***********
$
$ Flow areas are areas of each annulus at top of problem domain.
$ Hs are delta-r's of each ring.
$
$ number of locations for outlet pressure boundaries (npbc)
0
$*** end outlet bc section
$ the following cards (to the end of fluids in) not included in restart
$*** fluid region input
$ number of fluid regions
4
$ FLUID REGION 1 (Water)
1 1 7 20
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.0e6
$ initial fluid volume fractions (1 to nf)
0.0001 0.9999 0.0 0.0
$ initial temperatures (4 fluids)
2*536.8 3073.0 3073.0
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ FLUID REGION 2 (vapor)
1 21 7 30
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.7e6
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
4*536.0
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ FLUID REGION 3 (vapor)
8 27 12 30
$ initial system pressure (spatially uniform)
5.1e6
$ initial hydrogen partial pressure
0.7e6
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
4*536.0
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ FLUID REGION 4 (Blank Region)
8 1 12 26
$ initial system pressure (spatially uniform)
0.1e6
$ initial hydrogen partial pressure
0.08006e6
$ initial fluid volume fractions (1 to nf)
1.0 0.0 0.0 0.0
$ initial temperatures (4 fluids)
4*332.69
$ initial fluid axial velocities (1 to nf)
4*0.0
$ initial fluid radial velocities (1 to nf)
4*0.0
$ volume fraction equivalent to zero
 1.e-16
$*** end fluid ic section
$*** vessel geometry
$ axial length of cell (m)
 20*0.1008 10*0.1035
$
$ location of radial nodes, 1 to nrpi (1 = 0.0)
 0.0 0.05071 0.1014 0.1521 0.2029 0.2536 0.3043 0.355 0.4462 0.5375
 0.6287 0.7604 0.8921
$
$ additional embedded interface cell connections
0
$
$*** structures input
$
$ structure input table size, convergence criteria, iterations
$ this has maxmod=0 to turn off structures input
$
0 1.0e-6 1.0e-6 10 10
$*** end structures
$
$*** radiation input
$
$ number of radiation groups
1
$ max number of iterations
50
$ convergence criteria
1.0e-5
$ thebound
300.
$ emissivities
0.3 0.3 0.3 0.3 0.3 0.3
$ mass absorption coefficient
4*0.1
$
$*** end radiation
$*** debris data
0
$ 1 2
 0.8 0.70 0.08 0.0045 0.0
$
$*** end debris
$*** end input deck ***
$

IFCI KAERI
F.7 - Participants comments

The underprediction of pressure seems mainly due to the inefficient heat transfer from melt to other interfacing fluids (water and gas). Also reportedly, current version of IFC1 needs improvement in the area of condensation. I was able to increase the pressure rise similar to the experimental value by cutting off the condensation (via Input data), but this wouldn't be the ISP-39 interest.
G. - IVA KA-FZK Calculations

G.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Forschungszentrum Karlsruhe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>L. Vaeth, H. Jacobs</td>
</tr>
<tr>
<td>Address:</td>
<td>Institut furNeutronenphysik und Reaktortechnik</td>
</tr>
<tr>
<td></td>
<td>Postfach 3640</td>
</tr>
<tr>
<td></td>
<td>D-76021 Karlsruhe</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
</tr>
<tr>
<td>Tel:</td>
<td>0049-7247-822443</td>
</tr>
<tr>
<td>Fax:</td>
<td>0049-7247-823824 or 4874</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:lisa.vaeth@fzk.inr.de">lisa.vaeth@fzk.inr.de</a></td>
</tr>
</tbody>
</table>

G.2 - Initial and boundary conditions

Two calculations have been performed with IVA-KA code. Initially only one calculation was submitted to the ISP-39. Since the energy balance in this calculation was not satisfactory, FZK decided to run a second calculation in February 1997 introducing an approximate correction of the error in the entropy equation. During the second ISP-39 workshop in April 1997, it was decided to add the results of the second calculation to the final report.

The initial and boundary conditions valid for both calculations are reported in the following Table.

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>FZK</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>124.75</td>
<td>-0.25</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092252</td>
<td>+0.000252</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>Gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
<td>-</td>
</tr>
</tbody>
</table>

**Water in test vessel**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>631.6</td>
<td>+8.6</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536.8</td>
<td>-</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>2.09</td>
<td>+0.89</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.818</td>
<td>+0.02</td>
</tr>
</tbody>
</table>

**Gas Phase**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>82.3 steam + 17.7 air</td>
<td>air instead of Ar</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.26</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536</td>
<td>-</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>

IVA-KA FZK
G.3 - Code nodalization

The calculation is 2d cylindrical.

The FARO geometry has to be cut off at the level of the melt outlet in order to accommodate the prescribed melt inlet velocity (only possible as boundary condition on an outer boundary in IVA-KA). All volume situated above this level had to be modelled as volume radially surrounding the test vessel. This results in three radial rings around the test vessel, the first one simulating the test vessel volume above the melt outlet, the second one the communication line, and the third one the separator + additional volume until exhaust valve.

Junctions of the radial volumes: The test vessel is radially closed at radius .355 m except for the uppermost axial zone, which is radially open. The first radial ring is connected to the second one via the outer radial surface of the lowest axial zone, which has a permeability of .078; this results in about the cross section of the communication line. The second radial ring is connected to the third one via the outer radial surface of the uppermost axial zone with a permeability of .05, which is again about the cross section of the communication line.

The total volume is closed on the outside except for the two radially innermost, axially uppermost zones, which are open on top in order to accommodate the melt. Only melt enters the volume through this opening, with the prescribed velocity, and no material enters or leaves the calculational domain after .975 s.

Number of radial nodes: 8 in test vessel, 11 total

Number of axial nodes: 45
1SP-38 geometry
used by IVA-KA

open boundary
permeable boundary (p = 0.05)

permeable boundary (p = 0.02)

HEI GHT (cm)
0 10 20 30 40 50 60

MINIMUM (cm)
0 10 20 30 40 50 60
G.4 - Comparison of calculations with the experiment

G.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position

IVA-KA FZK
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>IVA-KA FZK</td>
<td>0.34 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>IVA-KA FZK</td>
<td>0.92 s</td>
</tr>
</tbody>
</table>
G.4.2 Additional calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

IVA-KA FZK
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position

IVA-KA FZK
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time
G.5 - Code description or code models/options

No code description is available at the moment. IVA-KA has been derived from the older code IVA-3, which is described in the following three reports:


Many of the models contained in the old code remain unchanged. The most important options used are summarised below:

Three material "fields" are modelled by the code. The first one contains a mixture of steam and air, the second one liquid water, and the third one a normally hot, heavy material ("corium") in the liquid or solid state. A Cartesian mesh is used. The model can be up to 3d (2d is used for this calculation), rectangular or cylindrical (cylindrical for this calculation), and is to be subdivided into a number of cells in a rectangular grid. Time dependent volume fractions of the three material fields (and their state variables, velocities etc.) are calculated for each cell. A flow regime is assigned to each cell, depending on the volume fraction of the fields and in part on their physical state and the modelling of the transfer of mass, momentum and energy depends on this flow regime.

Heat transfer between gas, water and melt is by film boiling and radiative heat transfer to water and steam with a model distinguishing between radiant heat transferred to the surface of the water (instant vaporisation) and to its bulk (heating of the bulk water). Radiative heat transfer is restricted to one calculational cell, i.e. the radiative heat transfer over long distances is not modelled. Steam condensation takes place in regions where the water temperature is below saturation.

Melt fragmentation/coalescence: The code does not contain an explicit jet model, but as long as the melt has not solidified, a flow regime with continuous melt can (and does in the case of ISP-39) occur. When changing from this regime to one with discontinuous melt, an initial particle size of .1 m is assumed. Further fragmentation and coalescence are calculated by the code until the melt cools down to 40% liquidus, where solidification is assumed. Fragmentation tends to dominate as long as the melt moves, whereas coalescence tends to dominate in melt settling down. Particle sizes do not change any more after solidification except through thermal shrinking and mixing with particles from other calculational zones. The following results on the downward progression of the "jet" are calculated for ISP-39:

Continuous melt reaching down to a height of: 1.21 m
Material with droplet diameter > .01 m down to: The bottom
G.6 - Code input deck

ISP-39 CALCULATION A CODE: IVA-KA SUBMITTED BY: KFK-INR (L. VAETH)
ALL UNITS: INTERNATIONAL STANDARD UNITS

IVA-KA INPUT FOR ISP-39, STATUS 20. 11. 96

** 1. GENERAL INPUT **
*CONTROL PARAMETERS (K1-K3)
  F
  T T T
  400 200 5

*ACCURACIES (K4)
  L.E-5 1.0E+1 1.0E-4 1.0E-6 1.0E-3 1.0E-4

*TIMES (K5)
  0.9 250. 0. 1.0E-7 .1 .2

*CONTROL PARAMETERS, TYPE OF GEOMETRY (K6-K8)
  3
  0 0 0
  F F F

*TITLE (K9)
  'BENCHMARK. ISP-39' '125 KG 3073 K' 'CALC. A' '' ''

*LIMIT FOR FRACTION OF COMPONENTS, ACCURACIES (K10-K11)
  3*1.0E-6
  1.0E+5 30. 10. 10.

*RELAXATION PARAMETERS, NUMBER OF ITERATIONS (K12-K13)
  6*1.
  1 1

** 2. GEOMETRY **
*NUMBER OF SPATIAL NODES, KIND OF GRID (K15-K17)
  T F
  11 1 45

*RADIAL, ANGULAR, AXIAL NODES (K21)
  0 0 0 23063 .946126 .1 .15 .20 .25 .30 .355
  .461953 .474276 .509865
  0 .785398
  .80 .04 .09 .16 .23 .30 .37 .44 .51 .58 .65 .72 .79 .86
  .93 1.00 1.07 1.14 1.21 1.28 1.35 1.42 1.49 1.56 1.63 1.70 1.77 1.84
  1.91 1.98 2.05
  2.12 2.19 2.26 2.33 2.40 2.47 2.54 2.61 2.68 2.75 2.82 2.89 2.96 3.03

*RROUGHNESS, PARTICLE DIAMETERS, DVOL (K22)
  0.0001 .0001 .0001

*RADIAL PERMEABILITIES (K23-K25)
  5
  9 2 2 2 45 0.
  10 2 2 2 4 0.
  10 2 2 2 2 0.78
  11 2 2 2 4 0.
  11 2 2 2 4 0.
  12 2 2 2 4 0.

*AZIMUTHAL PERMEABILITIES (K26)
  0

*AXIAL PERMEABILITIES (K29-K31)
  2
  46 2 3 2 2 2 2 2 2 2 1. *MELT INLET
  47 2 3 2 2 2 2 2 2 2 1. *MELT INLET, VIRTUAL CELL

*VOLUMETRIC POROSITIES - ALL VOLUME FREE (K32)
  0

*HYDRAULIC DIAMETERS (K35-K37)
  3
  2 10 2 2 2 4 6 1. 1. 1. 1.1 *VESSEL
  11 11 2 2 2 2 4 6 1. 1. 1. 1.1 *SEPARATOR LINE
  12 12 2 2 2 2 4 6 1. 1. 1. 1.1 *SEPARATOR

*ADDITIONAL HYDRAULIC DIAMETERS (NONE) (K38)
  0

*NUCLEAR REACTOR? (NONE) (K41)
  F F

*FINAL CORRECTION OF PERMEABILITIES AND POROSITIES (NONE) (K42)
  0

** 3. INITIAL CONDITIONS **
*INITIAL PRESSURE DISTRIBUTION BY VOLUME (K45-K47)
  2
  1 13 1 3 1 47 5100000. 5100000.
  1 10 1 3 2 31 5115500. 5100300. *GAS SPACE

*ADDITIONAL PRESSURE INITIALIZATION BY PLANE OR NODE (NONE) (K48-K51)

IVA-KA FZK
<table>
<thead>
<tr>
<th>Field 1 (Gas): Temp., Inert Mass Conc., Vol. Fraction</th>
<th>(K55-K57)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 13 1 3 1 47 536. 536. 2.177 1. 1.</td>
<td>*Gas</td>
</tr>
<tr>
<td>2 9 2 2 2 31 536.8 536.8 2.177 0.0</td>
<td>*Water</td>
</tr>
<tr>
<td>Field 2 (Water): Temp., Inert Mass Conc., Vol. Fraction</td>
<td>(K55-K57 FF)</td>
</tr>
<tr>
<td>1 13 1 3 1 47 536. 536. 0 0. 0. 0</td>
<td>*Gas</td>
</tr>
<tr>
<td>2 9 2 2 2 31 536.8 536.8 0 0. 1.0</td>
<td>*Water</td>
</tr>
<tr>
<td>Field 3 (Metal): Temp., Inert Mass Conc., Vol. Fraction</td>
<td>(K55-K57 FF)</td>
</tr>
<tr>
<td>1 13 1 3 1 47 3073. 3073. 1. 1. 0. 0</td>
<td>*Water</td>
</tr>
</tbody>
</table>

**Composition of Field 3 (Not Used) (K62-K65)**

**Initial Velocities for all 3 Fields (Nom. Assumption) (K68-K70)**

**4. Boundary Conditions**

**Definition of Cells for Melt Inlet (BC 1) (K76-K78)**

**Number of Points for Defining Time Dependence (K86)**

**Time Dependence of Pressure (K82)**

**Time Dependence of Inert Mass Concentrations (K84)**

**Time Dependence of Volume Fractions (K86)**

**Time Dependence of Temperatures (K88)**

**Time Dependence of Particle Number Densities (K90)**

**Definition of Cells for Melt Velocity (BC 4) (K76-K78)**

**Number of Points for Defining Velocity (K97)**

**Time Dependence of Melt Velocity (K99)**

---

**IVA-KA FZK**
<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
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<td>0.</td>
</tr>
</tbody>
</table>

**5. VARIABLE SURFACE PERMEABILITIES**

**VARIABLE PERMEABILITIES (NO) (K103)**

**F**

**6. EXTERNAL MASS SOURCES**

**SOURCES (NONE) (K113)**

0

**7. VISART INPUT**

**VISART INPUT (K133)**

1

**SPACE DEPENDENT QUANTITIES** (K135-K138)

1. 'P' 'AL' 'AL' 'AL' 'T' 'T' 'T' 'DIAPM'

**TIME DEPENDENT INTEGRAL QUANTITIES** (K139-K143)

19. 'MASSTOT' 'SURFACE' 'ENTHALP' 'WATRTOT' 'GASTOT'

**VINAMI1' 'VINAMI2' 'VINAMI3' 'VINAMI4' 'VINAMI5'**

**VINAMI6' 'VINAMI7' 'VINAMI8' 'VINAMI9' 'VINAMI10'**

**VINAMI11' 'VINAMI12' 'VINAMI13' 'VINAMI14'**

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

**TIME AND CELL DEPENDENT QUANTITIES** (K145-K149)

8. 'P' 'P' 'T' 'T' 'T' 'T' 'T' 'T'

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0


2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2

46 38 8 8 14 14 19 19

IVA-KA FZK
G.7 - Participants comments

Comments to calculation 1

- Due to the geometry adopted, some water and melt are transported out of the test vessel into radial ring 1 during the transient. They fall down through ring 1 and gather in the downmost zones of ring 1 and 2 at the end of the calculation. The masses are:
  - water: 19.85 kg
  - melt: .22 kg

- The quenching rate (quantity 15) had to be deduced from the large, slowly varying total energies of water and steam, which are the plot data provided by the code. This resulted in differences of nearly equal numbers for the small time steps used by the code. I therefore chose to calculate only an average for every 10 time steps combined, as is evident from the list of time dependent results.

- Quantity 16 is the mass of corium with droplet/particle diameter < .01 m.

- Quantities 17 and 22 are D(50%) according to Technical Note No. I.96.64, with all continuous melt and all melt with diameters >= .01 m disregarded. Note that IVA-KA models either continuous material or droplets/particles with one diameter per calculational zone. The average values given are values averaged over the calculational domain.

Comments to calculation 2

- The geometry, code input and initial and boundary conditions for this calculation are all identical to calculation 1, the calculation submitted in December 1996.

The only difference between calculations 1 and 2 is the approximate correction of the error in the entropy equation.

- One of the main differences between the results of the two calculations, that is not evident from the data submitted, is in the formation of the "jet" (i.e. the string of cells containing continuous melt, since IVA-KA does not contain a real jet model). This "jet" penetrates down to 1.21 m in calculation 1 and is dispersed below - see data at the end of item 4 in my December 1996 communication. In calculation 2, the "jet" reaches down all the way to the bottom. There it forms large (10 cm diameter) drops and/or regions filled with continuous melt, and, in the outer zones, smaller droplets or solid particles. All melt disintegrates at solidification at the latest, since a model for continuous solidified melt is not foreseen in IVA-KA.

The following comments are a repetition of those made for calculation 1:

- The quenching rate (quantity 15) had to be deduced from the large, slowly varying total energies of water and steam, which are the plot data provided by the code. This resulted in differences of nearly equal numbers for the small time steps used by the code. I therefore chose to calculate only an average for every 10 time steps combined, as is evident from the list of time dependent results.

- Quantity 16 is the mass of corium with droplet/particle diameter < .01 m.

- Quantities 17 and 22 are D(50%) according to Technical Note No. I.96.64, with all continuous melt and all melt with diameters >= .01 m disregarded. Note that IVA-KA models either continuous material or droplets/particles with one diameter per calculational zone. The average values given are values averaged over the calculational domain.
### H. - IVA 4-Siemens Calculations

#### H.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>SIEMENS KWU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>N. Kolev</td>
</tr>
<tr>
<td>Address:</td>
<td>SIEMENS KWU</td>
</tr>
<tr>
<td></td>
<td>KWU NA-M</td>
</tr>
<tr>
<td></td>
<td>D-91050 Erlangen</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
</tr>
<tr>
<td>Tel:</td>
<td>0049-9131-18 6340</td>
</tr>
<tr>
<td>Fax:</td>
<td>0049-9131-18 3374</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:kolev@na-m.kwu.siemens.de">kolev@na-m.kwu.siemens.de</a></td>
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</table>

#### H.2 - Initial and boundary conditions

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<thead>
<tr>
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<th>EXPERIMENT</th>
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<th>Difference</th>
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<tr>
<td><strong>Melt</strong></td>
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</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
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</tr>
<tr>
<td>Mass, Kg</td>
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<td>125</td>
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</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
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</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1</td>
<td>+0.008</td>
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<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
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</tr>
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<td>Free fall in gas, m</td>
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<td><strong>Water in test vessel</strong></td>
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<td>Mass, Kg</td>
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<td>Depth, m</td>
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<tr>
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<tr>
<td>Subcooling at melt contact, °C</td>
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<td>Total water volume, m³</td>
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<td><strong>Gas Phase</strong></td>
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<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>77 steam + 23 air</td>
<td>air instead of Ar</td>
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<td>Pressure, MPa</td>
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</table>
H.3 - Code nodalization

The simulation was performed assuming axisymmetric process in 2D geometry with (9x62=558) cells.
H.4 - Comparison of calculations with the experiment

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

IVA-4 Siemens
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position

IVA-4 Siemens
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level

IVA-4 Siemens
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
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<tr>
<td>IVA-4 Siemens</td>
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Quantity: 21 - Melt/Bottom contact

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H.5 - Code description or code models/options

The computer code IVA4 models transient multiphase flows consisting of water, steam, noncondensable gases, microscopic and macroscopic solid particles and/or molten materials. Three velocity fields in 3D space in thermal and mechanical non equilibrium to each others are used. The geometry is defined by surface permeabilities and volumetric porosities as time functions in such a manner that arbitrary technical facilities can be represented. The concept of dynamic fragmentation and coalescence of all the velocity fields is used, which is very important for instance for steam explosion analysis. This is the first time computer code for multi-phase flow analysis simulating dynamic fragmentation and coalescence for each of the velocity fields simultaneously. Complete list of IVA4 references documenting the history of the development and the verification procedure is published in [2]. Uncertainty of the final results due to the propagation of the uncertainty of the separate effect models are analysed by Kolev and Hoffer in [3].

All elements of the code are addressed in such complicated simulation e.g. code architecture, numerical methods, constitutive models etc. The simulation of the FARO test will reveal the capability of the code to handle such flows with simultaneous evaporation condensation fragmentation of all participating velocity fields etc. Among these are some important constitutive models which are addressed during the computation and their performance will also be tested. These models are verified by comparison with experimental data for separated effect test - for the chronology of the verification see [1]. Here the model interaction in such complicated flow is challenged.

The simulation was performed assuming axisymmetric process in 2D geometry with (9x62=558) cells on an SGI Indigo 2 work station with a 1.3 MBt load module. It takes 6443 CPU seconds.


### H.6 - Code input deck

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**48**

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**52**

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<tbody>
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<tbody>
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<td><em>final correction of some surface perm. and v. porosities</em></td>
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<tbody>
<tr>
<td><em>additional pressure initialization by plane (none)</em></td>
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**2**

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<tbody>
<tr>
<td><em>additional pressure initialization by node (none)</em></td>
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**5**

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<tbody>
<tr>
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<tbody>
<tr>
<td><em>field 2 (water) initialization: temp., inert mass conc., vol. fr</em></td>
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<tr>
<td><em>field 3 (melt) initialization: temp., inert mass conc., vol. fr</em></td>
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<tbody>
<tr>
<td><em>initial conditions T,cn,al, l=1, point by point</em></td>
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<tbody>
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<tbody>
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### INITIAL VELOCITIES

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<th>Field</th>
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<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>63</td>
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</tbody>
</table>

### ADDITIONAL VELOCITIES

**Field 1** (Gas) initialization: Particle number. Vol. regs. 0
**Field 2** (Water) initialization: Particle number. Vol. regs. 0
**Field 3** (Melt) initialization: Particle number. Vol. regs. 0

### OTHER CONDITIONS

- **Number of structures**: 1
- **Number of heat sources**: false
- **Transverse changes of the heat surface sources**: 0

### MESH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>1.000000E+00</td>
</tr>
<tr>
<td>0.100000E+00</td>
<td>0.100000E+00</td>
</tr>
<tr>
<td>0.100000E+00</td>
<td>0.307306E+04</td>
</tr>
<tr>
<td>0.100000E+00</td>
<td>0.125000E+03</td>
</tr>
<tr>
<td>0.100000E+00</td>
<td>0.700000E+00</td>
</tr>
</tbody>
</table>

### MATERIAL PROPERTIES

- **Density**: 125 kg/m³
- **Specific Heat**: 2000 KJ/kg
- **Thermal Conductivity**: 50 W/mK

### SOURCE LIST

- **Rauz, dfg, dth**: 0.000001
- **Radial permeabilities**: 0.000001
- **Axial permeabilities**: 0.000001

### GEOMETRY

- **AZIMUTHAL SECTION**: 0
- **RADIAL PERMEABILITIES**: 0
- **AXIAL PERMEABILITIES**: 0

### THERMODYNAMICS

- **FUEL CATCHER, MODELED AS TUBE**: 0
- **FUEL CATCHER, MODELED AS TUBE**: 0
- **FUEL CATCHER, MODELED AS TUBE**: 0

### VESSEL WALL

- **VESSEL BOTTOM**: 0
- **VESSEL HEAD**: 0
- **VESSEL/separator connection**: 0
* VOLUMETRIC FOROSITIES * ALL VOLUME FREE
* HYDRAULIC DIAMETERS
* FUEL CATHETER
* ADDITIONAL HYDRAULIC DIAMETERS (NONE)
* NUCLEAR REACTOR? (NONE)
* FINAL CORRECTION OF SOME SURFACE PERM. AND V. FOROSITIES
* INITIAL PRESSURE DISTRIBUTION BY VOLUME
* ADDITIONAL PRESSURE INITIALIZATION BY PLANE (NONE)
* ADDITIONAL PRESSURE INITIALIZATION BY NODE (NONE)
* FIELD 1 (GAS) INITIALIZATION: TEMP., INERT MASS CONC., VOL. FRA
* FIELD 2 (WATER) INITIALIZATION: TEMP., INERT MASS CONC., VOL. F
* FIELD 3 (MELT) INITIALIZATION: TEMP., INERT MASS CONC., VOL. FR

<p>| | | | | | |</p>
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<tr>
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*INITIAL VELOCITIES FOR field 1

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*INITIAL VELOCITIES FOR field 2

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*INITIAL VELOCITIES FOR field 3

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<td>3</td>
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*INITIAL VELOCITIES FOR field 1

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<table>
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*INITIAL VELOCITIES FOR field 2

<p>| | | | | | |</p>
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<td>5</td>
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</table>

*INITIAL VELOCITIES FOR field 3
1 11 1 3 1 64 0.0 0.0
4  *FIELD 3 (Melt) INITIALIZATION: Particle number. Vol. regs.
1 11 1 3 1 64 0.0 0.0
2 7 2 2 48 48 1280. 1280.
2 8 2 2 49 49 1280. 1280.
0  *FIELD 1 (GAS) INITIALIZATION: Particle number. Cell by cell
0  *FIELD 2 (Water) INITIALIZATION: Particle number. Cell by cell
0  *FIELD 3 (Melt) INITIALIZATION: Particle number. Cell by cell
0  *BOUNDARY CONDITIONS (NONE = CLOSED SPACE)
F  *VERIBLE GEOMETRY (NO)
0  *SOURCES (NONE)
0  * Number of structures
0  * Transient changes of the vol. heat sources = .false.
F  * Number of heat surfaces
0  * Transient changes of the heat surface sources
0.100000E+01 1.000000E+00 0.000000E+00 0.000000E+00 0.100000E+01
1.000000E+00 0.1000000E+01 0.1000000E+01 0.1000000E+01 0.1000000E+01
0.100000E+01 1.000000E+00 0.0307306E+04 0.1200000E+03 0.1000000E+01
0.150000E+01 0.500000E+03 0.1000000E+06 0.5000000E+02 0.7000000E+00
H.7 - Participants comments

The outlet velocity was approximately estimated without feedback of the pressure formation and assumption for one-dimensional process. The differences between the 3 m/s maximum velocity as estimated in [4] and the here predicted 3.2 m/s are not very large.

The experimentally observed leading edge position as a function of time is indicated by thermocouples placed on discrete positions in the vessel. The computed leading edge position is defused due to (a) fragmentation and (b) to numerical diffusion. We take as a measure the well recognisable interface between water and gas. There is a good agreement between the IVA4 prediction and the measurements. Nevertheless, numerical diffusion associated with first order donor-cell method has to be reduced in future sophistication of the IVA4 method.

The water level was defined as the boundary with cells with less than and more than 5% water volume concentration. The level is very strong function of radius and one signal curve is not representative. The estimated computational level position in accordance with the above criterion seems to be reasonable in view of the several uncertainties associated with this comparison.

The most important comparison is between the predicted and the measured pressure as a function of time. The agreement is good. There is proportionality between the evaporated mass and the pressure increase of the system which, of course, is expected. The pressure increase at the end of the simulated process compared with the experimental one is attributed to non-appropriated poked bed motion modelling at the bottom and neglecting the melt-structure interaction. The modelling of the stagnation of packed solid particles at horizontal surfaces requires further attention.

The pressure increase in the first seconds is caused mainly by film boiling in three-phase bubble flow.

IVA4 predicts in this case, complete melt fragmentation after 1.5 to 2 seconds. The debris bed analysis after the experiment shows 16% non fragmented melt. The reason for this disagreement is very simple. IVA4 does not predict the freezing interaction with the cold bottom and let the melt sloshing further in the lower head. This causes freezing of the fragments before building a cake at the bottom. We see the melt is freezing with an interface of about 26 m². The post test analysis gives about 33 m², which is about 20% higher.

We see that during the melt-water contact the fragmentation is very strong and the average particle size drops to about 3 mm. After 0.5 seconds collisions and coalescences are responsible for the particle size increase up to 8 mm. Sloshing processes and melt water interaction at the bottom increases the fragmentation leading to about 3 mm particle size at the third second. The equivalent mean size estimated after the experiment is about 2.4 mm. Due to the use of the concept of mono-dispersity in a single cell, the difference between the surface average and the volume average diameter associated with particle distributions in a single cell have to be taken into account. In this case the heat transfer was computed with 0.82 reduced volume average mean diameter. This is in accordance with the discussion presented in [7].

IVA4 predicts about 35 MJ power release by the melt after 3 seconds. From the measured gas temperatures at the beginning of the process and at the 3rd second, from the measured pressure and the initial Argon concentration a total energy increase of the gas space can be estimated of about 54 MJ. Not knowing the average water temperature at this time it is difficult to estimate the total energy change in the water. Nevertheless, we see that IVA4 underpredicts the total release of thermal energy with at least 35%.

About the melt temperature at the centre of the vessel, note that during the process the melt inventor in this computational cell may appear and disappear, so that in case of no melt in the cell the temperature is not defined and not necessary. This is the reason for the default value of the initial temperature history equal to the initial melt temperature. Only cells with permanent melt inventor have continuous temperature time histories. The arrival of the melt at this point, about 0.325s, is
clearly indicated and compares well with the measured 0.36. The arrival of the melt at the bottom at 1 s is clearly indicated. It is larger than the measured 0.79 s with 20%. The gas dome temperature is overpredicted by IVA4 compared with the measurements. The model for melt-gas interaction requires obviously further sophistication.

The water temperature comparison is in a transient with measured signals seems to be impossible. The thermocouples being initially in water are generally exposed to three phase flows with variable concentration of melt, water and gas, and, of course, to variable temperatures. The measured water temperature at the end of the process was about 563 K. Note that this is a temperature obtained at the 6th s, after settling down of water and convective intermixing due to the natural boiling convection. Obviously the bulk temperature of water not being in contact with melt remains unchanged during the transient.

For this simulation we put all radiative energy in the surface evaporation process accounting for the optical interference with strongly turbulent wavy water interface. The partitioning of the radiative heat between the adsorbed at the surface and the dissipated in the liquid, requires further attention. Results for water gas least with ideal flat interface are at best a guide line for appropriate modelling.

It is also realised that inter-cellular radiation model is necessary for some flow situations for proper description of high temperature melt-water interaction.

CONCLUSIONS

1. The local volume and time average multi-field conservation equations in porous media and the concept of dynamic fragmentation and coalescence for all velocity fields as implemented in IVA4 computer code, are powerful tools for simulation of such a complicated multi-phase flow with strong, non-linear inter-field interactions.

2. Generally IVA4 computational model predicts well the main characteristics of the FARO-L14 experiment.


4. Numerical diffusion associated with first order donor-cell method has to be reduced in future sophistication of the IVA4 method.

5. Due to using the mono-dispersity concept in a single cell, the difference between the average surface and the average volume diameter associated with particle distributions in a single cell has to be taken into account. In this case the heat transfer was computed with 0.82 reduced average volume mean diameter. This is in accordance with the discussion presented in [7].

6. For this simulation we put all radiative energy in the surface evaporation process accounting for the interferences with strongly turbulent wavy water interface. The partitioning of the radiative heat between the absorbed at the surface and the dissipated in the liquid requires additional improvement.

7. It is realised that inter-cellular radiation model is necessary for some local flow situations for proper description of high temperature melt-water interaction.

8. The model for melt-gas interaction requires further sophistication, because the existing one overpredicts the heating of the gas.

9. The modelling of the stagnation of packed solid particles at horizontal surfaces requires further attention.

IVA-4 Siemens


IVA-4 Siemens
I. - JASMINE-JAERI Calculations

1.1 - Participant Identification

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<tr>
<th>Organisation:</th>
<th>Japan Atomic Energy Research Institute</th>
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<tbody>
<tr>
<td>Contact Person(s):</td>
<td>MORIYAMA Kiyofumi</td>
</tr>
<tr>
<td>Address:</td>
<td>JAERI</td>
</tr>
<tr>
<td></td>
<td>Severe Accident Research Laboratory</td>
</tr>
<tr>
<td></td>
<td>Tokai-mura, Naka-gun, Ibaraki-ken 319-11</td>
</tr>
<tr>
<td></td>
<td>Japan</td>
</tr>
<tr>
<td>Tel:</td>
<td>0081-29-282-5871</td>
</tr>
<tr>
<td>Fax:</td>
<td>0081-29-282-5570</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:mori@sun2sar1.tokai.jaeri.go.jp">mori@sun2sar1.tokai.jaeri.go.jp</a></td>
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1.2 - Initial and boundary conditions

Four cases of calculation by JASMINE are submitted. All of them are in the category "a". Also, those analyses were performed with the same initial and boundary conditions, and the same nodalization. "a1" is the base case and "a2-4" is to show the sensitivity on several parameters related to the break-up control. In the base case "a1", break-up of melt was suppressed in the bottom 3 layers. This condition is the same in cases "a2" and "a3" while in case "a4" the suppression was quit.

The difference between cases is summarised below:

a1: base case, break-up of melt suppressed in the bottom three layers (best agreement in the pressure)
a2: the primary break-up factor CPB was changed to 0.600 (base case 0.577) (enhanced break-up caused heat transfer increase)
a3: the drag coefficient for melt particles was changed to 1.0 (base case 0.5) (relative velocity between melt and coolant decreased and it suppressed the break-up, and caused heat transfer decrease)
a4: limitation of melt break-up near the floor was removed (break-up was enhanced in the strong vortices near the floor)

The initial and boundary conditions valid for all 4 calculations are reported in the following Table.

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<th>EXPERIMENT</th>
<th>JAERI</th>
<th>Difference</th>
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<td>80 UO₂ + 20 ZrO₂</td>
<td>-0.7</td>
</tr>
<tr>
<td>Mass, Kg</td>
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<td>124.3</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
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<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
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<tr>
<td>Depth, m</td>
</tr>
<tr>
<td>Temperature (average), K</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
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<tr>
<td>Total water volume, m³</td>
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</table>

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Composition, w%</td>
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<tr>
<td>Volume, m³</td>
</tr>
<tr>
<td>Temperature, K</td>
</tr>
<tr>
<td>Pressure, MPa</td>
</tr>
</tbody>
</table>

JASMINE JAERI
1.3 - Code nodalization

Nodalization

2-D Cylindrical field
r-direction: 4 cells
- 0.10 x 3 cells (i=2-4)
- 0.055 x 1 cell (i=5)
z-direction: 39 cells
- 0.085 x 1 cell (k=2)
- 0.10 x 30 cells (k=3-32)
- 0.20 x 5 cells (k=33-37)
- 0.30 x 1 cell (k=38)
- 0.50 x 2 cells (k=39-40)

Total system volume: 2.06m³
Water initial volume: 0.799m³
(vessel i.d. 0.71m, depth 2.02m)
Initial free volume: 1.261m³

Position of melt inlet: z=3.085 m
1.4 - Comparison of calculations with the experiment

1.4.1 Base calculation

Quantity: 1 - Pressure
Quantity: 2 - Temperature in the steam dome

Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position

JASMINE JAERI
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

Experimental 0.45 s
JASMINE JAERI 0.31 s

Quantity: 21 - Melt/Bottom contact

Experimental 0.87 s
JASMINE JAERI 1.11 s
1.4.2 Additional calculations

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

JASMINE JAERI
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position

JASMINE JAERI
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time
1.5 - Code description or code models/options

Present developmental version of JASMINE-pre (2.01) is a premixing simulation code for steam explosion analysis. JASMINE-pre solves three sets of mass, momentum and energy conservation equations for steam water and melt. These fundamental equations were formulated on Eulerian field, discretized by Finite Difference Method (FDM). A staggered grid and semi-implicit scheme were employed in the discretization. Numerical solution was obtained by Newton-Raphson method. The momentum exchange model, heat transfer model, and characteristic size and surface area models are included as constitutive equations. These models and related input options are described in the followings.

Flow regime map:

A simple flow regime map based on volume fractions is used in the analysis of ISP-39. The melt was always assumed to be a dispersed phase. Water was considered to be continuous if the void fraction (steam fraction in the coolant) was less than 0.3. While, steam was considered to be continuous if the void fraction was more than 0.7. Constitutive models for water-continuous and steam-continuous regimes were averaged if the void fraction was in between 0.3 and 0.7. To do this, following flow regime functions were used.

\[
\text{CHIG} = \begin{cases} 
1 \quad & \text{if } \text{ALPHA} < 0.3 \\
2.5(0.7-\text{ALPHA}) \quad & \text{if } 0.3 \leq \text{ALPHA} < 0.7 \\
0 \quad & \text{if } \text{ALPHA} > 0.7 
\end{cases}
\]

\[
\text{ALPHA} = \frac{\text{ALPHA}_{\text{G}}}{(\text{ALPHA}_{\text{G}}+\text{ALPHA}_{\text{L}})}
\]

\text{ALPHA}_{\text{G}}: \text{steam volume fraction, ALPHA}_{\text{L}}: \text{water volume fraction}

CHIG gives 1 in the steam-continuous regime, and CHIL gives 1 in the water-continuous regime.

Using CHIG and CHIL as weight functions, the constitutive equations for steam-continuous and water-continuous regimes were averaged as follows,

\[
\text{VALUE} = \text{CHIG} \times (\text{VALUE}_{\text{G-CONT}}) + \text{CHIL} \times (\text{VALUE}_{\text{L-CONT}})
\]

Momentum exchange model:

Ishii-Zuber (1979) drag model was used. The friction factor between dispersed phase i and continuous phase j was expressed as below.

\[
\text{Kij} = 0.75 \times \Phi_{ij} \times \text{ALPHA}_{i} \times \text{RHO}_{j} / (\text{D}_{i} \times \text{CD}_{ij} \times \text{abs} \times \text{U}_{i} - \text{U}_{j})
\]

\[
\Phi_{ij} = \text{ALPHA}_{j} / (1 - \text{ALPHA}_{i})
\]

\[
\text{CD}_{ij} = 2/3 \times \text{Di} \times (\text{GRAV}_{i} \times \text{abs} \times \text{RHO}_{i} - \text{RHO}_{j}) / (\text{SIGMA}_{ij})^{0.5} \times (1 + 17.67 \times \text{Fij}^{**2} / 18.67 / \text{Fij})^{**2}
\]

\[
\text{ETA} = \begin{cases} 
3 \quad & \text{if } \text{MU}_{i} < \text{MU}_{j} \\
1.5 \quad & \text{otherwise}
\end{cases}
\]


For melt particles, constant drag coefficient CD was also enabled as an option (ICDMELT, CDMELT). This constant melt drag coefficient option was activated in the ISP-39 analysis.

In the case a1, a2 and a4, CDMELT = 0.5 was used, while in the case a3, CDMELT was changed into 1.0.

Heat transfer and phase change model:

Following models were used for the heat transfer coefficients.

- Radiation

\[
\text{HRAD} = \Phi \times \text{SIGMASB} \times (\text{TM}^{**4} - \text{TS}^{**4}) / (\text{TM} - \text{TS})
\]

\Phi = 0.79: melt emissivity
SIGMASB: Stefan-Boltzmann constant

- Film boiling (Epstein-Hauser (1980) + Dhir-Purohit (1978))
  HFB = max(HFBSUB, HFBSAT)
  HFBSUB = Epstein-Hauser correlation
  HFBSAT = Dhir-Purohit correlation

- Convection HT between dispersed phase i and continuous phase j (Rantz-Marshall (1952))
  HCNVij = C*\(\text{LAMBj/\text{Di}}\^{2+0.6*\text{REij}**0.5*\text{PRj}**0.33}\)
  LAMB: heat conductance
  REij = RHOj*Di*abs(Ui-Uj)/MUj: Reynolds number
  PRj: Prandtl number
  C: tuning constant (1.0 was used)

- Conduction inside dispersed phase i
  HCNDi = C*2*LAMBj/\text{Di}
  C: tuning constant (10.0 was used)

Heat transfer models above were combined to express the heat transfer rate between phases and the steam generation rate.

HLS: Heat transfer rate between water and saturation interface
HGS: Heat transfer rate between steam and saturation interface
HML: Heat transfer rate between water and melt
HMG: Heat transfer rate between steam and melt
HMS: Heat transfer rate between saturation interface and melt
GAMMAG: steam generation rate

HLS = CHIL*[^\text{ARGL}HCNVgl + \text{ARM}HCVfl + \text{CHIG}ARLHCNDi]
HGS = CHIL*[^\text{ARGL}HCNVd + \text{CAIG}ARLHCNVg]
HML = CHIL[^\text{ARML}HRAD*(1-KIR) + \text{ARM}HFB*(1-KIF)]
HMG = CHIG[^\text{ARM}HCNVmg + \text{ARM}HRAD*(1-KIR2)]
HMS = CHIL[^\text{ARM}HRAD*KIR + \text{ARM}HFB*KIF]
GAMMAG = (HLS*(\text{TL-TS}) + HGS*(\text{TG-TS}) + HMS*(\text{TM-TS}))/DHLG

ARG, ARL, ARM: volumetric surface area of steam, water and melt.
DHLG: latent heat of steam generation
KIR: fraction of radiation HT deposited on the saturation interface in water-continuous regime
KIR2: fraction of radiation HT deposited on water droplet surface in steam-continuous regime
KIF: fraction of film boiling HT deposited on saturation interface in water-continuous regime

The model constants above: KIR, KIR2 and KIF were introduced to control the radiation and film boiling heat transfer models.
If KIR=1 and KIF=1, all the radiation and film boiling heat release is deposited on the saturation interface, and contributed to produce steam. On the other hand, if KIR=0 and KIF=0, all the radiation heat release is absorbed into the bulk water and consumed to heat it up.
KIR2 works in the steam-continuous regime. If KIR2=1, the radiation heat goes to the water droplets, otherwise if KIR2=0 it goes to the steam. It should be noted that if KIR2=1 and there is no water in the cell, the radiation heat transfer is neglected. Also, it was found that KIR2=0 is likely to cause numerical instability because the steam in the cell is heated up too quickly.
In the ISP-39 analysis submitted, KIR=1, KIR2=1, KIF=1 was used.

These parameters were also controlled to keep convergence in case of numerical difficulties.

The strategy of heat transfer control to keep convergence:
KK(100) in the input file is the switch of the strategy to keep convergence in case of numerical difficulties. In the analysis submitted, option 4 was used. This is the following method.
- If the Newton-Raphson method does not converge, dt is reduced. However, if dt is less than the value defined in RR(86) (1.0e-4), heat transfer control is tried instead of dt reduction.

- HT control 1: reduce KIR and KIF (try to decrease the steam generation by film boiling and radiation HT)

- If KIR and KIF is already reduced down to 1.0e-10, 2nd method is applied instead.

- HT control 2: reduce the heat transfer factor related to the saturation interface (try to reduce the whole steam generation)

- If the heat transfer factor related to the saturation interface is already smaller than the value defined in RR(146) (1.0e-3), quit the heat transfer control and go back to dt reduction.

- If dt is less than the lower limit (DTMIN, 1.0e-10 sec.), give up the calculation.

Surface area and particle diameter evaluation:

Water/Steam:
There is a switch to select the method. (KK(115)) Constant particle number densities (option 2) were used because it was found that instantaneous We criterion is likely to cause numerical difficulty due to sudden change of the heat transfer area related to steam generation. Particle number density was set 1.0e8 (RR(171)).

Using the constant number density, the particle diameter and the surface area was evaluated as follows.

\[ D_i = (6 \times \text{ALPHA}_i / P_i / N_i)^{1/3} \]

\[ A_Ri = 6 \times \text{ALPHA}_i / D_i \]

\[ N_i: \text{particle number density of phase i} \]

\[ P_i: \text{the circular constant} \]

Melt:
A transport equation of surface area was solved explicitly, and the source term of the surface area was given by the particle break-up model. IFCl model (Davis-Young (1994)) with constant primary break-up factor was used.

\[ \text{GAMMA}_{AA} = \text{CPB} \times \text{ARM}^2 / (6 \times \text{ALPHAM}) \times \text{abs(UM-Uj)} \times (\text{RHO}_j / \text{RHOM})^{0.5} \]

\[ \text{GAMMA}_{AA}: \text{source term of the surface area transport equation} \]

\[ \text{CPB}: \text{primary break-up factor} \]

j: continuous phase surrounding the melt particle

In the case a1, a3 and a4, CPB was set 0.577, in the case a2, CPB was changed into 0.6.

Break-up control near the vessel floor:
Present version of JASMINE does not have any physics-based debris settling/packing model. The present melt break-up model may not treat the melt break-up behaviour near the vessel floor properly. Therefore, some input switch to limit the melt break-up near the floor were provided. (KK(110), KK(102))

KK(110) defines the area where the melt break-up model is inactivated. In the calculations a1-a3, KK(110) was set 4, then 3 layers (k=2-4) near the floor were defined as the non-break-up area, while in the case a4, this limitation was removed.

KK(102) defines the way how to treat the melt surface area on the floor (k=2 cells). Option 3 was used in all cases. This method assumes that the melt is instantaneously spreads on the floor if the temperature is above the melting point, so that the melt surface area is the same as the floor area. However, if the fully spread melt layer on the floor is thinner than the value defined in RR(181) (5mm), melt surface area was reduced keeping the defined layer thickness.
1.6 - Code input deck

Input deck for calculation 1

* JASMINe input FILE
* ISP-39 (FARO-LI4)
*%SYNTAX-CHECK
*%END
*TITLE
  TITLE = ai
* (i14or)
*%END
*%COORDINATE
  TYPE = CY
*%END
*%MESH
  X-START = 0.000 X-END = 0.30 X-DIV = 3
  Y-START = 0.000 Y-END = 0.355 Y-DIV = 1
  Z-START = 0.000 Z-END = 0.085 Z-DIV = 1
  Z-END = 3.085 Z-DIV = 30
  Z-END = 4.085 Z-DIV = 5
  Z-END = 4.385 Z-DIV = 1
  Z-END = 5.385 Z-DIV = 2
*%END
*%OBSTACLE-SOLID
  I-S = 2, J-S = 2, K-S = 33
  I-E = 2, J-E = 2, K-E = 40
*%END
*%BOUNDARY-AREA
  NAME = INJECT
  DIR = Z
  I-S = 2, J-S = 2, K-S = 32
  I-E = 2, J-E = 2, K-E = 32
* bottom
  NAME = WALL1
  DIR = Z
  I-S=2, J-S=2, K-S=1
  I-E=5, J-E=2, K-E=1
* side
  NAME = WALL2
  DIR = X
  I-S=5, J-S=2, K-S=2
  I-E=5, J-E=2, K-E=40
*%END
*%BOUNDARY-DEFAULT
  VEL = SLIP
  TEMP = ADIABATIC
*%END
*%TABLE
  NAME = INJV
  * A. Annunziato et al. (Apr.1996)
  TIME=0.00, VAL=0.00
  TIME=0.005, VAL=0.091
  TIME=0.025, VAL=0.453
  TIME=0.045, VAL=0.809
  TIME=0.075, VAL=1.293
  TIME=0.10, VAL=1.654
  TIME=0.125, VAL=1.976
  TIME=0.15, VAL=2.234
  TIME=0.175, VAL=2.445
  TIME=0.20, VAL=2.617
  TIME=0.25, VAL=2.852
  TIME=0.30, VAL=2.991
  TIME=0.35, VAL=3.041
  TIME=0.40, VAL=3.059
  TIME=0.45, VAL=3.047
  TIME=0.50, VAL=3.021

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TIME=0.55, VAL=-2.985  
TIME=0.60, VAL=-2.943  
TIME=0.65, VAL=-2.887  
TIME=0.70, VAL=-2.817  
TIME=0.75, VAL=-2.740  
TIME=0.80, VAL=-2.598  
TIME=0.825, VAL=-2.466  
TIME=0.85, VAL=-2.277  
TIME=0.875, VAL=-2.017  
TIME=0.90, VAL=-1.677  
TIME=0.925, VAL=-1.242  
TIME=0.95, VAL=-0.690  
TIME=0.975, VAL=-0.000  
TIME=1.00, VAL=-0.000  
  
%END  
  
%BOUNDARY-INLET  
AREA = INJECT  
TYPE = FIX  
P-VAL = 5.10D6  
W-G-VAL = 0.00  
W-L-VAL = 0.00  
W-M-VAL = INJ1  
VOL-G-VAL = 0.7884  
VOL-L-VAL = 0.0000  
* am=0.2116  
T-G-VAL = 535.0  
T-L-VAL = 535.0  
T-M-VAL = 3073.0  
* AREAM at inlet should be specified in unit.f  
* (AREAM=6*AM/DM)  
* 13.8 (m-1) at (2,2,33) (9mm dia. jet in r=10 cm cell)  
%END  
  
%BOUNDARY-WALL  
AREA=WALL1  
VEL=SLIP  
TEMP=HEAT-TRANSFER  
TEMP-VALUE=536.0  
TYPE=CONSTANT  
COEF-G-VAL=5.0e3  
COEF-L-VAL=5.0e3  
COEF-M-VAL=5.0e3  
* AREAM=WALL2  
VEL=SLIP  
TEMP=HEAT-TRANSFER  
TEMP-VALUE=536.0  
TYPE=CONSTANT  
COEF-G-VAL=5.0e3  
COEF-L-VAL=5.0e3  
COEF-M-VAL=5.0e3  
%END  

%FUEL-PROPERTY  
TYPE=FUNCTION  
* TYPE=CONSTANT  
* Corium UF2, ZrO2  
* rho and cp/e are specified in functions at MELT if TYPE=FUNCTION  
* RHO = 7960.0  
* CV = 565.0  
* VISC=4.23D-3  
* COND=2.80  
* melting point, surface tension -> %RVAL block RR(127)(128)  
%END  

%GRAVITY  
GX = 0.000  
GY = 0.000  
GZ = -9.8100  
%END  

%INITIAL  
TYPE = FUNCTION  
%END  

%TIME  
TIME-START = 0.00  
TIME-END = 6.00  
DT = 1.0D-3  
DT-MIN = 1.0D-10
DT-MAX = 1.0D-3  
MAX-STEP = 100001 
\%END  

\%ITERATION 
MAX-ITER = 60  
CONVERGE = MAX  
* convergence is judged comparing max residual with EPS defined below  
MASS-L = 1.0D-4  
MASS-G = 1.0D-4  
MASS-M = 1.0D-4  
ENERGY-L = 1.0D-4  
ENERGY-G = 1.0D-4  
ENERGY-M = 1.0D-4  
* if bad conv., ave. residual is compared with ALLOW*EPS  
ALLOW = 10.0  
\%END  

\%MATRIX  
EPS = 1.0D-6  
MAX-ITER = 50  
TYPE = MILU  
DIVER = 1.0D20  
PRINT = NO  
\%END  

\%TERM  
VISC = NO  
THERM = NO  
VIRTUAL = CA  
MOMENT = CA  
LINEAR = YES  
\%END  

\%LIST-FILE  
TIME=0.000  
TIME=0.200  
TIME=0.300 TIME=0.400  
TIME=0.500  
TIME=0.600 TIME=0.700 TIME=0.800  
TIME=0.900  
TIME=1.000  
TIME=1.100  
TIME=1.200  
TIME=1.300  
TIME=1.400  
TIME=1.500  
TIME=1.60  
TIME=1.70  
TIME=1.80  
TIME=1.90  
TIME=2.00  
TIME=2.50  
TIME=3.00  
TIME=3.50  
TIME=4.00  
SECT-DIRE=Y SECT-COO=2  
PHT=P  
PHT=ADAM  
* USER-S1 : Dm  
* USER-S2 : Tmat  
* USER-S3 : Tgy-Tmat (0 if aG<1e-5)  
* USER-S4 : Tl-Tmat (0 if aL<1e-5)  
PHT=USER-S1  
PHT=USER-S2  
PHT=USER-S3  
PHT=USER-S4  
PHT=AL  
PHT=AM  
PHT=AG  
PHT=TO  
PHT=TL  
PHT=TM  
PHT=UG  
PHT=MO  
PHT=UL  
PHT=ML  
PHT=UM  
PHT=MM  
\%END
% PLOT-FILE
TIME=0.100 TIME=0.200 TIME=0.300 TIME=0.400 TIME=0.500
*TIME=0.600
TIME=0.700
*TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.100
TIME=1.20 TIME=1.40
*TIME=1.60 TIME=1.80
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
*PHS=P
*PHS=AREAM
PHS=AG
PHS=AL
PHS=AM
*PHS=TR
*PHS=TL
PHS=TM
PHS=AL+UL
PHS=AL*WL
PHS=AG*UG
PHS=AG*WG
PHS=AM*UM
PHS=AM*WM
MERGE=YES
% END

%HISTORY-FILE
TYPE = ASCII
I = 4 J = 2 K =30
I = 4 J = 2 K =6
STEP-S = 1
STEP-I = 10
* PHS = P 
PHS = TL
* PHS = AG
* PHS = AM
* PHS = WM
% END

%IVAL
** message if alpha<0 at end of newton loop (newton)
31=1
** message if alpha<0 at end of newton loop (alpset)
* K(44)= (default 1): linearization method of source term (alpset)
** message if alpha<0 at end of newton loop (solver)
* K(50) = (default 1): discretization of advection term in momentum eq. (solver)
* K(50) = (default 0): 0: use expen2 (implicit T), 1: use expen (explicit T)
** message if alpha<0 at end of newton loop (solver)
* K(82) = (default 1): switch of 53 at impact of jet on water surface (solver)
** message if alpha<0 at end of newton loop (solver)
** message if alpha<0 at end of newton loop (solver)
* K(90)=1 (default 0): output total balance data (*.tot)
90 = 1
** message if alpha<0 at end of newton loop (solver)
* K(91) = (default 1): interval of *.tot data
91 = 10
** message if alpha<0 at end of newton loop (solver)
* K(92)=1: correction in temp./vel. of rare phase (correc)
92 = 1
** message if alpha<0 at end of newton loop (solver)
** message if alpha<0 at end of newton loop (solver)
* K(93)=0 (default 0): no breakup, 1: breakup (use area transport eq) (cnarea)
93 = 1
** message if alpha<0 at end of newton loop (solver)
* K(170)=0: dm from We, 1:dm=const(KR(170)) (cnarea)
* (this setting is ignored if K(93)=1)

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* 170=1

* KK(110)(default 0) : KNDBRK: no breakup at Ks2-KNDBRK
  110 = 4

* KK(102)(default 0) breakup control on the floor (brkup)
  1: no more breakup on the floor (Ks2=2),
  2: agglomeration on the floor (Ks2) (agglomeration time constant is RR(177))
  3: use the floor area as melt surface area at Ks2 (min melt layer thickness
     under which melt area is less than the floor area -> RR(181))
  102=3

* KK(175)(default 0) brkup coefficient switch
  0: use Pilch model (Pilch 1987) (parameters: RR(178,179,180))
  1: use constant Cpb & Cse (defined in RR(175)(176))
  175 = 1

* KK(104)(default 0) (brkup)
  1-3: jet fall mode consideration (cease breakup in jet body)
  1: no control on melt relative velocity at jet leading edge
  2: melt relative velocity to stagnant fluid at jet leading edge
  3: melt relative velocity to side way fluid at jet leading edge
  104 = 3

* heat transfer control

* KK(100)(default 2) HT control
  0: heat transfer always OFF,
  1:HTC factor for phase change is set 0 if LOOPFM>=2,
  2:always ON
  3:HTC factor for phase change is reduced if LOOPFM>=2 and dt<RR(86)
  4:HTC factor kic,kif[RR(160,162)] is reduced if LOOPFM>=2 and dt<RR(86)
  5:HTC factor for phase change is reduced if kic,kif<1.e-10 and dt<RR(86)
  100 = 4

* KK(111)(default 1) active kic2, 0:const. kic2 (--RR(161))
  kic2=al*rhol/(al*rhol+ar*rho) in vapor cont. regime (cnhtc)
  111 = 0

* KK(112)(default 0) radiation HT control radctrl (cnhtc)
  0: take all rad. HT into account
  1: take only rad. HT in film boiling
  2: neglect all rad. HT
  112 = 1

* KK(160)(default 0)
  0: use hclim function in cnhtc for rare phases (vapor, water)
  1: kill hclim for vapor & water in cnhtc (HT control by cnarea -> KK(162))
  (definition of limiting parameter is in RR(163,164))

* KK(161)(default 0)
  0: use hclim function in cnhtc for rare phases (melt)
  1: kill the hclim in cnhtc (HT control by cnarea -> KK(163))
  (definition of limiting parameter is in RR(165))

* KK(162)(default 0)
  0: let ar=0 at a=0 min in cnarea (vapor, water)
  1: keep ar=0 even when a>armin in cnarea (vapor, water)
  (if KK(160) is set 1, this should be 0)
  162 = 1

* KK(163)(default 0) (in effect only when KK(93) = 1)
  0: let armin=0 at amin in cnarea
  1: keep armin=0 even when am<amin in cnarea
  (if KK(161) is set 1, this should be 0)

* initial condition control

* KK(120-159): reserved to specify initial conditions in uinit.r
  123 = 1
  125 = 1
  126 = 1
  127 = 1
  128 = 1
  129 = 1
  130 = 1
  131 = 1: set area=2,2,33=0.0
* 131 = 1
* 132: set area (2,2,33) = 9.2
  132 = 1
* -------------------------------------------
* jet-mode
* -----------------------
* KK(106) (default 0) jet-mode ON:1, OFF:0
  106 = 1
* -------------------------------------------
* KK(105) (default 0) jet inlet cell k used in jet-mode
  105 = 33
* -------------------------------------------
* KK(107) (default 1) (solver) (jet related output interval: step)
  107 = 50
* -------------------------------------------
* KK(108) (default 1) (jet-mode fragmentation model switch)
  1: Kataoka-Ishii based, 2: Epstein-Fauke based
  108 = 2
* -------------------------------------------
* KK(109) (default 0) (jet-mode HT model switch)
  0: jet-mode HT model, 1: usual model HT model
  109 = 1
* -------------------------------------------
* Surface area of water/vapor
* -------------------------------------------
* KK(115) (default 0) switch of water & vapor particle size evaluation
  0: We number with DMAX & DMIN limits
  1: We + number density with DMIN limit
  2: number density with DMIN limit
  (number density is specified in RR(171))
  115 = 2
* -------------------------------------------
* Friction factor
* -------------------------------------------
* KK(50) (default 1): 0:CD=0.45, 1:CD by correlation (cnfric)
  50 = 0
* -------------------------------------------
* KK(185) (default 0) ICDMELT: switch of melt drag coefficient (cnfric)
  0: use Ishii-Zuber distorted particle correlation
  1: use constant CDMELT (RR(185)) for melt particles
  185 = 1

%END

%RVAL

* volume fraction control
* -------------------------------------------
* RR(36,37,43) (default 1.0e-6): min limit volume fraction
  36, 37, 43 for AGMIN, ALMIN, AMMIN
* -------------------------------------------
* RR(68) (default 1.e-10): relaxation of Newton method (upvar)
* -------------------------------------------
* Heat Transfer control
* -------------------------------------------
* RR(141-145) (default 1.0): heat transfer factor for sat_interface
  * liq-to-bub, liq-to-film, gas-to-drop, in-drop, in-bubb respectively
  * (cnhtc, solver)
  141 = 1.0
  142 = 1.0
  143 = 1.0
  144 = 1.0
  145 = 1.0
* -------------------------------------------
* RR(96) (default 1.e-6): time step under which HT control starts
  * to keep convergence (solver)
  96 = 1.e-4
* -------------------------------------------
* RR(146) (default 1.0e-6): minimum limit of reduction of HT factor for
  * sat. interface (solver)
  146 = 1.e-3
* -------------------------------------------
* RR(160-162) (default 1.0) radiation & film boiling HT control (cnhtc)
  * 160: kin (radiation HT fraction to evap.)
  * 161: kin2 (radiation HT fraction to droplets in cont. vapor)
  * 162: kif (film boiling HT fraction to evap.)
  * --> KK(111) : active kir2 mode (control by material density)
  160 = 1.0
  161 = 1.0

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RR(183-165) (default 1.e-4) limitation volume fraction for HT involving rare phase (cnhtc)
163:anglimht, 164:allimht, 165:amlimht
should be larger than a7min

RR(126) (default 1.0e3): correction factor for gas momentum eq. CRCT in case of bad convergence (1.0 : no effect) (solver,upv)
126=1.0e3

melt properties

RR(60) (default 0.79): radiation emmisivity of melt (cnhtc)
60 = 0.79

RR(127) (default 2840.0): melting temperature of melt material TMELT (K)
127= 2830.0

RR(28) (default 0.45): surface tension of melt (N/m) (cnmain)
128= 0.45

surface area & particle diameter control

RR(130-132) (default 1.0): max dia. of phases (m) (cnarea)
130,131,132 for DBMAX(vapor),DMAX(water),DMAX(melt)

RR(133-135) (default 1.0e-9): min dia. of phases (m) (cnarea)
133,134,135 for DBMIN(vapor),DMIN(water),DMIN(melt)
135 = 2.0e-3

RR(136-139) (default 8.12,12.8,) critical We (cnarea)
136,137,138,139 for WEBUB(vapor),WEBUB(water),WEBUB(melt),
WEBUB(drp in continuous melt)

RR(171) (default 1.0e6) particle number density of discrete phase
[number/m^3] (cnarea)
171 = 1.0e6

RR(170) (default 1.e-2): constant dia. of melt when KK(170)=1 & KK(93)=0
170=2.4e-3

parameters for simple melt breakup model (when KK(175)=1)

RR(175) (default 0.25) CPB primary breakup constant in effect
if KK(175)=1 (brkup)
definition: (d_n/d_n+1 - 1)/tan_b
175 = 0.577

RR(176) (default 0.089) CSE surface entrainment constant in effect
if KK(175)=1 (brkup)
176 = 0.0

parameter for Pilch model (when KK(175)=0)

RR(178) (default 2.5) CDDRPT droplet acceleration drag coeff. during breakup
178 = 2.5

RR(179) (default 1.0): correction factor for Pilch model CPILCH
179=1.0

RR(180) (default 1.5): correction in Pilch model CPILCH2
[min number of particles in one-step breakup]**(1/3) (should be > 1.0)
180=5.0

parameters for simple melt agglomaration model (when KK(102)=2)

RR(177) (default 0.0 -> evaluated by gravitational settle)
time constant of melt jet settling on the bottom [sec]
177 = 0.1

parameters for simple melt agglomaration model (when KK(102)=3)

RR(181) (default 0.005)
THMIN min melt layer thickness under which the melt surface area is less than
the floor area
181 = 5.0e-3
Friction factor

RR(185) (default 0.45) CDMLST const. drag coeff. for melt when KK(185)=1
185 = 0.5

jet-mode (Jet-mode switch is KK(106))

RR(148) (default 0.1) jet diameter at inlet cell
148 = 0.092

RR(150) (default 1.e-3) min jet diameter under which jet is handled in usual mode
150 = 1.0e-3

RR(155) (default 1.0) enhancement of droplet entrainment
put on Kataoka-Ishii model
155 = 100.0

RR(157) (default 1.0) enhancement of droplet entrainment
put on Epstein-Fauske model
157 = 1.0e-4

RR(158) (default 1.0) droplet diameter factor
put on Epstein-Fauske model
158 = 1.0

%END

%SCHEME
  TYPE = DONOR
%END

%STOP
%END

%DEBUG
TIME = 1.4460
TIME = 1.4470
TIME = 1.4480
*SECT-DIR = X  SECT-COORD = 2
SECT-DIR = Y  SECT-COORD = 2
*SECT-DIR = Z  SECT-COORD = 2
  FLAG = 1  FLAG = 2  FLAG = 3  FLAG = 4  FLAG = 5
  FLAG = 6  FLAG = 7  FLAG = 8  FLAG = 9  FLAG = 10
  FLAG = 11
*FLAG = 12
  FLAG = 13  FLAG = 14  FLAG = 15
  FLAG = 16  FLAG = 17  FLAG = 18  FLAG = 19  FLAG = 20
  FLAG = 21
  FLAG = 22
  FLAG = 23
  FLAG = 24  FLAG = 25
  FLAG = 26  FLAG = 27  FLAG = 28  FLAG = 29  FLAG = 30
  FLAG = 31  FLAG = 32  FLAG = 33  FLAG = 34  FLAG = 35
  FLAG = 36  FLAG = 37  FLAG = 38  FLAG = 39  FLAG = 40
  FLAG = 41  FLAG = 42  FLAG = 43  FLAG = 44  FLAG = 45
  FLAG = 46  FLAG = 47  FLAG = 48  FLAG = 49  FLAG = 50
  FLAG = 55
%END

%STOP
%END

Input deck for calculation 2

* JASMINe INPUT FILE
* 166-39 (PARO-L14)
*%SYNTAX-CHECK
*%END
*TITLE
  TITLE = a2
    (114041)
%END

%COORDINATE
  TYPE = CY
%END

JASMINE JAERI
%MESH
  X-START = 0.000 X-END = 0.30 X-DIV = 3
  X-END = 0.355 X-DIV = 1
  Y-START = 0.000 Y-END = 6.2832 Y-DIV = 1
  Z-START = 0.000 Z-END = 0.085 Z-DIV = 1
  Z-END = 1.085 Z-DIV = 30
  Z-START = 4.085 Z-DIV = 5
  Z-END = 5.385 Z-DIV = 1
  Z-END = 5.385 Z-DIV = 2
%END

%OBSTACLE-SOLID
  I-S = 2, J-S = 2, K-S = 33
  I-E = 2, J-E = 2, K-E = 40
%END

%BOUNDARY-AREA
  NAME = INJECT
  DIR = Z
  I-S=2, J-S=2, K=S=32
  I-E=2, J-E=2, K-E=32
  bottom
  NAME = WALL1
  DIR = Z
  I-S=2, J-S=2, K=S=1
  I-E=2, J-E=2, K=E=1
  side
  NAME = WALL2
  DIR = X
  I-S=5, J-S=2, K=S=2
  I-E=5, J-E=2, K=E=40
%END

%BOUNDARY-DEFAULT
  VEL = SLIP
  TEMP = ADIABATIC
%END

%TABLE
  NAME= INJ
  A. Annunziato et al. (Apr.1996)
  TIME=0.00, VAL=-0.00
  TIME=0.005, VAL=-0.091
  TIME=0.025, VAL=-0.453
  TIME=0.05, VAL=-0.889
  TIME=0.075, VAL=-1.293
  TIME=0.10, VAL=-1.654
  TIME=0.125, VAL=-1.967
  TIME=0.15, VAL=-2.23
  TIME=0.175, VAL=-2.445
  TIME=0.20, VAL=-2.617
  TIME=0.25, VAL=-2.852
  TIME=0.30, VAL=-2.981
  TIME=0.35, VAL=-3.041
  TIME=0.40, VAL=-3.057
  TIME=0.45, VAL=-3.047
  TIME=0.50, VAL=-3.021
  TIME=0.55, VAL=-2.985
  TIME=0.60, VAL=-2.943
  TIME=0.65, VAL=-2.887
  TIME=0.70, VAL=-2.817
  TIME=0.75, VAL=-2.740
  TIME=0.80, VAL=-2.598
  TIME=0.825, VAL=-2.466
  TIME=0.85, VAL=-2.277
  TIME=0.875, VAL=-2.027
  TIME=0.90, VAL=-1.677
  TIME=0.925, VAL=-1.242
  TIME=0.95, VAL=-0.690
  TIME=0.975, VAL=-0.00
  Z-END=1.00, VAL=-0.00
%END

%BOUNDARY-INLET
  AREA = INJECT
  TYPE = FIX
  P-VAL = 5.1006
  W-G-VAL = 0.00
  W-L-VAL = 0.00

JASMIN JAEI
W-M-TAB = INJVF
VOL-G-VAL = 0.7884
VOL-L-VAL = 0.0000
* ams0.2116
T-G-VAL = 535.0
T-L-VAL = 535.0
T-M-VAL = 3073.0
* AREAM at inlet should be specified in uinit.f
* [AREAM=6*AM/DM]
* 13.8 (m-1) at (2,2,33) (92mm dia. jet in r=10cm cell)
%END

%BOUNDARY-WALL
* AREA=WALL1
* VEL=SLIP
* TEMP=HEAT-TRANSFER
* TEMP-VALUE=536.0
* TYPE=CONSTANT
* COEF-G-VAL=5.0e3
* COEF-L-VAL=5.0e3
* COEF-M-VAL=5.0e3
* AREA=WALL2
* VEL=SLIP
* TEMP=HEAT-TRANSFER
* TEMP-VALUE=536.0
* TYPE=CONSTANT
* COEF-G-VAL=5.0e3
* COEF-L-VAL=5.0e3
* COEF-M-VAL=5.0e3
%END

%FUEL-PROPERTY
* TYPE=FUNCTION
* TYPE=CONSTANT
* Corium UF2,2202
* rho and cp/e are specified in functions at MELT if TYPE=FUNCTION
* RH0 = 7960.0
* CV = 565.0
* VISC=4.23D-3
* CONC=2.88
* melting point , surface tension -> %RAL block RR(127)(128)
%END

%GRAVITY
GX = 0.0D0
GY = 0.0D0
GZ = -9.81D0
%END

%INITIAL
* TYPE = FUNCTION
%END

%TIME
TIME-START = 0.00
TIME-END = 6.00
DT = 1.0D-3
DT-MIN = 1.0D-10
DT-MAX = 1.0D-3
MAX-STEP = 100001
%END

%ITERATION
* MAX-ITER = 60
* CONVERGE = MAX
* convergence is judged comparing max residual with EPS defined below
* MASS-L = 1.0D-4
* MASS-G = 1.0D-4
* MASS-M = 1.0D-4
* ENERGY-L = 1.0D-4
* ENERGY-G = 1.0D-4
* ENERGY-M = 1.0D-4
* if bad conv., ave. residual is compared with ALLOW*EPS
* ALLOW = 10.0
%END

%MATRIX
* EPS = 1.0D-6
* MAX-ITER = 50
* TYPE = MILU

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DIVER = 1.0020
PRINT = NO

%END

%TERM
VISC = NO
THERM = NO
VIRTUAL = CA
* MOMENT = CA
LINEAR = YES
%END

%LIST-FILE
TIME=0.000
TIME=0.200
TIME=0.300 TIME=0.400
TIME=0.500
TIME=0.600 TIME=0.700 TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.100
TIME=1.200
TIME=1.300
TIME=1.400
TIME=1.500
TIME=1.60
TIME=1.70
TIME=1.80
TIME=1.90
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
SECT-DIR=Y SECT-COO=2
PHS=P
PHS=AREAM
* USER-S1 = Dm
* USER-S2 = Tsat
* USER-S3 = Ty-Tsat (0 if ag<1e-5)
* USER-S4 = Tl-Tsat (0 if al<1e-5)
PHS=USER-S1
PHS=USER-S2
PHS=USER-S3
PHS=USER-S4
PHS=AL
PHS=AM
PHS=AG
PHS=LG
PHS=TL
PHS=TM
PHS=UG
PHS=WG
PHS=UL
PHS=XL
PHS=UM
PHS=WM
%END

%PLOT-FILE
TIME=0.100 TIME=0.200 TIME=0.300 TIME=0.400 TIME=0.500
*TIME=0.600
TIME=0.700
*TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.200 TIME=1.40
TIME=1.50
*TIME=1.60 TIME=1.80
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
*PHS=P
*PHS=AREAM
PHS=AG
PHS=AL
PHS=AM
*PHS=LG

JASMINE JAERI
**PHS=TL**
**PHS=TM**
**PHS=AL**
**PHS=AL*VL**
**PHS=AL*WL**
**PHS=AG**
**PHS=AG*WG**
**PHS=AM**
**PHS=AM*WM**
**MERGE=YES**

```plaintext
%HISTORY-FILE
TYPE = ASCII
I = 4 J = 2 K = 60
I = 4 J = 2 K = 6
STEP-S = 1
STEP-I = 10
* PHS = P
PHS = TO
* PHS = TL
* PHS = AG
* PHS = AM
* PHS = WM

%END

%%VAL

* KK31=1: message if alpha<0 at end of newton loop (newton)
  * 31=1

* KK44=def 1): linearization method of source term (alpset)
  
* KK53=def 1): discretization of advection term in momentum eq. (solver)
  
* KK55=def 0): 0:use expen2(implicit T), 1:use expen(explicit T)
  fluid temp. adjacent to wall for evaluation of wall heat transfer (solver)

* KK82=def 1): switch of 53 at impact of jet on water surface (solver)
  
* total balance data output

* KK90=1 (default 0): output total balance data (*.tot)
  90 = 1

* KK91=def 1): interval of *.tot data
  91 = 10

* KK92=1: correction in temp./vel. of rare phase (correct)
  92 = 1

* breakup control

* KK93=0(def 0): no breakup, 1:breakup(use area transport eq) (cnarea)
  93 = 1

* KK178=0:dm from We, 1:dm=const(RR178)) (cnarea)
  * this setting is ignored if KK93=1

* KK179=1

* KK110=def 0) : KNOBRK: no breakup at K=2-KNOBRK
  110 = 4

* KK102=def 0) breakup control on the floor (brkup)
  1: no more breakup on the floor (K=2),
  2: agglomeration on the floor (K=2) (agglomeration time constant is RR177))
  3: use the floor area as melt surface area at K=2 (min melt layer thickness
  under which melt area is less than the floor area -> RR181))

102=3

* KK175=def 0) brkup coefficient switch
  0: use Pilch model (Pilch 1987) (parameters : RR178,179,180)
  1: use constant Cpb & Cse (defined in RR175) (178)
  175 = 1

* KK104=def 0) (brkup)
  1-3: jet fall mode consideration (cease breakup in jet body)
  1: no control on melt relative velocity at jet leading edge
  2: melt relative velocity to stagnant fluid at jet leading edge
  3: melt relative velocity to side way fluid at jet leading edge
```

JASMINE JAERI
heat transfer control

** KK(100) (default 2) HT control
  0: heat transfer always OFF,
  1: HT factor for phase change is set 0 if LOOPNN>=2,
  2: always ON,
  3: HT factor for phase change is reduced if LOOPNN>=2 and dt<RR(86)
  4: HT factor kir,kif(RR(160,162)) is reduced if LOOPNN>=2 and dt<RR(86)
  5: HT factor for phase change is reduced if kif,kir<1.e-10 and dt<RR(86)
  6: HT factor for phase change is reduced if kir,kif<1.e-10 and dt<RR(86)
  7: HT factor for phase change is reduced if kir,kif<1.e-10 and dt<RR(86)
  8: HT factor for phase change is reduced if kir,kif<1.e-10 and dt<RR(86)
  9: HT factor for phase change is reduced if kir,kif<1.e-10 and dt<RR(86)

(cnhtc, solver)

100 = 4

** KK(111) (default 1) 1:active kir2 , 0:const. kir2 (--RR(161))
  kir2=al*rhol/(al*rhol+ag*rhog) in vapor cont. regime (cnhtc)
111 = 0

** KK(112) (default 0) radiation HT control radctrl (cnhtc)
  0: take all rad. HT into account
  1: take only rad. HT in film boiling
  2: neglect all rad. HT
112 = 1

** KK(160) (default 0)
  0: use htlim function in cnhtc for rare phases (vapor, water)
  1: kill the htlim for vapor & water in cnhtc(HT control by cnarea --> KK(162))

  definition of limiting parameter is in RR(163,164)

** KK(161) (default 0)
  0: use htlim function in cnhtc for rare phases (melt)
  1: kill the htlim for melt in cnhtc (HT control by cnarea --> KK(163))

  definition of limiting parameter is in RR(165)

** KK(162) (default 0)
  0: let ar>=0 at a?min in cnarea (vapor, water)
  1: keep ar>0 even when a?<a?min in cnarea (vapor, water)

  if KK(160) is set 1, this should be 0
162 = 1

** KK(163) (default 0) (in effect only when KK(93) = 1)
  0: let arm0 at amamin in cnarea
  1: keep arm>0 even when am<amin in cnarea

  if KK(161) is set 1, this should be 0

** initial condition control

** KK(120-150): reserved to specify initial conditions in uinit.f

123 = 1
125 = 1
126 = 1
127 = 1
128 = 1
129 = 1
130 = 1
131 = 1: set aream(2,2,33)=0.0
132 = 1
132 = 1: set aream(2,2,33)=9.2
132 = 1

** jet-mode

** KK(106) (default 0) jet-mode ON: 1, OFF: 0
106 = 1

** KK(105) (default 0) (jet inlet cell k used in jet-mode)
105 = 33

** KK(107) (default 1) (solver) (jet related output interval:step)
107 = 50

** KK(108) (default 1) (jet-mode fragmentation model switch)
  1: Kataoka-Ishii based, 2: Epstein-Pauke based
108 = 2

** KK(109) (default 0) (jet-mode HT model switch)
  0: jet-mode HT model, 1: usual model HT model
109 = 1

JASMINE JAERI
surface area of water/vapor

KK(115) (default 0) switch of water & vapor particle size evaluation
* 0: We number with EMAX & EMIN limits
* 1: We + number density with EMIN limit
* 2: number density with EMIN limit
  (number density is specified in RR(171))
  115 = 2

friction factor

KK(50) (default 1): 0:CD=0.45, 1:CD by correlation (cnfric)
  50 = 0

KK(185) (default 0) ICDMELT: switch of melt drag coefficient (cnfric)
  0: use Ishii-Zuber distorted particle correlation
  1: use constant CDMELT (RR(185)) for melt particles
  185 = 1

%END

%RVAL

volume fraction control

RR(36,37,43) (default 1.0e-6): min limit volume fraction
  36,37,43 for AGMIN, ALMIN, AMMIN

RR(68) (default 1.e-10): relaxation of Newton method (upvar)

Heat Transfer control

RR(141-145) (default 1.0): heat transfer factor for sat_interface
  liq-to-bub, liq-to-film, gas-to-drop, in-drop, in-bubb respectively
  (cnhtc,solver)
  141 = 1.0
  142 = 1.0
  143 = 1.0
  144 = 10.0
  145 = 10.0

RR(86) (default 1.e-6): time step under which HT control starts
  * to keep convergence (solver)
  86 = 1.e-4

RR(146) (default 1.0e-6): minimum limit of reduction of HT factor for
  sat_interface (solver)
  146 = 1.e-3

RR(160-162) (default 1.0) radiation & film boiling HT control (cnhtc)
  160: kir (radiation HT fraction to evap.)
  161: kir2 (radiation HT fraction to droplets in cont. vapor)
  162: kif (filmboiling HT fraction to evap.)
  -- RR(111): active kir2 mode (control by material density)
  160=1.0
  161=1.0
  162=1.0

RR(163-165) (default 1.e-4) limitation volume fraction for HT involving
  rare phase (cnhtc)
  163:aqlimht, 164:alllimht, 165:sallimht
  should be larger than a7min

RR(126) (default 1.0e3): correction factor for gas momentum eq. CRCT
  in case of bad coverage (1.0 : no effect) (solver,upv)
  126 = 1.0e3

melt properties

RR(160) (default 0.79): radiation emissivity of melt (cnhtc)
  60 = 0.79

RR(127) (default 2840.0): melting temperature of melt material TMEILT (K)
  (cnmain)
  127 = 2830.0

RR(128) (default 0.45): surface tension of melt (N/m) (cnmain)

JASMINE JAERI
128 = 0.45

* surface area & particle diameter control

* RR(130-132) (default 1.0): max dia. of phases (m) (marea)
  * RR(132,133,135) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(133,134,135) (default 1.0e-9): max dia. of phases (m) (marea)

* RR(130-132) (default 1.0e-9): max dia. of phases (m) (marea)
  * RR(130,131,132) (default 1.0e-9): max dia. of phases (m) (marea)

* RR(131-133): min dia. of phases (m) (marea)
* RR(132,133): min dia. of phases (m) (marea)

* RR(136-139) (default 8., 12., 12., 8.) critical We (marea)
  * RR(136-139) (default 8., 12., 12., 8.) critical We (marea)
  * RR(136,137,138,139) (default 8., 12., 12., 8.) critical We (marea)

* RR(131-133) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(132,133) (default 1.0e-9): min dia. of phases (m) (marea)

* RR(133-135) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(133-135) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(134-136) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(135-137) (default 1.0e-9): min dia. of phases (m) (marea)

* RR(135) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(135) (default 1.0e-9): min dia. of phases (m) (marea)

* RR(134) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(136) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(137) (default 1.0e-9): min dia. of phases (m) (marea)

* RR(138) (default 1.0e-9): min dia. of phases (m) (marea)
  * RR(139) (default 1.0e-9): min dia. of phases (m) (marea)

* RR(171) (default 1.0e6) particle number density of discrete phase
  * (number/m^3) (marea)

171 = 1.0e6

* RR(170) (default 1.0): constant dia. of melt when KK(170)=1 & KK(93)=0

170 = 2.4e-3

* parameters for simple melt breakup model (when KK(175)=1)

* RR(175) (default 0.25) CPB primary breakup constant in effect
  * RK(175)=1 (brkup)
  * definition: (d_n/d_n+1 - 1)/tau_b

175 = 0.60

* RR(176) (default 0.089) CSE surface entrainment constant in effect
  * RK(175)=1 (brkup)

176 = 0.0

* parameters for Pilch model (when KK(175)=0)

* RR(178) (default 2.5) COOP droplet acceleration drag coeff. during breakup

178 = 2.5

* RR(179) (default 1.0): correction factor for Pilch model CPILCH

179 = 1.0

* RR(180) (default 1.5): correction in Pilch model CPILCH2

180 = 5.0

* parameter for simple melt agglomeration model (when KK(102)=2)

* RR(177) (default 0.0 -> evaluated by gravitational settle)
  * time constant of melt jet settling on the bottom [sec]

177 = 0.1

* parameter for simple melt agglomeration model (when KK(102)=3)

* RR(181) (default 0.005)
  * 0.005 min melt layer thickness under which the melt surface area is less than

181 = 5.0e-3

* friction factor

* RR(185) (default 0.45) CDMELT const. drag coeff. for melt when KK(185)=1

185 = 0.5

* jet-mode (jet-mode switch is KK(106))

* RR(148) (default 0.1) jet diameter at inlet cell

148 = 0.092

* RR(150) (default 1.0e-3) min jet diameter under which jet is handled in usual mode

150 = 1.0e-3

* RR(155) (default 1.0) enhancement of droplet entrainment
  * put on Kataoka-Ishii model

155 = 100.0

* RR(157) (default 1.0) enhancement of droplet entrainment
  * put on Epstein-Fauske model

157 = 1.0e-4

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\* RR(158) (default 1.0) droplet diameter factor
\* put on Epstein-Pauske model
\* 158 = 1.0
\*--------------------------------------------------------
\*END
\*SCHEME
\* TYPE = DONOR
\*END
\*STOP
\*END
\*DEBUG
\*TIME = 1.4460
\*TIME = 1.4470
\*TIME = 1.4480
\*SECT-DIR = X  SECT-COORD = 2
\*SECT-DIR = Y  SECT-COORD = 2
\*SECT-DIR = Z  SECT-COORD = 2
\*FLAG = 1  FLAG = 2  FLAG = 3  FLAG = 4  FLAG = 5
\*FLAG = 6  FLAG = 7  FLAG = 8  FLAG = 9  FLAG = 10
\*FLAG = 11
\*FLAG = 12
\*FLAG = 13  FLAG = 14  FLAG = 15
\*FLAG = 16  FLAG = 17  FLAG = 18  FLAG = 19  FLAG = 20
\*FLAG = 21
\*FLAG = 22
\*FLAG = 23
\*FLAG = 24  FLAG = 25
\*FLAG = 26  FLAG = 27  FLAG = 28  FLAG = 29  FLAG = 30
\*FLAG = 31  FLAG = 32  FLAG = 33  FLAG = 34  FLAG = 35
\*FLAG = 36  FLAG = 37  FLAG = 38  FLAG = 39  FLAG = 40
\*FLAG = 41  FLAG = 42  FLAG = 43  FLAG = 44  FLAG = 45
\*FLAG = 46  FLAG = 47  FLAG = 48  FLAG = 49  FLAG = 50
\*END
\*STOP
\*END

Input deck for calculation 3

\* JASMIN INPUT FILE
\* ISP-39 (FARO-114)
\*\*SYNTAX-CHECK
\*\*END
\*TITLE
\* TITLE = a3
\* (114000)
\*END
\*COORDINATE
\* TYPE = CY
\*END
\*MESH
\* X-START = 0.000  X-END = 0.30  X-DIV = 3
\* Y-START = 0.000  Y-END = 0.155  Y-DIV = 1
\* Z-START = 0.000  Z-END = 0.085  Z-DIV = 1
\* Z-END = 3.085  Z-DIV = 30
\* Z-END = 4.085  Z-DIV = 5
\* Z-END = 4.385  Z-DIV = 1
\* Z-END = 5.385  Z-DIV = 2
\*END
\*OBSTACLE-SOLID
\* I-S = 2, J-S = 2, K-S = 33
\* I-E = 2, J-E = 2, K-E = 40
\*END
\*BOUNDARY-AREA
\* NAME = INJECT
\* DIR = Z
\* 1-S = 2, J-S = 2, K-S = 32
\* 1-E = 2, J-E = 2, K-E = 32

JASMINE JAERI
* bottom
NAME = WALL1
DIR = Z
I-S=2, J-S=2, K-S=1
I-E=5, J-E=2, K-E=1

* side
NAME = WALL2
DIR = X
I-S=5, J-S=2, K-S=2
I-E=5, J-E=2, K-E=40

%END

%BOUNDARY-DEFAULT
VEL = SLIP
TEMP = ADIABATIC
%END

%TABLE
NAME= INJVT
* A. Annunziato et al. (Apr.1996)
TIME=0.00, VAL=-0.00
TIME=0.005, VAL=-0.091
TIME=0.025, VAL=-0.453
TIME=0.05, VAL=-0.889
TIME=0.075, VAL=-1.293
TIME=0.10, VAL=-1.654
TIME=0.125, VAL=-1.967
TIME=0.15, VAL=-2.230
TIME=0.175, VAL=-2.445
TIME=0.20, VAL=-2.617
TIME=0.25, VAL=-2.852
TIME=0.30, VAL=-2.981
TIME=0.35, VAL=-3.041
TIME=0.40, VAL=-3.057
TIME=0.45, VAL=-3.047
TIME=0.50, VAL=-3.021
TIME=0.55, VAL=-2.985
TIME=0.60, VAL=-2.943
TIME=0.65, VAL=-2.887
TIME=0.70, VAL=-2.817
TIME=0.75, VAL=-2.740
TIME=0.80, VAL=-2.598
TIME=0.825, VAL=-2.466
TIME=0.85, VAL=-2.277
TIME=0.875, VAL=-2.017
TIME=0.90, VAL=-1.677
TIME=0.925, VAL=-1.242
TIME=0.95, VAL=-0.690
TIME=0.975, VAL=-0.00
TIME=1.00, VAL=-0.00
%END

%BOUNDARY-INLET
AREA = INJECT
TYPE = FIX
P-VAL = 5.10D6
W-G-VAL = 0.00
W-L-VAL = 0.00
W-M-TAB = INJVT
VOL-G-VAL = 0.7884
VOL-L-VAL = 0.0000
* am=0.2116
T-G-VAL = 535.0
T-L-VAL = 535.0
T-M-VAL = 3073.0
* AREA at inlet should be specified in unit.f
* (AREA=6*AM/DM)
* 13.8 (m-1) at (2,2,33) (92mm dia. jet in r=10cm cell)
%END

*BOUNDARY-WALL
* AREA=WALL1
VEL=SLIP
TEM=HEAT-TRANSFER
TEMP-VALU=536.0
TYPE=CONSTANT
COEF-G-VAL=5.0e3
COEF-L-VAL=5.0e3
COEF-M-VAL=5.0e3
AREA=WALL2

JASMINE JAERI
* VEL=SLIP
* TEMP=HEAT-TRANSFER
* TEMP=VALUE=536.0
* TYPE=CONSTANT
* COEF-G-VAL=5.0e3
* COEF-L-VAL=5.0e3
* COEF-M-VAL=5.0e3
*END

%FUEL-PROPERTY
TYPE=FUNCTION
* TYPE=CONSTANT
* Corium UPZ,2r02
* rho and cp/e are specified in functions at MELT if TYPE=FUNCTION
* RHO = 3960.0
* CV = 565.0
* VISC=4.23D-3
* COND=2.88
* melting point , surface tension -> %VAL block RR(127)(128)
*END

%GRAVITY
GX = 0.000
GY = 0.000
GZ = -9.8120
*END

%INITIAL
TYPE = FUNCTION
*END

%TIME
TIME-START = 0.00
TIME-END = 6.00
DT = 1.0D-3
DT-MIN = 1.0D-10
DT-MAX = 1.0D-3
MAX-STEP = 100000
*END

%ITERATION
MAX-ITER = 60
CONVERGE = MAX
* convergence is judged comparing max residual with EPS defined below
MASS-L = 1.0D-4
MASS-O = 1.0D-4
MASS-M = 1.0D-4
ENERGY-L = 1.0D-4
ENERGY-O = 1.0D-4
ENERGY-M = 1.0D-4
* if bad conv., ave. residual is compared with ALLOW*EPS
ALLOW = 10.0
*END

%MATRIX
EPS = 1.0D-6
MAX-ITER = 50
TYPE = MILLU
DIVER = 1.0020
PRINT = NO
*END

%TERM
VISC = NO
THERM = NO
VIRTUAL = CA
MOMENT = CA
LINEAR = YES
*END

%LIST-FILE
TIME=0.000
TIME=0.200
TIME=0.300 TIME=0.400
TIME=0.500
TIME=0.600 TIME=0.700 TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.100
TIME=1.200

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TIME=1.300
TIME=1.400
TIME=1.500
TIME=1.60
TIME=1.70
TIME=1.80
TIME=1.90
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
SECT-DIRE=Y SECT-COO=2
PHS=P
PHS=AREAM
* USER-S1 : Dm
* USER-S2 : Tsat
* USER-S3 : Ty-Tsat (0 if ag<1e-5)
* USER-S4 : Tl-Tsat (0 if al<1e-5)
PHS=USER-S1
PHS=USER-S2
PHS=USER-S3
PHS=USER-S4
PHS=AL
PHS=AM
PHS=AG
PHS=TO
PHS=TL
PHS=TM
PHS=UG
PHS=WG
PHS=UL
PHS=WL
PHS=UM
PHS=WH
%END

%PLOT-FILE
TIME=0.100 TIME=0.200 TIME=0.300 TIME=0.400 TIME=0.500
*TIME=0.600
TIME=0.700
*TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.20 TIME=1.40
TIME=1.50
*TIME=1.60 TIME=1.80
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
*PHS=P
*PHS=AREAM
PHS=AG
PHS=AL
PHS=AM
*PHS=TO
*PHS=TL
PHS=TM
PHS=AL*UL
PHS=AL*WL
PHS=AG*UG
PHS=AG*WG
PHS=AM*UM
PHS=AM*WM
MERGE=YES
%END

%HISTORY-FILE
TYPE = ASCII
I = 4 J = 2 K =30
I = 4 J = 2 K =6
STEP-S = 1
STEP-I = 10
* PHS = P
PHS = TO
PHS = TL
* PHS = AG
* PHS = AM

JASMINE JAERI
PHS = WM

\%END

\%IVAL

* KK(31)=1: message if alpha<0 at end of newton loop (newton)
* 31=1
* __________________________
* KK(44) (default 2): linearization method of source term (alpset)
* __________________________
* KK(53) (default 1): discretization of advection term in momentum eq. (solver)
* __________________________
* KK(55) (default 0): 0: use expen2 (implicit T), 1: use expen (explicit T)
* fluid temp. adjacent to wall for evaluation of wall heat transfer (solver)
* __________________________
* KK(82) (default 1): switch of 53 at impact of jet on water surface (solver)
* __________________________
* total balance data output
* __________________________
* KK(90)=1 (default 0): output total balance data (*.tot)
* 90 = 1
* __________________________
* KK(91) (default 1): interval of *.tot data
* 91 = 10
* __________________________
* KK(92)=1: correction in temp./vel. of rare phase (correct)
* 92 = 1
* __________________________
* breakup control
* __________________________
* KK(93)=0 (default 0): no breakup, 1: breakup (use area transport eq) (cnarea)
* 93 = 1
* __________________________
* KK(170)=0: dm from We, 1: dm=const (RR(170)) (cnarea)
* (this setting is ignored if KK(93)=1)
* 170 = 1
* __________________________
* KK(1110) (default 0): NOBK: no breakup at K = 2, NOBK
* 110 = 4
* __________________________
* KK(102) (default 0): breakup control on the floor (brkup)
* 1: no more breakup on the floor (K=2),
* 2: agglomeration on the floor (K=2) (agglomeration time constant is RR(177))
* 3: use the floor area as melt surface area at K=2 (min melt layer thickness
* under which melt area is less than the floor area -> RR(181))
* 102 = 1
* __________________________
* KK(175) (default 0) brkup coefficient switch
* 0: use Pich model (Pich 1987) (parameters : RR(178,179,180))
* 1: use constant Cpb & Cse (defined in RR(175) (176))
* 175 = 1
* __________________________
* KK(104) (default 0) (brkup)
* 1-3: jet fall mode consideration (cease breakup in jet body)
* 1: no control on melt relative velocity at jet leading edge
* 2: melt relative velocity to stagnant fluid at jet leading edge
* 3: melt relative velocity to side way fluid at jet leading edge
* 104 = 3
* __________________________
* heat transfer control
* __________________________
* KK(100) (default 2) HT control
* 0: heat transfer always OFF,
* 1: HT factor for phase change is set 0 if LOOPNM->2,
* 2: always ON
* 3: HT factor for phase change is reduced if LOOPNM->2 and dt<RR(86)
* 4: HT factor kif.kif(RR(160,162)) is reduced if LOOPNM->2 and dt<RR(86)
* & HT factor for phase change is reduced if kif.kif<1.e-10 and dt<RR(86)
* (chntc, solver)
* (chntc, solver)
* 100 = 4
* __________________________
* KK(111) (default 1) 1: active kif, 0:const. kif2 (="RR(161)"
* kif=al*rhol/(a)*rholag*rholag)*vapor cont. regime (chntc)
* 111 = 0
* __________________________
* KK(112) (default 0) radiation HT control radctr (chntc)
* 0: take all rad. HT into account

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* 1: take only rad. HT in film boiling
* 2: neglect all rad. HT
112 = 1

* KK(160)(default 0)
  * 0: use htm function in cmhc for rare phases (vapor, water)
  * 1: keep the htm for vapor & water in cmhc (HT control by cnarea -> KK(162))
  * (definition of limiting parameter is in RR(163,164))
* KK(161)(default 0)
  * 0: use htm function in cmhc for rare phases (melt)
  * 1: keep the htm for melt in cmhc (HT control by cnarea -> KK(163))
  * (definition of limiting parameter is in RR(165))

* KK(162)(default 0)
  * 0: let ar? = 0 at a?min in cnarea (vapor, water)
  * 1: keep ar? > 0 even when a? < a?min in cnarea (vapor, water)
  * (if KK(160) is set 1, this should be 0)
162 = 1

* KK(163)(default 0) (in effect only when KK(93) != 1)
  * 0: let arm = 0 at am?min in cnarea
  * 1: keep arm > 0 even when am? = am?min in cnarea
  * (if KK(161) is set 1, this should be 0)

* initial condition control

* KK(120-150): reserved to specify initial conditions in uinit.f
  * 123 = 1
  * 125 = 1
  * 126 = 1
  * 127 = 1
  * 128 = 1
  * 129 = 1
  * 130 = 1
  * 131 = 1: set aream(2,2,33) = 0.0
  * 131 = 1
  * 132 = 1: set aream(2,2,33) = 9.2
  * 132 = 1

* jet-mode

* KK(106)(default 0) jet-mode ON:1 , OFF:0
  * 106 = 1

* KK(105)(default 0) (jet inlet cell k used in jet-mode)
  * 105 = 33

* KK(107)(default 1) (solver)(jet related output interval:step)
  * 107 = 50

* KK(108)(default 1) (jet-mode fragmentation model switch)
  * 1: Kataoka-Ishii based, 2: Epstein-Fauke based
  * 108 = 2

* KK(109)(default 0) (jet-mode HT model switch)
  * 0: jet-mode HT model, 1: usual model HT model
  * 109 = 1

* surface area of water/vapor

* KK(115)(default 0) switch of water & vapor particle size evaluation
  * 0: We number with DMAX & DMIN limits
  * 1: We number density with DMIN limit
  * 2: number density with DMIN limit
  * (number density is specified in RR(171))
  * 115 = 2

* Friction factor

* KK(50)(default 1): 0:CD=0.45, 1:CD by correlation (cnfrric)
  * 50 = 0

* KK(185)(default 0) ICDMELT: switch of melt drag coefficient (cnfrric)
  * 0: use Ishii-Zuber distorted particle correlation
  * 1: use constant CD MELT (RR(185)) for melt particles
  * 185 = 1

END

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volume fraction control
- RR(36, 37, 43) (default 1.0e-6): min limit volume fraction
- 36, 37, 43 for AGMIN, ALMIN, AMIN
- RR(68) (default 1.0e-10): relaxation of Newton method (upvar)

Heat Transfer control
- RR(141-145) (default 1.0): heat transfer factor for sat. interface
- liq-to-bub, liq-to-film, gas-to-drop, in-drop, in-bubb respectively
- (cnhtc, solver)
  141 = 1.0
  142 = 1.0
  143 = 1.0
  144 = 10.0
  145 = 10.0
- RR(86) (default 1.0e-6): time step under which HT control starts
to keep convergence (solver)
  86 = 1.0e-4
- RR(146) (default 1.0e-6): minimum limit of reduction of HT factor for
  sat. interface (solver)
  146 = 1.0e-3
- RR(160-162) (default 1.0) radiation & film boiling HT control (cnhtc)
  160: kir (radiation HT fraction to evap.)
  161: kir2 (radiation HT fraction to droplets in cont. vapor)
  162: klf (film boiling HT fraction to evap.)
  -> KK(111): active kir2 mode (control by material density)
  160=1.0
  161=1.0
  162=1.0
- RR(163-165) (default 1.0e-4) limitation volume fraction for HT involving
  rare phase (cnhtc)
  163:aglimh1, 164:alllimit, 165:amlimit
  should be larger than a7min
- RR(126) (default 1.0e3): correction factor for gas momentum eq. CRCT
  in case of bad convergence (1.0 : no effect) (solver, upv)
  126 = 1.0e3

melt properties
- RR(60) (default 0.79): radiation emissivity of melt (cnhtc)
  60 = 0.79
- RR(127) (default 2840.0): melting temperature of melt material TMELT (K)
  (cnmain)
  127 = 2830.0
- RR(128) (default 0.45): surface tension of melt (N/m) (cnmain)
  128 = 0.45

surface area & particle diameter control
- RR(130-132) (default 1.0): max dia. of phases (m) (cnarea)
  130, 131, 132 for DBMAX(vapor), DBMAX(water), DBMAX(melt)
- RR(133-135) (default 1.0e-9): min dia. of phases (m) (cnarea)
  133, 134, 135 for DBMIN(vapor), DBMIN(water), DBMIN(melt)
  135 = 2.0e-3
- RR(136-139) (default 8.12, 12.6, .) critical We (cnarea)
  136, 137, 138, 139 for WEBUB(vapor), WEBUB(water), WEBUB(melt),
  WEC(bub/drop in continuous melt)
- RR(171) (default 1.0e6) particle number density of discrete phase
  [number/m^3] (cnarea)
  171 = 1.0e6
- RR(170) (default 1.0e-2): constant dia. of melt when KK(170)=1 & KK(93)=0
  170 = 2.4e-3

JASMINE JAERI
* parameters for simple melt breakup model (when KK(175)=1)
* -----------------------------------------------
* RR(175) (default 0.25) CPB primary breakup constant in effect
*   if KK(175)=1 (brkup)
*   definition: (d_n/d_n+1 - 1)/tau_b
*   175 = 0.577
* -----------------------------------------------
* RR(176) (default 0.089) CSE surface entrainment constant in effect
*   if KK(175)=1 (brkup)
*   176 = 0.0
* -----------------------------------------------
* parameter for Pilch model (when KK(175)=0)
* -----------------------------------------------
* RR(178) (default 2.5) CDDRP droplet acceleration drag coeff. during breakup
*   178 = 2.5
* -----------------------------------------------
* RR(179) (default 1.0): correction factor for Pilch model CPILCH
*   179 = 1.0
* -----------------------------------------------
* RR(180) (default 1.5): correction in Pilch model CPILCH2
*   (min number of particles in one-step breakup)**(1/3) (should be > 1.0)
*   180 = 5.0
* -----------------------------------------------
* parameter for simple melt agglomeration model (when KK(102)=2)
* -----------------------------------------------
* RR(177) (default 0.0 -> evaluated by gravitational settle)
*   time constant of melt jet settling on the bottom [sec]
*   177 = 0.1
* -----------------------------------------------
* parameter for simple melt agglomeration model (when KK(102)=3)
* -----------------------------------------------
* RR(181) (default 0.005)
*   THMIN min melt layer thickness under which the melt surface area is less than
*   the floor area
*   181 = 5.0e-3
* -----------------------------------------------
* Friction factor
* -----------------------------------------------
* RR(185) (default 0.45) CDMELT const. drag coeff. for melt when KK(185)=1
*   185 = 1.0
* -----------------------------------------------
* Jet-mode (jet-mode switch is KK(106))
* -----------------------------------------------
* RR(148) (default 0.1) jet diameter at inlet cell
*   148 = 0.092
* -----------------------------------------------
* RR(150) (default 1.e-3) min jet diameter under which jet is
*   handled in usual mode
*   150 = 1.0e-3
* -----------------------------------------------
* RR(155) (default 1.0) enhancement of droplet entrainment
*   put on Kataoka-Ishii model
*   155 = 100.0
* -----------------------------------------------
* RR(157) (default 1.0) enhancement of droplet entrainment
*   put on Epstein-Pauske model
*   157 = 1.0e-4
* -----------------------------------------------
* RR(158) (default 1.0) droplet diameter factor
*   put on Epstein-Pauske model
*   158 = 1.0
* -----------------------------------------------

%END

%SCHEME
  TYPE = DONOR
%END

%STOP
%END

%DEBUG
TIME = 1.4460
TIME = 1.4470
TIME = 1.4480
SECT-DIR = X
SECT-DIR = Y
SECT-DIR = Z
  SECT-COORD = 2
  SECT-COORD = 2
  SECT-COORD = 2
FLAG = 1  FLAG = 2  FLAG = 3  FLAG = 4  FLAG = 5
FLAG = 6  FLAG = 7  FLAG = 8  FLAG = 9  FLAG = 10

JASMINE JAERI
* FLAG = 11
* FLAG = 12
* FLAG = 13 FLAG = 14 FLAG = 15
* FLAG = 16 FLAG = 17 FLAG = 18 FLAG = 19 FLAG = 20
* FLAG = 21
* FLAG = 22
FLAG = 23
* FLAG = 24 FLAG = 25
* FLAG = 26 FLAG = 27 FLAG = 28 FLAG = 29 FLAG = 30
* FLAG = 31 FLAG = 32 FLAG = 33 FLAG = 34 FLAG = 35
* FLAG = 36 FLAG = 37 FLAG = 38 FLAG = 39 FLAG = 40
* FLAG = 41 FLAG = 42 FLAG = 43 FLAG = 44 FLAG = 45
* FLAG = 46 FLAG = 47 FLAG = 48 FLAG = 49 FLAG = 50
FLAG = 55
%END
%STOP
%END

Input deck for calculation 4

* JASMINE INPUT FILE
* ISP-39 (PARO-L14)
%SYNTAX-CHECK
%END
%TITLE
TITLE = a4
* (114ov)
%END
%COORDINATE
TYPE = CY
%END
%MESH
X-START = 0.000 X-END = 0.30 X-DIV = 3
Y-START = 0.000 Y-END = 0.355 Y-DIV = 1
Z-START = 0.000 Z-END = 0.085 Z-DIV = 1
Z-END = 3.085 Z-DIV = 10
Z-END = 4.085 Z-DIV = 5
Z-END = 5.085 Z-DIV = 2
%END
%OBSTACLE-SOLID
I-S = 2, J-S = 2, K-S = 33
I-E = 2, J-E = 2, K-E = 40
%END
%BOUNDARY AREA
NAME = INJECT
DIR = Z
I-S = 2, J-S = 2, K-S = 32
I-E = 2, J-E = 2, K-E = 32
* bottom
NAME = WALL1
DIR = Z
I-S=2, J-S=2, K-S=1
I-E=5, J-E=2, K-E=1
* side
NAME = WALL2
DIR = X
I-S=5, J-S=2, K-S=2
I-E=5, J-E=2, K-E=40
%END
%BOUNDARY-DEFAULT
VEL = SLIP
TEMP = ADIABATIC
%END
%TABLE
NAME= INJV
* A. Annunziato et al. (Apr.1996)
TIME=0.00, VALs=0.00

JASMINE JAERI
TIME=0.005, VAL=0.091
TIME=0.025, VAL=0.453
TIME=0.05, VAL=0.889
TIME=0.075, VAL=1.293
TIME=0.10, VAL=1.654
TIME=0.125, VAL=1.967
TIME=0.15, VAL=2.23
TIME=0.175, VAL=-2.445
TIME=0.20, VAL=2.617
TIME=0.25, VAL=2.852
TIME=0.30, VAL=2.981
TIME=0.35, VAL=3.041
TIME=0.40, VAL=3.057
TIME=0.45, VAL=3.047
TIME=0.50, VAL=3.021
TIME=0.55, VAL=-2.985
TIME=0.60, VAL=-2.943
TIME=0.65, VAL=-2.887
TIME=0.70, VAL=-2.817
TIME=0.75, VAL=-2.740
TIME=0.80, VAL=-2.598
TIME=0.825, VAL=-2.466
TIME=0.85, VAL=-2.277
TIME=0.875, VAL=-2.017
TIME=0.90, VAL=-1.677
TIME=0.925, VAL=-1.242
TIME=0.95, VAL=-0.690
TIME=0.975, VAL=0.00
TIME=1.00, VAL=0.00

%BOUNDARY-INLET
- AREA = INJECT
  TYPE = FIX
  P-VAL = 5.10D6
  W-G-VAL = 0.00
  W-L-VAL = 0.00
  W-M-VAL = INCF
  VOL-G-VAL = 0.7894
  VOL-L-VAL = 0.0000
* amq=0.2116
  T-G-VAL = 535.0
  T-L-VAL = 535.0
  T-M-VAL = 3073.0
* AREA at inlet should be specified in unit.f
  (AREAN=6*AM/DM)
* 13.8 (m-1) at (2,2,33) (92nm dia. jet in r=10cm cell)

%END

%BOUNDARY-WALL
- AREA=WALL1
  VEL=SLIP
  TEMP=HEAT-TRANSFER
  TEMP-VALUE=536.0
  TYPE=CONSTANT
  COEF-G-VAL=5.0e3
  COEF-L-VAL=5.0e3
  COEF-M-VAL=5.0e3
- AREA=WALL2
  VEL=SLIP
  TEMP=HEAT-TRANSFER
  TEMP-VALUE=536.0
  TYPE=CONSTANT
  COEF-G-VAL=5.0e3
  COEF-L-VAL=5.0e3
  COEF-M-VAL=5.0e3

%END

%FUEL-PROPERTY
  TYPE=FUNCTION
  TYPE=CONSTANT
  Corium UP2,2,0,2
  rho and cp/e are specified in functions at MELT if TYPE=FUNCTION
  RHO = 7960.0
  CV = 565.0
  VISC=4.23D-3
  COND=2.88
  * melting point, surface tension -> %VAL block RR(127)(128)

%END

JASMINE JAERI
%GRAVITY
GX = 0.000
GY = 0.000
GZ = -9.8100
%END

%INITIAL
TYPE = FUNCTION
%END

%TIME
TIME-START = 0.00
TIME-END = 6.00
DT = 1.0D-3
DT-MIN = 1.0D-10
DT-MAX = 1.0D-3
MAX-STEP = 1000000
%END

%ITERATION
MAX-ITER = 60
CONVERGE = MAX
* convergence is judged comparing max residual with EPS defined below
MASS-L = 1.0D-4
MASS-G = 1.0D-4
MASS-M = 1.0D-4
ENERGY-L = 1.0D-4
ENERGY-G = 1.0D-4
ENERGY-M = 1.0D-4
* if bad conv., ave. residual is compared with ALLOW*EPS
ALLOW = 10.0
%END

%MATRIX
EPS = 1.0D-6
MAX-ITER = 50
TYPE = MILU
DIVER = 1.0020
PRINT = NO
%END

%TERM
VISC = NO
THERM = NO
VIRTUAL = CA
MOMENT = CA
LINEAR = YES
%END

%LIST-FILE
TIME=0.000
TIME=0.200
TIME=0.300 TIME=0.400
TIME=0.500
TIME=0.600 TIME=0.700 TIME=0.800
TIME=0.900
TIME=1.000
TIME=1.100
TIME=1.200
TIME=1.300
TIME=1.400
TIME=1.500
TIME=1.60
TIME=1.70
TIME=1.80
TIME=1.90
TIME=2.00
TIME=2.50
TIME=3.00
TIME=3.50
TIME=4.00
SECT-DIR=X SECT-COD=2
PHS=P
PHS=AREAM
* USER-S1 : Dm
* USER-S2 : Tsat
* USER-S3 : Ty-Tsat (0 if ag<1e-5)
* USER-S4 : Tl-Tsat (0 if ai<1e-5)
PHS=USER-S1
PHS=USER-S2

JASMINE JAERI
KK(91) (default 1): interval of .tot data
91 = 10

KK(92) = 1: correction in temp./vel. of rare phase (correct)
92 = 1

breakup control

KK(93) = 0 (default 0): no breakup, 1: breakup (use area transport eq) (cnarea)
93 = 1

KK(170) = 0: dm from We, 1: dm = const (RR(170)) (cnarea)
(this setting is ignored if KK(93) = 1)
170 = 1

KK(110) (default 0): KNORRX: no breakup at K=2-KNOBRK
110 = 0

KK(102) (default 0): breakup control on the floor (brkup)
0: no special control on/near the floor
1: no more breakup on the floor (K=2)
2: agglomaration on the floor (K=2) (agglomaration time constant is RR(177))
3: use the floor area as melt surface area at K=2 (min melt layer thickness
under which melt area is less than the floor area -> RR(181))
102 = 0

KK(175) (default 0): brkup coefficient switch
0: use Pilch model [Pilch 1987] (parameters : RR(178,179,180))
1: use constant Cpb & Cse (defined in RR(175)-(176))
175 = 1

KK(104) (default 0): (brkup)
1-3: jet fall mode consideration (cease breakup in jet body)
1: no control on melt relative velocity at jet leading edge
2: melt relative velocity to stagnant fluid at jet leading edge
3: melt relative velocity to side way fluid at jet leading edge
104 = 3

heat transfer control

KK(100) (default 2): HT control
0: heat transfer always OFF,
1: HTC factor for phase change is set 0 if LOOPNM=2,
2: always ON
3: HTC factor for phase change is reduced if LOOPNM=2 and dt<RR(86)
down to RR(146)
4: HTC factor & HTC factor for phase change is reduced if kif,kif<1.e-10 and dt<RR(86)
down to RR(146)
(cnhctc, solver)
100 = 4

KK(111) (default 1): active kif2 , 0:const. kif2 (->RR(161))
kif2=alpha*rhol/alpha*rhol+ag*rhog in vapor cont. regime (cnhctc)
111 = 0

KK(112) (default 0): radiation HT control radctrl (cnhctc)
0: take all rad. HT into account
1: take only rad. HT in film boiling
2: neglect all rad. HT
112 = 1

KK(160) (default 0): 0: use htlm function in cnhctc for rare phases (vapor, water)
1: HT control by cnhctc(HT control by cnhctc -> KK(162))
(definition of limiting parameter is in RR(163,164))

KK(161) (default 0): 0: use htlm function in cnhctc for rare phases (melt)
1: HT control by cnhctc (HT control by cnhctc -> KK(163))
(definition of limiting parameter is in RR(165))

KK(162) (default 0): 0: let ar=0 at amin in cnhctc (vapor, water)
1: keep ar>0 even when a<amin in cnhctc (vapor, water)
162 = 1

JASMINE JAERI
* KK(163) (default 0) (in effect only when KK(93) := 1)
  0: let arm = 0 at arm in cnaera
  1: keep arm > 0 even when arm<armin in cnaera
* (if KK(161) is set 1, this should be 0)
* initial condition control
* -------------------------------
* KK(120-150): reserved to specify initial conditions in uinit.f
  123 = 1
  125 = 1
  126 = 1
  127 = 1
  128 = 1
  129 = 1
  130 = 1
  131 = 1: set aream(2,2,33)=0.0
  132 = 1
  132 = 1: set aream(2,2,33)=9.2
  133 = 1
* jet-mode
* -------------------------------
* KK(106) (default 0) jet-mode ON: 1, OFF: 0
  106 = 1
* ----------------------------------------
* KK(105) (default 0) jet inlet cell k used in jet-mode
  105 = 33
* ----------------------------------------
* KK(107) (default 1) (solver) (jet related output interval: step)
  107 = 50
* ----------------------------------------
* KK(108) (default 1) (jet-mode fragmentation model switch)
  1: Kataoka-Ishii based, 2: Epstein-Pauke based
  108 = 2
* ----------------------------------------
* KK(109) (default 0) (jet-mode HT model switch)
  0: jet-mode HT model, 1: usual model HT model
  109 = 1
* surface area of water/vapor
* ----------------------------------------
* KK(115) (default 0) switch of water & vapor particle size evaluation
  0: We number with DMAX & DMIN limits
  1: We number with DMAX & DMIN limit
  2: number density with DMIN limit
  * (number density is specified in RR(171) )
  115 = 2
* ----------------------------------------
* Friction factor
* ----------------------------------------
* KK(50) (default 1): 0,CD=0.45, 1:CD by correlation (cnfric)
  50 = 0
* ----------------------------------------
* KK(185) (default 0) ICMDILT: switch of melt drag coefficient (cnfric)
  0: use Ishii-Zuber distorted particle correlation
  1: use constant CICMDILT (RR(185)) for melt particles
  185 = 1

%END

%RVAL
* volume fraction control
* -------------------------------
* RR(36,37,43) (default 1.0e-6): min limit volume fraction
  36,37,43 for AGRMIN,ALMIN,AMMIN
* ----------------------------------------
* RR(68) (default 1.e-10): relaxation of Newton method (upvar)
* Heat Transfer control
* ----------------------------------------
* RR(141-145) (default 1.0): heat transfer factor for sat. interface
  (cnfric,solver)
  141 = 1.0
  142 = 1.0
  143 = 1.0
  144 = 10.0
  145 = 10.0
• RR[86] (default 1.e-6): time step under which HT control starts
to keep convergence (solver)
86 = 1.e-4

• RR[146] (default 1.e-6): minimum limit of reduction of HT factor for
sat. interface (solver)
146 = 1.e-3

• RR[160-162] (default 1.0): radiation & film boiling HT control (cnnct)
160: kIr (radiation HT fraction to evap.)
161: kIr2 (radiation HT fraction to droplets in cont. vapor)
162: kif (film boiling HT fraction to evap.)
-> RR[111]: active kIr2 mode (control by material density)
160 = 1.0
161 = 1.0
162 = 1.0

• RR[163-165] (default 1.e-4) limitation volume fraction for HT involving
rare phase (cnnct)
163:aglimt, 164:allimt, 165:amlimt
should be larger than a7min

• RR[126] (default 1.0e3): correction factor for gas momentum eq. CRCT
in case of bad convergence (1.0 : no effect) (solver,upv)
126 = 1.0e3

• melt properties

• RR[69] (default 0.79): radiation emissivity of melt (cnnct)
69 = 0.79

• RR[127] (default 2840.0): melting temperature of melt material TMELT (K)
(cnnct)
127 = 2830.0

• RR[128] (default 0.45): surface tension of melt (N/m) (cnnct)
128 = 0.45

• surface area & particle diameter control

• RR[130-132] (default 1.0): max dia. of phases (m) (carea)
130,131,132 for DBMAX(vapor),DOMAX(water),DMAX(melt)

• RR[133-135] (default 1.0e-9): min dia. of phases (m) (carea)
133,134,135 for DMIN(vapor),DMIN(water),DMIN(melt)
135 = 2.0e-3

• RR[136-139] (default 6.,12.,12.,8.): critical We (carea)
136,137,138,139 for WEUB(vapor),WEDRP(water),WEMLT(melt),
WEC(bub/drp in continuous melt)

• RR[171] (default 1.0e6) particle number density of discrete phase
number"*"m^3 (carea)
171 = 1.0e6

• RR[170] (default 1.e-2): constant dia. of melt when KK[170]=1 & KK[93]=0
170 = 2.4e-3

• parameters for simple melt breakup model (when KK[175]=1)

• RR[175] (default 0.25): CPB primary breakup constant in effect
if KK[175]=1 (brkup)
definition: (dh/dn+1 - 1)/tau_b
175 = 0.577

• RR[176] (default 0.089): CSE surface entrainment constant in effect
if KK[175]=1 (brkup)
176 = 0.0

• parameter for Pilch model (when KK[175]=0)

• RR[178] (default 2.5): CDDRd droplet acceleration drag coeff. during breakup
178 = 2.5

• RR[179] (default 1.0): correction factor for Pilch model CPILCH
179 = 1.0

• RR[180] (default 1.5): correction in Pilch model CPILCH2
*(min number of particles in one-step breakup)**(1/3) (should be > 1.0)

180 = 5.0

* parameter for simple melt agglomeration model (when KK(102)=2)
* RR(177) (default 0.0 -> evaluated by gravitational settle)
  time constant of melt jet settling on the bottom [sec]
  177 = 0.1

* parameter for simple melt agglomeration model (when KK(102)=3)
* RR(181) (default 0.005)
  * MIN melt layer thickness under which the melt surface area is less than
  * the floor area
  181 = 5.0e-3

* Friction factor
* RR(185) (default 0.45) CDRELMELT const. drag coeff. for melt when KK(185)=1
  185 = 0.5

* jet-mode (jet-mode switch is KK(106))
* RR(148) (default 0.1) jet diameter at inlet cell
  148 = 0.092

* RR(150) (default 1.e-3) min jet diameter under which jet is
  handled in usual mode
  150 = 1.0e-3

* RR(155) (default 1.0) enhancement of droplet entrainment
  put on Kataoka-Ishii model
  155 = 100.0

* RR(157) (default 1.0) enhancement of droplet entrainment
  put on Epstein-Fauske model
  157 = 1.0e-4

* RR(158) (default 1.0) droplet diameter factor
  put on Epstein-Fauske model
  158 = 1.0

%END

%SCHEME
  TYPE = DONOR
%END

%STOP
%END

%DEBUG
  TIME = 1.4460
  TIME = 1.4470
  TIME = 1.4480
  *SECT-DIR = X  SECT-COORD = 2
  *SECT-DIR = Y  SECT-COORD = 2
  *SECT-DIR = Z  SECT-COORD = 2
  FLAG = 1  FLAG = 2  FLAG = 3  FLAG = 4  FLAG = 5
  FLAG = 6  FLAG = 7  FLAG = 8  FLAG = 9  FLAG = 10
  FLAG = 11
  FLAG = 12
  FLAG = 13  FLAG = 14  FLAG = 15
  FLAG = 16  FLAG = 17  FLAG = 18  FLAG = 19  FLAG = 20
  FLAG = 21
  FLAG = 22
  FLAG = 23
  FLAG = 24  FLAG = 25
  FLAG = 26  FLAG = 27  FLAG = 28  FLAG = 29  FLAG = 30
  FLAG = 31  FLAG = 32  FLAG = 33  FLAG = 34  FLAG = 35
  FLAG = 36  FLAG = 37  FLAG = 38  FLAG = 39  FLAG = 40
  FLAG = 41  FLAG = 42  FLAG = 43  FLAG = 44  FLAG = 45
  FLAG = 46  FLAG = 47  FLAG = 48  FLAG = 49  FLAG = 50
%END

%STOP
%END
1.7 - Participants comments

Because JASMINE does not have proper models to handle the melt spreading, debris settling on the floor and heat transfer from a debris bed, also heat loss from the vessel wall is not modelled, all the calculation was aimed at the early phase. Therefore, the calculation time was limited to 6 seconds.

Comments:

1. pressure
In comparison with the experimental data, the start of pressure increase tends to delay about 0.2 seconds in all cases. Possible reason is that the radiation heat release in the steam field is practically neglected in the analysis. In reality, the radiation heat should penetrate the steam field and reach the vessel wall, heat it up and also heat up the steam. However, such kind of non-local heat transfer cannot be handled in the present version of JASMINE because all the heat transfer models are limited in a local cell. Also, if the radiation heat is deposited on the steam in a cell, steam temperature increases too quickly and likely to cause a numerical difficulty. A non-local radiation modelling should be an important development subject for the next step.
Another possible reason of the delay is a difference between the actual jet break-up characteristics and the present particle break-up model. This point is also an important development subject for us.
The bumps in the pressure result are because of the time step and heat transfer control to keep the convergence.

2. steam temperature
There are two kinds of output data comparable to the steam temperature data specified as no. 2: the average steam temperature and the local steam temperature. In the latter, the data at the position (i,j,k)=(4,2,30) (z=2.80m) should be taken for comparison.
Compared with the experimental data at z=2.80m, the averaged temperature tends to reach much higher value because the experimental data was actually not the steam temperature after the mixture level reached the thermocouple position.
The local temperature result agreed with the experimental data pretty well in the base case (a1).

3-11. water temperature
Two kinds of output data are comparable with the water temperature data (no.3-11) as same as the previous item. The local data at (i,j,k)=(4,2,6) should be taken for the comparison with the experimental data no.3-5. The averaged temperature from the calculation can also be compared in this case.
The water temperature in the base case result (a1) was about 10K higher than the experimental data. It is a good agreement as same as the steam temperature.

12. mixture level
Mixture level was the position where the steam volume fraction in the cell adjacent to the wall was 0.95.
The base case result showed a considerable over estimation. Possible reason of this deviation is that evaporation occurred deeper position than reality or the separation of steam bubbles from water was too slow.

13-14. energy released to the water and steam
The total energies can be compared with the energy release to the water, steam and the total. Comparing the total energy release to the coolant with the experimental data, the base case result showed a quite good agreement although the start up of the quenching was late.

15. quenching rate
The global profile of the quenching rate in the base case (a1) was very similar to the experimental data. But the calculated profile was shifted right by about 0.2 seconds.
17. Fragment diameter (melt particle diameter)
Average melt particle diameter versus time represents the surface-area-basis-average-diameter of whole melt, because JASMINE does not separate between the fragment and melt in the jet column. Base case calculation (a1) showed that the melt particle diameter decreased quickly after the melt jet penetrated into water and reached the final value of about 6 mm.

18. Heat transfer surface
The base case result (a1) showed that the surface area at the final state was 13.1 m², which is less than half of the experimental value 33.2 m² even though the experimental value does not include the fused cake.

19. Jet leading edge
20. Time of melt-water contact
21. Time of melt bottom contact
The jet leading edge position was evaluated with two criteria of the melt volume fraction 0.001 or 0.01. The timing of the melt-water contact and melt-bottom contact was deduced from this quantity. The results were almost same for all the cases in spite of the difference of the input parameters. The melt-water contact was 0.31 seconds with the criterion am=0.001, and 0.34 seconds with am=0.01. The latter is nearer the experimental observation of 0.36 seconds. However, no good agreement was obtained for the melt-bottom contact time.

22. Vertical melt fragments average size distribution
There was no big difference between cases except the case a3. It indicated that the friction factor on melt particles had a strong effect on the break-up characteristics.

23. Vertical average void fraction distribution
The result was very similar for all cases. A steam pocket was created near the melt jet leading edge.
J. - MC3D-CEA Calculations

J.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>CEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>G. Berthoud, Michel Valette, Francois de Crecy</td>
</tr>
<tr>
<td>Address:</td>
<td>CEA Grenoble DTP/STR/LTEM - Bat. 10.05 17 rue des Martyrs 38054 GRENOBLE CEDEX 9 France</td>
</tr>
<tr>
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<td>0033-76 88 3244</td>
</tr>
<tr>
<td>Fax:</td>
<td>0033-76 88 5036</td>
</tr>
<tr>
<td>e-mail</td>
<td></td>
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<table>
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<tr>
<th>Organisation:</th>
<th>IPSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>Nicolas Vivien</td>
</tr>
<tr>
<td>Address:</td>
<td>BP6 92265 Fontenay-aux-Roses France</td>
</tr>
<tr>
<td>Tel:</td>
<td>0033-1-46543244</td>
</tr>
<tr>
<td>Fax:</td>
<td></td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:vivien@berne.far.cea.fr">vivien@berne.far.cea.fr</a></td>
</tr>
</tbody>
</table>

J.2 - Initial and boundary conditions

A total number of 5 calculations have been performed. The first 4 calculations have been performed with the 7x17 cell grid reported in Figure 1 including 3 with the 4-field model and 1 with the 3-field model. The first 4-field calculation is referred as the reference calculation. In the second calculation the inlet corium temperature has been changed from 3073 K to 3123 K. In the third calculation the inlet corium flowrate has been decreased by 10% increasing the duration by 10% keeping the total corium mass unchanged. The fourth calculation has been performed with a 3-field model. In addition, another 4-field calculation has been run with a real geometry 6x27 cell grid.
Initial and boundary conditions valid for reference calculation and calculations 3, 4, and 5

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>CEA (ref., 3, 4, 5)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>124.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td></td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td></td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td></td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
<td></td>
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</tbody>
</table>

**Water in test vessel**

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>CEA (ref., 3, 4, 5)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>633*</td>
<td>+10</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.05 **</td>
<td></td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536</td>
<td></td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>2.64</td>
<td>+1.44</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20*</td>
<td></td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.811</td>
<td>+0.013</td>
</tr>
</tbody>
</table>

**Gas Phase**

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>CEA (ref., 3, 4, 5)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>100 steam</td>
<td>no argon</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.266</td>
<td>+0.006</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>537</td>
<td>+1</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
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</table>

Initial and boundary conditions valid for calculation 2

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>CEA (2)</th>
<th>Difference</th>
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<tbody>
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<td><strong>Melt</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>124.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3123</td>
<td></td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
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</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td></td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
<td></td>
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</tbody>
</table>

**Water in test vessel**

<table>
<thead>
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</tr>
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<tbody>
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<td>536</td>
<td></td>
</tr>
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<td>0.811</td>
<td>+0.013</td>
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</tbody>
</table>

**Gas Phase**

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>CEA (2)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>100 steam</td>
<td>no argon</td>
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<td>1.266</td>
<td>+0.006</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>537</td>
<td>+1</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>

* recalculated from volume and pressure values
** the mixture level results, however, 2.26 m

MC3D CEA
J.3 - Code nodalization

The reference calculation plus calculations 2, 3, and 4 have been performed with the reference nodalization in Figure 1. Calculation 5 has been performed with the real geometry 6x27 cell nodalization.

![Diagram of calculation domain]

Figure 1 - Code nodalization drawing
J.4 - Comparison of calculations with the experiment

J.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

MC3D CEA
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>MC3D CEA</td>
<td>0.38 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>MC3D CEA</td>
<td>0.82 s</td>
</tr>
</tbody>
</table>

MC3D CEA
J.4.2 Additional calculations

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantities: 13, 14 - Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

MC3D CEA
Quantity: 19 - Jet leading edge position versus time
J.5 - Code description or code models/options

Most multi-dimensional premixing codes use a 3-field model, with liquid water, steam and melt droplet fields. In MC3D, in addition to such a classical model, we chose to build a 4-field application in which the melt is described by 2 fields: one corresponding to a jet and a second one corresponding to the droplets issued from the jet fragmentation. All calculations presented here have been performed with the version 3.0 corrected at the beginning of December 96.

Most physical models, heat and momentum transfer laws have been presented in [1]. These models are, as far as possible, common to the 3-field and 4-field applications of MC3D. Here is summarised the jet model in the 4-field application.

Summary of jet model and jet fragmentation

In all the calculations performed (except the 3-field one), corium enters the calculation domain as a coherent jet, with a pre-calculated flow rate. Then, the jet flows down through the calculation domain and may be fragmented into droplets. The mass, momentum and energy of the fragmented part of the jet is transferred to the droplet field. In addition, one must calculate the diameter of the created droplets. At the moment, we take a diameter of 3 mm for all calculations. This value has been chosen from the jet fragmentation model of R. Meignen [2]. The jet penetrates in some cells, where a straight interface (for 2D calculations) separates the jet field from the 3 other field. This boundary is taken into account in convection term calculations. In addition, we assume that jet fragmentation occur on this boundary and is proportional to its area.

The rate of jet fragmentation depends on the water volume fraction around the jet. When the average relative water fraction around at the cell level is above .15, the volumetric rate by unit area is equal to .1 m³/s/m². This is the value calculated in [2] for fragmentation of a hot corium jet surrounded by water with a steam film. This value decreases to .001 when the water fraction decreases to .05, i.e. when the steam is quite alone without water.

The jet fragmentation rate is also lowered at slow jet velocities, in order to avoid fragmentation when the jet is spread motionless on the vessel bottom; the threshold velocity is equal to 1 m/s.

So, the jet fragmentation model depends on several parameters:

- Created drop diameter: 3 mm
- Water fraction threshold for using the "film" jet fragmentation rate: 15%
- Film fragmentation rate: .1 m³/s/m²
- Water fraction threshold for using the "steam" jet fragmentation rate: 5%
- Steam fragmentation rate: .001 m³/s/m²
- Jet velocity threshold: 1 m/s

Drop fragmentation

Melt droplets are fragmented by hydrodynamic forces related to their relative motion in water and steam. Experimental results of droplet fragmentation in liquids or gas have been studied and correlated by Pilch [3]. This correlation for high Weber numbers has been adapted for a 3 field model and used also in the 4-field application for drop-in-coolant fragmentation.

It is a source term in the interfacial area transport equation of the melt droplets. This equation is activated only if the volume fraction of droplets relative to the coolant+drop volume is lower than .7, otherwise, the droplet diameter is kept constant.

When droplets are advected from compacted corium cells (fraction > 0.7) towards isolated droplet cells (fraction < 0.7), the advected diameter is taken as the same diameter than the diameter of droplets created from the jet.
L14 Calculations

A best estimate calculation has been performed as required with a corium inlet flowrate as a boundary condition. The height of the calculational domain is limited by the nozzle level: 3.09m. The total vessel volume is kept correct by joining an additional lateral volume initially filled with steam, connected with the real vessel at the upper cell. Corium enters the cylindrical domain in one cell at the top on the left, near the axis.

[1] Berthoud G., Valette M.
Development of a multidimensional model for the premixing phase of a fuel-coolant interaction
Nuclear Engineering and Design 149 (1994) 409-418

Modélisation de la fragmentation d’un jet liquide à très haute température dans un liquide froid volatil.
Thesis. Institut National polytechnique de Grenoble 1995

[3] Pilch M.
Acceleration induced fragmentation of liquid drops

The IPSN method for uncertainty and sensitivity analysis and the associated software: SUNSET.
ICONE 4 - 1996


**J.6 - Input Deck**

**Reference Calculation Input Deck**

TITRE 'PAROL14/PREMEL.ISP30.RUN1';

CIBLE UNIX;

PASDT DTMIN 1.0D-8
DTMAX 2.0D-2
DTINT 1.0D-5
TMAX 3.
NPIMAX 100000
DTVAR ITER 7 FREIN 0.5 ACCEL 1.25;

DOM = DOMAINE 8 2 18;

TPR = APPLI DOM PREMEL REPRI EAU
INCOND H2
PONDU CRMFARO ;

*------- calcul de Gamma avec Hv-H1 et non pas Hvsat-Hlsat -----* 
PHYTRFM HVHNL SVITJET 1. ;

MAILLA = MAILLAGE TPR CYLIND
R QUELC 0. 0.046 0.104 0.1625 0.226 0.29 0.355 0.4627
TETA QUEJU 0. 6.283
Z QUELC 0. .15 .45 .6 .8 1. 1.2 1.4 1.6 1.8 2. 2.2 2.4
2.6 2.8 2.94 3.09 ;

INIT TPR DIAJOU 7.0D-2
ULIQ -1.D-6 VLIQ 0. WLIQ -1.D-6 TDLIQ 0.00001 TEMPLIQ 536.8
UMEL -1.D-6 WMEL 0. WMEL -1.D-6 TXVAP 0.99999 TEMPMEL 537.0
UGOU -1.D-6 WGOU 0. WGOU -1.D-6 TXGOU 0.00001 TEMPGOU 3073.
UJET -1.D-6 WJET 0. WJET -1.D-6 TXJET 0. TEMPJET 3073.

PRESSION HYDROSTATA 51.05 ;

* zone pleine d'eau
ZEAU = ZONINT 1 7 1 2 1 12;
AFFECT ZEAU TXLIQ 0.99999 TEMPLIQ 536.0
TXVAP 0.00001;

* niveau d'eau
NIVEAU = ZONINT 1 7 1 2 12 13;
AFFECT NIVEAU TXLIQ 0.25 TXVAP 0.74999;

CREJET = FRONTIER 1 2 1 2 18 18 HAUT ;

**-----------------------------------------------**

CLIMHYDR CREJET VITESSE JET
TXJET 1.00 TEMPJET 3073.

VITJET TRANS 24
0.00 0.035 0.07 0.105 0.14 0.175 0.21 0.25 0.30 0.35
0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.835
0.87 0.905 0.94 0.975
0.000 -0.630 -1.215 -1.721 -2.131 -2.445 -2.675 -2.852 -2.981 -3.041
-2.075 -1.598 -0.927 0.000 ;

* separator

HSEPA = PLAQUE 7 7 1 2 1 17 ;

IMPRIMER DOM PERIODE 5.D-1 PLANXX
TXGOU TDLIQ TXVAP DIAJOU
ULIQ UMEL UGOU UJET
WLIQ WMEL WGOU WJET
TXJET TEMPLIQ TEMPMEL TEMPGOU
GOACOUJET AIMELGOOU HTMELJET
PRESSION ;

POST XMG R VIVIANE
TYPE 2.0D-4
4DIM
*donne les temperatures de l'eau
* tpre 400-000

MC3D CEA
'TEMP(1,1,1,3)'
* tpre 400-150
'TEMP(1,3,1,3)'
* tpre 400-330
'TEMP(1,6,1,3)'
* tpre 800-000
'TEMP(1,1,1,5) ' TEMP(1,1,1,6)'
* tpre 800-150
'TEMP(1,3,1,5) ' TEMP(1,3,1,6)'
* tpre 800-330
'TEMP(1,6,1,5) ' TEMP(1,6,1,6)'
* tpre 1200-000
'TEMP(1,1,1,7) ' TEMP(1,1,1,8)'
* tpre 1200-150
'TEMP(1,3,1,7) ' TEMP(1,3,1,8)'
* tpre 1200-330
'TEMP(1,6,1,7) ' TEMP(1,6,1,8)'
*done la temperature de vapeur 2800-200
'TEMP(2,4,1,15) ' TEMP(2,4,1,16)'
*DIM
*done la pression du ciel de vapeur
'P(2,1,17)'
*DIM
'AMH(1)' 'AMH(2)' 'AMH(4)' 'AMH(5)'
'AMH(1)' 'AMH(2)' 'AMH(4)' 'AMH(5)'
*SIMP
'HLLV()' 'DHT()' 'GR()' 'GC()'
'AIRJET()' 'AIRGOU()' 'DSAUTER()'
'NIVEAU()' 'PROJET()' 'DV()''
'TYP 5.2-2
TXGOU TXLIQ TXVAP TXJET :'

PHYGEN GX 0.00 GY 0. GZ -9.81;

CONVERG TPR CONVMAST EPSLIQ 1.D-1 EPSVAP 1.D-1 EPSINC 1.D-1
EPSGOU 1.D-1 EPSJET 1.D-1
CONVOL EPSVOL 1.D-6
CONVENER EPSLIQ 1.D4 EPSMEL 1.D4 EPSGOU 1.D4
CONVNWT VNWT10 20 ITERMAX 20;

INTERFAC MELANGE 4 SEUIL 1.0D-3 EPSVIT 1.D-3 ;

'REPRISE TEMPS .9 ;
SAUVGAR TSFREQ .3 ;

MC3D;
*
FIN;

Calculation 2 Input Deck

TITRE 'FAROL14/PREMEL.ISP39.RUN1 ':'

CIBLE UNIX;

PASDT DTMIN 1.0D-0
DTMAX 2.0D-2
DTINIT 1.0D-5
TMAX 49.999
MFTMAX 100000
ETVAR ITER 7 FREIN 0.5 ACCEL 1.25;

DOM = DOMAINE 0 2 18;
TPR = APPLI DOM PREMEL REFRI EAU
INCOND H2
FONDU CRMFARO ;

----- calcul de Gamma avec HV-Hi et non pas Hvsat-Hlsat -----
PHYTRPM HVHML SVTJET 1. ;

MAILLA = MAILLAGE TPR CYLIND
R QUELC 0. 0.046 0.104 0.1625 0.226 0.290 0.355 .4627
TEPRA REGU 0. 6.283
Z QUELC 0. .15 .3 .45 .6 .8 1. 1.2 1.4 1.6 1.8 2. 2.2 2.4
2.6 2.8 2.94 3.09 ;

INIT TPR DIACOU 7.0D-2
ULIQ -1.0D-6 VLIQ 0. WLIQ -1.0D-6 TXLIQ 0.00001 TEMPLIQ 536.8

MC3D CEA
* zone pleine d'eau
ZEAU = ZONINT 1 7 1 2 1 12;
AFFECT ZEAU TXLIQ 0.99998 TEMPLIQ 536.0 TXVAP 0.00001;
* niveau d'eau
NIVEAU = ZONINT 1 7 1 2 12 13;
AFFECT NIVEAU TXLIQ 0.25 TXVAP 0.74999;
CREUSET = FRONTIER 1 2 1 2 18 18 HAUT ;

*******
CLINHYDR CREUSET VITESSE JET
TXJET 1.00 TEMPJET 3123.
VITJET TRANS 24
0.00 0.035 0.07 0.105 0.14 0.175 0.21 0.25 0.30 0.35
0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85
0.87 0.905 0.94 0.975
0.000 -0.630 -1.215 -1.721 -2.131 -2.445 -2.675 -2.852 -2.981 -3.041
-2.075 -1.598 -0.927 0.000 ;

* separateur
HSEPA = PLAQUE 7 7 1 2 1 17 ;

IMPRIMER DOM PERIODE 2.00 PLANXZ
TXGOU TXLIQ TXVAP DIAGOU
ULIQ UMEL UGOU UJET
WLJQ WMEL WGOU WJET
TXJET TEMPLIQ TEMPMEL TEMPGOU
GAGOUJET AIMELOU HTMELJET
PRESSION ;

POST XMCR VIVIANE
TYPJ 2.0-4
4GIM
* donne les temperatures de l'eau
* tpre 400-000
' TEMP(1,1,1,3)'
* tpre 400-150
' TEMP(1,3,1,3)'*
* tpre 400-330
' TEMP(1,6,1,3)'*
* tpre 800-000
' TEMP(1,1,1,5)' ' TEMP(1,1,1,6)'*
* tpre 800-150
' TEMP(1,3,1,5)' ' TEMP(1,3,1,6)'*
* tpre 800-330
' TEMP(1,6,1,5)' ' TEMP(1,6,1,6)'*
* tpre 1200-000
' TEMP(1,1,1,7)' ' TEMP(1,1,1,8)'*
* tpre 1200-150
' TEMP(1,3,1,7)' ' TEMP(1,3,1,8)'*
* tpre 1200-330
' TEMP(1,6,1,7)' ' TEMP(1,6,1,8)'*
donne la temperature de vapeur 2800-200
'TEMP(2,4,1,15) ' 'TEMP(2,4,1,16)'
3DIM
* donne la pression du ciel de vapeur
'P(2,1,17)'
3DIM
' AMM(1)' ' AMM(2)' ' AMM(4)' ' AMM(5)'
' AMH(1)' ' AMH(2)' ' AMH(4)' ' AMH(5)'
SIMP
' MLVL' ' DHUT()' ' GE()' ' GC()' '
AIRJET()' 'AIRGOU()' 'DSEAUTER()' '
NIVEAU()' 'FRONJET()' 'DT()''
TYP 5.0-2
TXGOU TXLIQ TXVAP TXJET ;
* PHYGEO GX 0.00 GY 0. GZ -9.81;

MC3D CEA
CONVOL EPSVOL 1.0D-6
CONVEREP EPOLIQ 1.0D4 EPSMEL 1.0D4 EPSGOU 1.0D4
CONVENUP VNUMTON 20 ITMAX 20;

* INTERFAC MELANGE 4 SKU 1.0D3 EPSVIT 1.0D3 ;
* REPRISE TEMPS 0.9 ;
* SAVOURAR TSPREQ 1. ;
* MC3D;
* FIN;

Calculation 3 Input Deck

TITRE 'PAROLI4/PREMEL.ISF39.refdebdim ';

CIBLE UNIX:

PASDT DTMIN 1.0D8
DTMAX 2.0D2
DTINIT 1.0D5
TMAX 49.999
NPMTMAX 100000
DVAR ITER 7 FREIN 0.5 ACCEL 1.25;

DOM = DOMAINE 8 2 18;

TFR = APPLI DOM PREMEL REPRI EAU
INCOND H2
FONDU CRMARO ;

*---------- calcul de Gamma avec Hv-Hl et non pas Hvsat-Hlsat ----- PHYTRPM HVMLH SVTJET 1. ;

MAILLE = MAILLAGE TFR CYLIND
K QUELCC 0. 0.046 0.104 0.1625 0.226 0.29 0.355 .4627
TETA REGU 0. 6.283
Z QUELCC 0. 1.5 3 45 6 8 1 1.2 1 1.4 1 1.6 1.8 2 2.2 2.4
2.6 2.8 2.94 3 09 ;

INTT TFR DIAOQU 7.0D2
ULIQ -1.0D6 VLIQ 0. WLIQ -1.0D6 TXLIQ 0.00001 TEMPLIQ 536.8
UMEL -1.0D6 VME4 0. WME4 -1.0D6 TXVAP 0.99999 TEMPEML 537.0
GAOU -1.0D6 VGOU 0. WGOU -1.0D6 TXGOU 0.00001 TEMPGOU 3073.
UJET -1.0D6 VJET 0. WJET -1.0D6 TXJET 0. TEMPLJET 3073.
PRESSION HYDROSTA 51.05 ;

* zone pleine d'eau
ZEAU = ZONINT 1 7 1 2 1 12;
AFFECT ZEAU TXLIQ 0.99999 TEMPLIQ 536.0
TXVAP 0.00001;

* niveau d'eau
NIVEAU = ZONINT 1 7 1 2 12 13;
AFFECT NIVEAU TXLIQ 0.25 TXVAP 0.74999;

CREBSET = FRONTIER 1 2 12 18 18 HAUT ;

*--------------------------------------------------------------

CLIMHYDR CREBSET VITESSE JET
TXJET 1.00 TEMPJET 3073.

TXJET TRANS 24
* 0.00 0.035 0.07 0.105 0.14 0.175 0.21 0.25 0.30 0.35
  0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85
  0.87 0.905 0.94 0.975
* 0.000 -0.630 -1.215 -1.721 -2.131 -2.445 -2.675 -2.852 -2.981 -3.041
  -2.075 -1.598 -0.927 0.000 ;

  0.00 0.0385 0.077 0.1155 0.154 0.1925 0.231 0.275 0.33 0.385
  0.44 0.495 0.55 0.605 0.66 0.715 0.77 0.825 0.88 0.9285
  0.957 0.9955 1.034 1.0725
  0.000 -0.572727 -1.104545 -1.554545 -1.937273 -2.222727 -2.431818
  -2.592727 -2.7164545
  -2.779091 -2.77 -2.746364 -2.713636 -2.675455 -2.624545 -2.560909
  -2.490909 -2.361818 -2.18
  -1.886264 -1.452727 -0.842727 0.000 ;

*-------------------------------------------------------------

MC3D CEA
* separator

HSEPA = PLAQUE 7 7 1 2 1 17 ;

IMPRIMER DOM PERIODE 2.D0 PLANXZ
   TXGOU TLXIQ TXVAF DIAGOU
   ULIQ UMEL UGOU UJET
   WLIQ WMEL WGOU WJET
   TXJET TEMPLIQ TEMPSOL TEMPSOU
   GAGOUJET AIMELIOU AIMELJET
   PRESSION ;

POST XMGH VIVIANE
TYP1 2.D-4
4DIM
   * donne les temperatures de l'eau
     * tpre 400-000
       'TEMP(1,1,1,3)'
     * tpre 400-150
       'TEMP(1,3,1,3)'
     * tpre 400-330
       'TEMP(1,6,1,3)'
     * tpre 800-000
       'TEMP(1,1,1,5)'
     * tpre 800-150
       'TEMP(1,3,1,5)'
     * tpre 800-330
       'TEMP(1,6,1,5)'
     * tpre 1200-000
       'TEMP(1,1,1,7)'
     * tpre 1200-150
       'TEMP(1,3,1,7)'
     * tpre 1200-310
       'TEMP(1,6,1,7)'
   * donne la temperature de vapeur 2800-200
     'TEMP(2,4,1,15)'
   * donne la pression du ciel de vapeur
     'P(2,1,1,7)'
4DIM
   'AMM(1)' 'AMM(2)' 'AMM(4)' 'AMM(5)'
   'AMH(1)' 'AMH(2)' 'AMH(4)' 'AMH(5)'
   SIMP
   'HLV()' 'DHT()' 'BE()' 'GC()'
   'AIRJET()' 'AIRM()' 'DSAUTER()'
   'NIVEAU()' 'FRONJET()' 'UT()'

TYP2 5.D-2
TXGOU TLXIQ TXVAP TXJET ;

PHYGEN GX 0.D0 GY 0. GZ -9.81;

CONVERG TPR CONVMAS EPSLIQ 1.D-1 EPSVAF 1.D-1 EPSINC 1.D-1
   EPSGOU 1.D-1 EPSJET 1.D-1
   CONVOL EPSVOL 1.D-6
   CONVHM ERPSLIQ 1.D4 EPSMEL 1.D4 EPSGOU 1.D4
   CONVNXT VNNEWTON 20 ITERMAX 20;

INTERFAC MELANGE 4 SEUIL 1.0.D-3 EPSVIT 1.D-3 ;

*REPRISE TEMPS .9 ;
SAUVEGAR TFSFREQ 1. ;

MC3D;

FIN;

Calculation 4 Input Deck

TITRE 'FAROL14/PREMEL.ISP39.triph '

CIBLE UNIX;

PASUT DTMIN 1.0D-8
   DTMAX 2.0D-2
   DTINIT 1.0D-5
   TMAX 3.
   NPTMAX 100000
   DTVAR ITER 7 FREIN 0.5 ACCEL 1.25;

MC3D CEA
DOM = DOMAINE 8 2 18;

TPR = APPLI DOM TRITHYD REFRI EAU GOUTTE CRMPARO ;
*------- calcul de Gamma avec Hv-H1 et non pas Hvnet-Hlsat -------
PHYTRMP HVML ;

MAILLA = MAILLAGE TPR CYLIND
R  QUELC 0. 0.046 0.104 0.1625 0.226 0.29 0.355 .4627
TETA REGU 0. 6.283
Z  QUELC 0. 15.3 .45 .68 .81 1.12 1.4 1.6 1.8 2. 2.2 2.4
2.6 2.8 2.94 3.09 ;

INIT TPR DIAGOU 7.00-D-2
ULIQ -1. D-6 VLIQ 0. WLIQ -1. D-6 TXLIQ 0.00001 TEMPLIQ 536.8
UVAP -1. D-6 UVAP 0. WVAP -1. D-6 TXVAP 0.99998 TEMPFAP 537.0
UGOU -1. D-6 UGOU 0. WGOU -1. D-6 TXGOU 0.00001 TEMPGOU 3073.
PRESSION HYDROSTA 51.05 ;

* zone pleine d'eau
ZEAU = ZONINT 1 7 1 2 1 1 2;
AFFECT ZEAU TXLIQ 0.99998 TEMPLIQ 536.0
TXVAP 0.00001; 

* niveau d'eau
NIVEAU = ZONINT 1 7 1 2 12 13;
AFFECT NIVEAU TXLIQ 0.25 TXVAP 0.74999;
CREUSET = FRONTIER 1 2 1 2 18 18 HAUT ;

CLIMHYD CREUSET VITESSE GOU
TXGOU 1.00 TEMPGOU 3073. AIVAPGOU 60.D0
VITGOU TRANS 24
0.00 0.035 0.07 0.105 0.14 0.175 0.21 0.25 0.30 0.35
0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.835
0.87 0.905 0.94 0.975
0.000 -0.630 -1.215 -1.721 -2.131 -2.445 -2.675 -2.852 -2.981 -3.041
-2.075 -1.598 -0.927 0.000 ;

* separateur
HSEPA = PLAQUE 7 7 1 2 1 7 ;

IMPRIMER DOM PERIODE 5.D-1 PLANXZ
TXGOU TXLIQ TXVAP DIAGOU
ULIQ UMELE UGOU
WLIQ WMELE WGOU
TEMPLIQ TEMPFAP TEMPGOU
AIVAPGOU
PRESSION ;

POST XMGR VIVIANE
TYVI 2. D-4
4DIM
*donne les temperatures de l'eau
* tpre 400-000
'TEMP(1,1,1,3)'
* tpre 400-150
'TEMP(1,3,1,3)'
* tpre 400-330
'TEMP(1,6,1,3)'
* tpre 800-000
'TEMP(1,1,1,5) 'TEMP(1,1,1,6)'
* tpre 800-150
'TEMP(1,3,1,5) 'TEMP(1,3,1,6)'
* tpre 800-330
'TEMP(1,6,1,5) 'TEMP(1,6,1,6)'
* tpre 1200-000
'TEMP(1,1,1,7) 'TEMP(1,1,1,8)'
* tpre 1200-150
'TEMP(1,3,1,7) 'TEMP(1,3,1,9)'
* tpre 1200-330
'TEMP(1,6,1,7) 'TEMP(1,6,1,8)'
*donne la temperature de vapeur 2800-200
'TEMP(2,4,1,15) 'TEMP(2,4,1,16)'
3DIM
*donne la pression du ciel de vapeur
'P12,1,17' 10DIM
'AMM(1) 'AMM(2) 'AMM(3)'

MC3D CEA
Calculation 5 Input Deck

TITRE 'FAROL14/PREMEL.ISP39.creuset';

CIBLE UNIX;

PASDT DTMIN 1.0D-8
DTMAX 2.0D-2
DTNIT 1.0D-5
TMAX 3
NPTMAX 100000
DTVAR ITER 7 FREIN 0.5 ACCEL 1.25;

DOM = DOMAINE 7 2 28;

TPR = APPLI DOM PREMEL REFRI EAU
      INCOND H2
      FONDU CRMFARO ;

*--------- calcul de Gamma avec Hv-Hi et non pas Hvaat-Hisat -------
      PHYTRPM HVMLH SVITJET 1. ;

MAILLA = MAILLAGE TPR CYLIND
R QUELC 0. 0.046 0.104 0.1625 0.226 0.29 0.355
TETA REGU 0. 6.283
Z QUELC 0. 1.5 3.45 6.8 1. 1.2 1.4 1.6 1.8 2. 2.2 2.4
     10.66 11.69;

INIT TPR DIAGOU 7.0D-2
ULIQ -1.D-6 VLIQ 0. WLIQ -1.D-6 TXLIQ 0.00001 TEMPLIQ 536.8
UMEL -1.D-6 VMEL 0. WMEL -1.D-6 TXVAP 0.99998 TEMMPML 537.0
      TXINC 0.
UGOU -1.D-6 WGOU 0. WGOU -1.D-6 TXGOU 0.00001 TEMPGOU 3073.
UJET -1.D-6 WJET 0. WJET -1.D-6 TXJET 0. TEMPJET 3073.
PRESSION HYDROSTA 51.55 ;
* zone pleine d' eau
ZEAU = ZONINT 1 7 1 2 1 12;
AFFECT ZEAU TXLIQ 0.99998 TEMPLIQ 536.0
      TXVAP 0.00001;
* niveau d' eau
NIVEAU = ZONINT 1 7 1 2 12 13;
AFFECT NIVEAU TXLIQ 0.25 TXVAP 0.74999;
* zone du creuset
ZCOR1 = ZONINT 1 2 1 2 16 20;
ZCOR2 = ZONINT 1 4 1 2 20 21;
ZCOR3 = ZONINT 1 4 1 2 21 23;
ZCOR4 = ZONINT 1 4 1 2 22 23;
AFFECT ZCOR1 TXJET 0.99997 TXVAP 0.00001 TEMPMEL 3073;
AFFECT ZCOR2 TXJET 0.99997 TXVAP 0.00001 TEMPMEL 3073;
AFFECT ZCOR3 TXJET 0.97 TXVAP 0.02998 TEMPMEL 3073;
AFFECT ZCOR4 TXJET 0.00001 TXVAP 0.99997 TEMPMEL 3073;
* limite du creuset
NOZZLE = PLAQUE 2 2 1 2 18 20;
PARGOINC 1 2 2 20 4 21;

MC3D CEA
CREUSV = PLAQUE 4 4 1 2 21 23;
* limites de Termos
HTERMS = PLAQUE 3 7 1 2 25 25;
* tube de liaison
HTUBE = PLAQUE 3 3 1 2 25 27;
* séparateur
HSEPA = PLAQUE 3 7 1 2 27 27;

IMPRIMER DOM PERIODE 5.D-1 PLANKE
TXGOU TXLIQ TXVAP DIAGOU
ULIQ UMEL UGOU UJET
WLIQ WMEL WGOU WJET
TXJET TEMPLIQ TEMPMEL TEMPGOU
GAGOUT AIAMELGOU HTMELJET
PRESSION

POST XMGX VIVIANE

TYP 2.D-4
4DIM
* donne les températures de l'eau
* tpre 400-000
'TEMP (1,1,1,3)'
* tpre 400-150
'TEMP (1,3,1,3)'
* tpre 400-330
'TEMP (1,6,1,3)'
* tpre 800-000
'TEMP (1,1,1,5)' 'TEMP (1,1,1,6)'
* tpre 800-150
'TEMP (1,3,1,5)' 'TEMP (1,3,1,6)'
* tpre 800-330
'TEMP (1,6,1,5)' 'TEMP (1,6,1,6)'
* tpre 1200-000
'TEMP (1,1,1,7)' 'TEMP (1,1,1,8)'
* tpre 1200-150
'TEMP (1,3,1,7)' 'TEMP (1,3,1,8)'
* tpre 1200-330
'TEMP (1,6,1,7)' 'TEMP (1,6,1,8)'
* donne la température de vapeur 2800-200
'TEMP (2,4,1,15)' 'TEMP (2,4,1,16)'
3DIM
* donne la pression du ciel de vapeur
'P (2,1,17)'
1DIM
'AMM (1)' 'AMM (2)' 'AMM (4)' 'AMM (5)'
'AMM (1)' 'AMM (2)' 'AMM (4)' 'AMM (5)'
SIMP
'HLV ()' 'DHDT ()' 'G(E)' 'G (C)'
'AIRJET ()' 'AIRGOU ()' 'DSAUTER ()'
'NIVEAU ()' 'PRONJET ()' 'DT ()'
TYP 2 5.D-2
TXGOU TXLIQ TXVAP TXJET

PHYSGEN GX 0.DD GY 0. GZ 9.81;

CONVERG TPR CONVMAUS EPSLIQ 1.D-1 EPSVAP 1.D-1 EPSINC 1.D-1
EPSGOU 1.D-1 EPSJET 1.D-1
CONVOL EPSVOL 1.D-6
CONVENER EPSLIQ 1.D4 EPSMEL 1.D4 EPSGOU 1.D4
CONVENET VNEWTON 20 ITERM 50;

INTERFAC MELANGE 4 SEUIL 1.0D-3 EPSVIT 1.D-3

* REPRISE TEMPS .9 ;
SAUVGAR TSFRQ .3 ;

MC3D;

FIN;
J.7 - Participants comments

The calculation reference took about 29 min CPU time for a 50 physical seconds transient on a HP 9000/800 workstation. The total number of time steps was 3443, i.e. an average time step of 0.0145s.

![Graph showing pressure over time](image)

The reference calculation results show some discrepancies compared to the experimental results:
The initial slope of the pressure transient looks good up to 1.7 s. After 1.7s, the calculated pressure rises slower than in the experiment. A first maximum value of 80 Bars is seen at about 4 seconds, then the pressure decreases down to 75 Bars at about 8 seconds and rises again up to 83 Bars at 18 seconds. After that time, the pressure remains more or less constant and experimental and calculated values are very close. The calculation significantly underestimates the steam pressure between 1.7s and 18 s except for a narrow peak at 4 seconds.
The steam temperature in the dome region is slightly overestimated. The gap is between 2 and 5 Kelvin.

Water temperature far from the jet are strongly underestimated (up to 15 K) between 1 and 20 seconds; then both experimental and calculated values reach the saturation temperature. In some figures, lower cell and upper cell temperature are shown if the thermocouple level is located between two cells. In MC3D, we estimate the water level as the highest cell level where water volume fraction is greater than 5%. Numerical diffusion and the cell size give too much high values but the slope of the calculated water level is good.
The energy transferred to coolant is strongly underestimated, as well as the quenching rate between 0 and 3.5 seconds.

MC3D underestimates the fragmented mass: 86 versus 105 kg, as well as the heat transfer surface and the Sauter diameter.

However, the jet position is well predicted. The calculated jet front position remains constant (equal to the cell centre height) as far as the deepest jet interface does not leave a cell level.
The dynamics of both jet and water level look good. The second one corresponds to a right steam production linked to a right upward steam flow through water towards the dome.

Differences between MC3D results and experimental results can be explained mainly by the lack of extra-cell radiative heat transfer between corium and water. This leads to too low water temperatures, too low energy transferred to water and quenching rates when corium falls through the water. However, the pressure history seems not too bad, and so, the steam production rate would not be wrong, even with a too much low heat transfer surface and fragmented mass. So the internal models would have to be improved in increasing the jet fragmentation rate, decreasing the boiling rate per surface unit and implementing remote radiative transfer to liquid water. Another way to explain the
differences may be the poor model of film boiling heat transfer, which keeps steam film from being superheated; this may keep heating of remote subcooled water by condensation of superheated steam.

The different pressure transient shows that the 4-field calculation predict the experimental behaviour better than the 3-field calculation. The latter does not share the corium in non-fragmented part and fragmented part as well as the former. So the heat transfer area and consequently the quenching rate, the steam production and the pressure rise are overestimated. In fact, the pressurisation rate (and the final Sauter diameter) strongly depends on the user's imposed droplet diameter given in the boundary conditions.

The 4-field pressure transient is not very sensitive to the corium temperature or flow rate. The attempt to calculate the whole vessel including the crucible and the corium flow rate didn't give satisfactory results. The corium flow here strongly depends on the way the door is opened, which is not modelled.
### K. - TEXAS-JRC Calculations

#### K.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Joint Research Centre, Commission of the European Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>A. Yerkess</td>
</tr>
<tr>
<td>Address:</td>
<td>JRC Ispra</td>
</tr>
<tr>
<td></td>
<td>21020 Ispra (VA)</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
</tr>
<tr>
<td>Tel:</td>
<td>+39 (332) 789813 (Yerkess)</td>
</tr>
<tr>
<td>Fax:</td>
<td>+39 (332) 785584</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:arnold.yerkess@jrc.it">arnold.yerkess@jrc.it</a></td>
</tr>
</tbody>
</table>

#### K.2 - Initial and boundary conditions

One calculation has been performed with the TEXAS code - JRC version.

<table>
<thead>
<tr>
<th>Melt</th>
<th>EXPERIMENT</th>
<th>TEXAS-JRC</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition, w%</td>
<td>80 UO&lt;sub&gt;2&lt;/sub&gt; + 20 ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>80 UO&lt;sub&gt;2&lt;/sub&gt; + 20 ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>124.4</td>
<td>-0.6</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.085</td>
<td>+0.045</td>
</tr>
</tbody>
</table>

**Water in test vessel**

| | EXPERIMENT | TEXAS-JRC | Difference |
| | Mass, Kg | 623 | 616 | -7 |
| | Depth, m | 2.05 | 2.0 | -0.05 |
| | Temperature (average), K | 536.8 | 537 | +0.2 |
| | Subcooling at melt contact, °C | 1.2 | 3.41 | +2.21 |
| | Fuel to coolant mass ratio | 0.20 | 0.20 | - |
| | Total water volume, m³ | 0.798 | 0.801 | +0.003 |

**Gas Phase**

| | EXPERIMENT | TEXAS-JRC | Difference |
| | Composition, w% | 77 steam + 23 Argon | 100 steam | no Ar |
| | Volume, m³ | 1.26 | 1.268 | +0.008 |
| | Temperature, K | 536 | 537 | +1 |
| | Pressure, MPa | 5.1 | 5 | -0.1 |
Physical constants used in TEXAS for corium, water and gas phase

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value at 5.0 MPa</th>
<th>TEXAS Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WATER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation Temperature, K</td>
<td>537.1</td>
<td>C(13)</td>
</tr>
<tr>
<td>Specific heat capacity, KJ/kg·K</td>
<td>5.02</td>
<td>C(17)</td>
</tr>
<tr>
<td>Specific internal energy, MJ/kg</td>
<td>1.148</td>
<td>C(8)</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>777.5</td>
<td>C(9)</td>
</tr>
<tr>
<td>Thermal conductivity, W/m K</td>
<td>0.604</td>
<td>C(14)</td>
</tr>
<tr>
<td>Square of liquid reciprocal sound speed, s²/m² x 10⁻⁴</td>
<td>0.851</td>
<td>C(15)</td>
</tr>
<tr>
<td>Radiation emissivity</td>
<td>0.95</td>
<td>C(19)</td>
</tr>
<tr>
<td>Thermal expansion coeff, K⁻¹ x 10³</td>
<td>2.204</td>
<td>C(22)</td>
</tr>
<tr>
<td>Dynamic viscosity, Pa·s x 10⁻⁴</td>
<td>0.1</td>
<td>C(23)</td>
</tr>
<tr>
<td>Surface tension, N/m x 10⁻³</td>
<td>22.7</td>
<td>C(24)</td>
</tr>
<tr>
<td><strong>GAS PHASE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas constant, J/kg·K⁻¹</td>
<td>462.0</td>
<td>C(12)</td>
</tr>
<tr>
<td>Thermal conductivity, W/m K x 10⁻³</td>
<td>55.15</td>
<td>C(13)</td>
</tr>
<tr>
<td>Dynamic viscosity, Pa·s x 10⁻⁴</td>
<td>18.03</td>
<td>C(25)</td>
</tr>
<tr>
<td><strong>MELT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat capacity, J/kg·K</td>
<td>565 (liquid 565, solid 445)¹</td>
<td>CP</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>7960 (liquid 7960; solid 9430)¹</td>
<td>RHOP</td>
</tr>
<tr>
<td>Heat of fusion, MJ/kg</td>
<td>0.362</td>
<td>PHEAT</td>
</tr>
<tr>
<td>Fusion temperature, K</td>
<td>2850 (liquid 2850; solid 2830)¹</td>
<td>TMELT</td>
</tr>
<tr>
<td>Thermal conductivity, W/m K</td>
<td>2.88</td>
<td>KFUEL</td>
</tr>
<tr>
<td>Radiation emissivity</td>
<td>0.79</td>
<td>C(16)</td>
</tr>
<tr>
<td>Surface tension, N/m</td>
<td>0.5 (0.45)²</td>
<td>C(32)</td>
</tr>
</tbody>
</table>

¹ Taken from OECD-CSNI ISP 39 on FARO L-14 Reference Specification
K.3 - Code nodalization

<table>
<thead>
<tr>
<th>Nodalization Information</th>
<th>0.2 (2)</th>
<th>0.1 (3-43)</th>
<th>0.3 (44-47)</th>
<th>0.1 (48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cell no.), m</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Area (cell no.) m²</td>
<td>0.396</td>
<td>0.0163</td>
<td>0.387</td>
<td>0.163</td>
</tr>
<tr>
<td>Void fraction (cell no.)</td>
<td>0.01</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exhaust Valves

Separator, (0.348 m³)

Communication Line, (0.049 m³)

Vapour, (0.871 m³)

Particle Release

Water, (0.792 m³)

Debris Bed

TERMOS Vessel

Pressure

Vapour Temperatures

Liquid Temperatures

G1

G2

G3

G4

G5

G6

G7

G8

Vapour

Liquid
The cell numeration after input is automatically increased by 1 in order that the bottom boundary condition is accounted for in cell 1. Thus, for example, cells 1 to 47 become cells 2 to 48 with cell 1 containing the boundary condition to be applied at the junction between cells 1 and 2 (the bottom of the vessel). The figure shows the numeration of the cells after adjustment.

**Summary of TEXAS Input**

<table>
<thead>
<tr>
<th>WATER/GAS PHASE</th>
<th>Water temperature, K (cell no.)</th>
<th>537 (2-20)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas temperature, K (cell no.)</td>
<td>537 (21-48)</td>
</tr>
<tr>
<td></td>
<td>Vapour fraction (cell no.)</td>
<td>0.01 (2-20); 0.99 (21-48)</td>
</tr>
<tr>
<td></td>
<td>Pressure, MPa</td>
<td>5.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MELT</th>
<th>Particle radius, m</th>
<th>0.046</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Particle temperature, K (particle no.)</td>
<td>2856 (1); 2858 (2); 3073 (3-39)</td>
</tr>
<tr>
<td></td>
<td>IFRAG (particle no.)</td>
<td>1 (1-6); 0 (7-39)</td>
</tr>
<tr>
<td></td>
<td>IENTRY</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>IENTRY2</td>
<td>e</td>
</tr>
<tr>
<td></td>
<td>NBOTTOM</td>
<td>f</td>
</tr>
<tr>
<td></td>
<td>C(100)</td>
<td>g</td>
</tr>
</tbody>
</table>

* This is the nominal radius; last input value is adjusted to ensure mass conservation

b The first two particles are assumed to be cooler due to contact with release vessel hinged flap etc.

c IFRAG = 0/1, the particle is part of a coherent jet/discrete.

d IENTRY = 0/1, discrete particle/coherent jet entry mode.

e IENTRY2 = 0/1, coherent jet breaks up at trailing edge/leading edge.

f If the number of particles in a group > NBOTTOM in the debris catcher they can regroup

* C(100) = 0/1, particle recombination is possible if fuel temperature > TSOLID/any temperature

**Melt Velocity-Time Profile**

The JRC version of TEXAS is different from the standard University of Wisconsin version because it is possible to specify the velocity, radius and temperature of each individual master particle instead of using a group specification (maximum of 8 groups). This allows the user to closely follow the velocity-time specification as presented in the ISP 39. An auxiliary program xtex_sphere is used to read the ISP 39 data and produce an equivalent master particle velocity-time profile as shown in the figure below to be used as TEXAS input data. Mass conservation and mass flow can be more accurately maintained using this procedure.
Fig. 2 - Velocity-Time Profile for FARO Test L-14
K.4 - Comparison of calculations with the experiment

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm
Quantity: 4, 5, not present due to 1d calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantity: 7, 8, not present due to 1d calculation

TEXAS JRC
Quantity: 9 - Water temperature at 1200 mm
Quantity: 10,11 not present due to Id calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.45 s</td>
</tr>
<tr>
<td>TEXAS JRC</td>
<td>0.43 s</td>
</tr>
</tbody>
</table>

Quantity: 21 - Melt/Bottom contact

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.87 s</td>
</tr>
<tr>
<td>TEXAS JRC</td>
<td>1.14 s</td>
</tr>
</tbody>
</table>
K.5 - Code description or code models/options

A fuller description of the TEXAS-IV computer code is given in [1, 2, 3]. In brief, the computer model solves one-dimensional, three-field hydrodynamic equations for multiphase flow. Two Eulerian fields represent the coolant as liquid and vapour. The third field is Lagrangian and deals with discrete particles moving through the other two fields. Separate partial differential equations for each of the three-fields, written in one-dimensional form, express conservation of mass, momentum and energy for each individual component. This three field fluid model allows thermal and mechanical non-equilibrium between these phases to exist provided that mathematical expressions for exchange of mass, momentum and energy are calculated.

A semi-implicit technique is used to solve the fluid dynamic equations. Pressure iterations are continued until the error in the liquid or vapour continuity equations is reduced to zero. This is done by forming the partial derivatives of the mesh cell continuity error function with respect to pressure, giving a tridiagonal matrix. This is then used in a Newton-Raphson iteration to update the pressure for the entire mesh.

Due to thermal non-equilibrium, heat energy is transferred from one field to another. This takes place at the interfaces which separate the fields and is directly related to the phasic temperature difference. Focusing our attention to the FARO-LWR experiments, as the superheated particles fall through the freeboard volume, heat energy is transferred to the continuous vapour by convection and to dispersed liquid droplets by radiation. When the superheated particles enter into the water a vapour film forms around the particles so that direct liquid contact with the hot particle is minimal until the time the particle is fully quenched. Heat transfer is mainly by convective film boiling and radiation to the surrounding liquid/vapour interface in the bulk liquid. The convective film boiling heat transfer coefficient under subcooled conditions has been empirically correlated to the experimental data of Dhiri and Purohit [4]. Furthermore, interfacial heat transfer between a vapour bubble and the bulk liquid can occur by convection. The liquid droplet and vapour bubble surfaces are at the local saturation temperature.

Having determined the relative velocity between the continuous vapour field and liquid droplets or continuous liquid field and vapour bubbles from the interfacial drag force, the interfacial momentum transfer can be calculated. The drag forces acting between the two phases can be modelled by the standard steady-state drag force and a virtual mass transient flow force. The drag force acting on the dispersed phase under a steady-state condition can be given in terms of the interfacial drag coefficient based on the relative velocity formulated by Wallis [5] and experimental correlations provided by Rowe [6].

The virtual mass transient flow force depends on the relative acceleration of the dispersed and the continuous phase. For the FARO-LWR problem, this force is important for vapour bubbles accelerated in the continuous liquid field, but is less important for liquid droplets in the continuous vapour field. The interfacial drag force acting on the Lagrangian particle from the surrounding fluid determines the penetration depth and fragmentation rate as the particles fall into the coolant water pool. Hence, the criteria for particles to be fluidised and swept away from the particle-coolant mixture volume or to be mixed with the coolant are mainly dependent on the drag force. In the current model, regardless of the flow regime, the homogeneous coolant vapour-liquid mixture with mass-averaged velocity. This drag force is a function of coolant vapour-liquid mixture density, particle size, particle void fraction, and the relative velocity between the particle and the coolant mixture.

The exchange of mass across the liquid-vapour interface takes the form of liquid evaporation or vapour condensation at the interface and is fully implicit in the pressure iteration. The phase transition depends on the heat flow balance from the vapour field to the interface and then to the liquid field. The rate of phase transition is limited by the rate of heat conduction to and from the interface in the liquid. The total net mass transfer rate is the summation of the steam generation rate at the vapour film-liquid interface surrounding a hot particle, the vapour bubble-liquid interface in the continuous liquid field, and the liquid droplet surface in the continuous vapour field.
A hydrodynamic liquid-particle fragmentation model based on Rayleigh-Taylor instabilities is included. It was shown in /1/ that the Rayleigh-Taylor instabilities and dynamic pressure deformation are the dominant mechanisms for drop break-up, the shear force effects being negligible in the film-boiling regime /2/. It is assumed that a coherent jet subdivides into discrete particles and these progressively fragment. A technique to simulate the jet break-up and separately model the dynamic fragmentation of the discrete particles has been developed.

For the dynamic fuel fragmentation model a linear time-step dependent form has been chosen because the changes in local density ratio and local relative velocity cannot be neglected. The melt particle diameter is given by

$$D_{n+1} = D_n(1 - C_0\Delta T + We^{0.25})$$

where $\Delta T$ and $We$ are the dimensionless time step and Weber number, which are evaluated by the relative velocity and density ratio, $e$, of the continuous-dispersed phase at the old time (n). $C_0$ is equal to 0.108 - 0.0785$e^{0.5}$. Such a linear model predicts the progressive break-up of the fuel with reference to only current material property values and flow variables.

A coherent jet is considered to be composed of discrete masses or spheres that enter the coolant sequentially. The discrete masses upstream (behind) of the first mass or "leading edge," are not allowed to break-up until the leading edge has been fragmented and swept aside /3/. When the next mass overtakes these fragments it becomes the leading edge and thus can break-up. This leap-frog mechanism to produce a new leading edge will stop when the jet reaches the vessel bottom. A flag variable (iFRAG) in the TEXAS-IV input will also allow some or all particles to fragment independently of their position in the jet. This possibility is useful for predicting an upper bound of an MPCI event.

A very simple agglomeration model has been added to TEXAS-IV to cope with the problem of excessive heat transfer from the fuel particles to the water after a debris bed has been formed at the bottom of the vessel. Several fragmented particles are regrouped to form a larger particle. This is a simple but effective method to reduce the total surface area for the heat transfer.

Notes

a Although Raleigh-Taylor instabilities were considered to be the most important, current investigations suggest that this may not be the case - Kelvin-Helmholtz instabilities and Boundary Layer stripping also appear to be important (see Univ.Wisconsin contribution)

b In the latest version of TEXAS it is also possible to have a "trailing edge" model break-up. In this case any master particle that forms part of a coherent jet is allowed to break-up when it overtakes any other fragmented particle.

References

K.6 - Code input deck

TEXAS Input data for the calculation of L-14
0
Post FARO Test L14 - ISP input

4SET
I4=47, ILOPT=0, FLB=2, PLT=2, TMAX=5,
THISTAB=0.5, EPSL=1E-5, EPSG=3E-3, EPSD=0.5, EPSI=0.5, EPS=0.5,
THPLAG=.01, ETH=.1 &

4GRID
XMAX= 3.085,
DX1(1)=.20,
DXI(2)=.10,
DXI(3)=.30,
DXI(4)=.10,
NDX(1)=1,
NDX(2)=41,
NDX(3)=4,
NDX(4)=1,
ARYI(1)=.396,
ARYI(2)=.0163,
ARYI(3)=.387,
ARYI(4)=.0163,
ARY(1)=.396,
ARY(2)=.0163,
ARY(3)=.397,
ARY(4)=.05,
NARAY(1)=42,
NARAY(2)=1,
NARAY(3)=3,
NARAY(4)=1 &

4INIT
UGO=0., ULO=0., PO(1)=5e6, NPO(1)=47,
THO(1)=0.01, NTH(1)=19, THO(2)=0.99, NTH(2)=28,
THO(3)=537., NTH(3)=537., NTH(4)=47,
GRAVO=1.98, NGRAV(1)=47, THO=537. &

4PART
MPFUEL=2.88, MPTOT=0., MNPART=1, CNP=565., HRHO=7960., PHEAT=0.362D6, TMELT=2850.,
NPARN=0, NGROUP=2, INDEX=1, INDEX2=0 &

4BOUND
PIN=5D6, THOUT=1.0, POUT=5D6 &

4RUNTIM
TPT=0.0278, TJIEND=1.0, TGT=5D-2, TMAX=7.0,
DT=1D-5, TMAX=1D-4 &

4OUTPUT
LPR=3, TPL=0.1, TPL99=0.01, TPL15=0.01,
IFR(1)=37, IFR(2)=35, IFR(3)=28, IFR(4)=20, IFR(5)=16,
IFR(6)=12, IFR(7)=8, IFR(8)=4 &

4EXPL0
&

4CONST
C(5)=537., C(7)=5.02E3, C(8)=1.148E6, C(9)=778., C(11)=5E6, C(14)=0.604,
C(15)=0.851E-6, C(19)=.95, C(22)=2.204E-3, C(23)=0.1E-3, C(24)=22.78E-3,
C(12)=462.0, C(13)=5.15E-2, C(25)=1.803E-5,
C(18)=0.79, C(32)=0.5,
C(20)=0.5, C(21)=1.,
C(30)=1., C(31)=20., C(33)=0., C(34)=0.,
C(37)=0., C(39)=1., C(40)=1.,
C(41)=0.1, C(42)=1E-4, C(43)=0., C(44)=0., C(45)=0.1, C(46)=0., C(47)=2.3B-3,
C(48)=1., C(49)=0.1093, C(50)=0.0785, C(51)=1.0, C(52)=0.246,
C(53)=0., C(55)=0., C(56)=1., C(57)=0., C(59)=0.1,
C(60)=0.,
C(61)=0.005,
C(62)=0.5, C(63)=7.0, C(64)=0.0, C(65)=5.75,
C(66)=2., C(67)=1., C(68)=4.5, C(69)=9.5,
C(70)=3., C(71)=2., C(72)=260.0, C(73)=360.0,
C(74)=3., C(75)=3., C(76)=260., C(77)=360.0,
C(78)=4., C(79)=4., C(80)=260.0, C(81)=310.0,
C(82)=4., C(83)=5., C(84)=260.0, C(85)=310.0,
C(86)=4., C(87)=6., C(88)=260.0, C(89)=310.0,
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C(94)=4., C(95)=8., C(96)=260.0, C(97)=310.0,
C(98)=1.,
C(100)=1.0, C(101)=0.0, C(102)=0.05, C(103)=3.083E8,
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<th>C(106)</th>
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</tbody>
</table>
K.7 - Participants comments

- Cell 2 is made larger in order to reduce numerical difficulties when debris bed is formed.
- Heat exchange between the TERMOS vessel and contents is not modelled.
- Initial master particle diameters match the final discharge diameter of the release vessel.
- The first two master particles are assumed to be just above the solidus temperature
- Uses "trailing edge" model to allow fragmentation of the coherent jet.
- Simple agglomeration model used to model the debris bed, even in the case of solid particles
- The minimum bubble radius was set as 2.5 mm.
- The physical properties of the melt do not model the changes in going from liquidus to solidus and the liquidus values have been adopted.
- The physical properties for the water and steam remain constant, that is, the values corresponding to the initial reference conditions (pressure 5 MPa, saturated).
- The velocity-time profile for the melt outflow from the release vessel is as specified.
- The value of the surface tension of the melt was set to 0.5 N/m, not 0.45 N/m
- There is no break-up occurring in the freeboard volume.
L. - TEXAS-KEMA Calculations

L.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>KEMA Nederland B.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>Klaas Spijker</td>
</tr>
<tr>
<td>Address:</td>
<td>KEMA</td>
</tr>
<tr>
<td>Postbus 9035</td>
<td>6800 ET Arnhem</td>
</tr>
<tr>
<td>Netherland</td>
<td></td>
</tr>
<tr>
<td>Tel:</td>
<td>0031-26-356 3415</td>
</tr>
<tr>
<td>Fax:</td>
<td>0031-26-445 9035</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:klaas@nuc.kema.nl">klaas@nuc.kema.nl</a></td>
</tr>
</tbody>
</table>

L.2 - Initial and boundary conditions

One calculation has been performed with TEXAS 3 code.

<table>
<thead>
<tr>
<th>Melt</th>
<th>Experiment</th>
<th>KEMA</th>
<th>Difference</th>
</tr>
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<tbody>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
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<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
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<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1</td>
<td>+0.08</td>
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<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.035</td>
<td>-0.005</td>
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</tbody>
</table>

Water in test vessel

<table>
<thead>
<tr>
<th>Mass, Kg</th>
<th>Experiment</th>
<th>KEMA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Temperature (average), K</td>
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<tr>
<td>Subcooling at melt contact, °C</td>
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<tr>
<td>Fuel to coolant mass ratio</td>
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<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
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</table>

Gas Phase

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<th>KEMA</th>
<th>Difference</th>
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<td>-0.374</td>
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<tr>
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</tr>
<tr>
<td>Pressure, MPa</td>
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</table>

* value deduced from the input deck. The value reported from KEMA was 1.26 m³.
L.3 - Code nodalization

For the calculation the vessel is divided into 10 axial nodes. This choice is somewhat arbitrary, but the measurement points in the experiment were mostly 40 centimetres apart, so with this choice we have the same order of grid as in the measurements. Choosing more nodes will lead to longer calculation times and there is no possibility to check the extra data that are produced. In the TEXAS FORTRAN code the number of nodes, which are called cells there, is extended with two extra nodes at the upper and lower boundary. This means that the node numbers 1 to 10 map to cell numbers 2 to 11.

Initially the total gas volume of the vessel is 0.886 m$^3$ (*) and the total water volume is 0.798 m$^3$. The diameter is given as 71 cm and the melt is poured in from a height of 3.085 m.

Using these values the next nodalization is made:
- node height: 0.3085 m ($3.085 / 10$)
- node cross sectional surface: 0.396 m$^2$ ($\pi \times (0.71/2.0)^2$)

between node 9 and 10 the cross sectional area is 1.894 m$^2$ to include the total gas space above the point where the melt is poured in.

(*) The reported value was 1.26 m$^3$. But the input deck was initialised with 0.886 m$^3$. 

---

TEXAS KEMA
L.4 - *Comparison of calculations with the experiment*

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

TEXAS KEMA
Quantity: 3 - Water temperature at 400 mm
Quantity: 4, 5, not present due to 1d calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantity: 7, 8, not present due to 1d calculation
Quantity: 9 - Water temperature at 1200 mm
Quantity: 10,11 not present due to 1d calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate

Quantities: 16, 17, not present because they could not be extracted from the code output or were set to zero in the output

TEXAS KEMA
Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²

Quantity: 19 - Jet leading edge position versus time
Quantity: 20 - Melt/Water contact

<p>| | |</p>
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<tr>
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Quantity: 21 - Melt/Bottom contact

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<tr>
<td>TEXAS KEMA</td>
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L.5 - Code description or code models/options

The TEXAS code is "an experimental 3-field Eulerian-Lagrangian 1-D hydrodynamics model designed specifically for calculation of FCI's". The code is developed by Jian Tang and Cho-Chone C. Chu and others of the nuclear engineering department of the university of Wisconsin-Madison. The version used for the calculations is texas-iii for fuel-coolant fragmentation & mixing. This version is, according to the text in the code, from dec. 10, 1991, and was received at KEMA in May 1995, see (KEMA 1995b).

TEXAS contains models for Hydrodynamic fragmentation in the mixing phase and propagation phase, models for local liquid, gas and bubbly flow regimes and models for the phase changes. The thermo-thermodynamics are governed by analytical state equations. Provisions are incorporated for triggering of steam explosions.

The code is controlled by an input deck, usually called 'test.in'. In this deck a number of parameters is given, thus defining the problem to be solved and the constants to be used. A description of the parameters used in the input deck is given in (Chu, 1994) and a more annotated version can be found in (KEMA, 1995a).

TIME CONTROL, INPUT VELOCITY AND FUEL INJECTION

Values for the melt stream input velocity and the time interval between particle drops are derived from the experimental data. From the figure in (Annunziato, 1996, page 20), it can be seen that the time interval between start and stop of the jet pouring into the vessel is 0.84 s. In this time 125 kg of molten fuel comes down. The jet has a diameter of 0.1 m. To calculate the downward average velocity the amount of fuel (125 kg) is divided by the density (7960 kg/m³) to get the overall volume. This must be divided by the cross sectional area of the jet (π * (D/2)² = Π * 0.05 = 7.854.10⁻³ m³) to get the length of the jet 'cylinder'. This length divided by the time interval above gives the average drop velocity. Given the data this velocity is 2.4 m/s.

Using the graph in (Annunziato, 1996, page 20) an average speed of about 2 m/s can be calculated, which compares reasonably with 2.4 m/s.

This value is used to calculate the input parameter TPT, the time interval between the injected falling particles. In (KEMA, 1995a) a value of 2/3 * D/v is given for TPT, with D the diameter of the jet and v the velocity. This is valid for RPARN = D/2 and NPIN = 1, as is the case in this problem. Using this a value of 0.0281 s is calculated for TPT.

Another way to calculate TPT would be to calculate the mass of one injected particle. This is 4/3 * π * (D/2)³ * density = 4.1678 kg. A total mass of 125 kg is poured in the vessel. This means 125/4.1678 = 30 particles. They drop in 0.84 s, the first at time zero. So the interval time is 0.84/30 = 0.028 s, equal to the previous value.

Trials have shown that the initial timestep (DT) can have a major influence on the TEXAS calculations. Using a value for DT of 10⁻³ s causes the TEXAS program to use the lower limit timestep of 10⁻⁶ s at the problem time of 7.52 s. This stops in fact the calculation. An initial timestep of 10⁻³ proved adequate for this calculation.

PARTICLE INITIAL CONTROL DATA

The parameters NBOTTOM and NGROUP determine the fragmentation and regrouping behaviour of the TEXAS models.
NBOTTOM describes the maximum number of particles that is taken into account for regrouping. The value 4 was determined in another but similar calculation (KEMA, 1994). Trials showed that the default value of $10^7$ caused a lot of fragmentation and steep pressure rises above the experimental values.

NGROUP is used to describe the increase in the number of particles when fragmentation occurs. Trials with different numbers showed that values greater than 2 lead to a steep pressure rise, far above the values measured in the experiment. This suggests that no severe fragmentation occurs in the experiment.

The injection particle velocity is somewhat higher (4.7 m/s) than can be deduced from the experimental data, although this value is in accordance with the estimated value of the jet in water (Benuzzi, 1994, pages 6 and 8). Lower values of 2.0 m/s and 3.0 m/s showed very different timing of the leading edge reaching the water surface and the bottom of the vessel. Furthermore it seemed that for lower values the jet decelerated when reaching the water to accelerate again after a certain time. This did not seem physically right, nor did it resemble the experiment. Besides an effect on the leading edge timing, different velocity values in the range of 0.0 to 5.0 m/s only had small effects on other calculated quantities.

By setting the variables IENTRY and IFRAGMIX both to unity ("true"), the choice is made for coherent fuel entry and hydrodynamic fragmentation. Given the experiment, this seems to be physically correct.

**PHYSICAL PROPERTIES**

The critical Weber number of the fuel particles (constant C(31)) is taken from the TEXAS manual. A value of 11.0 was chosen. The manual gives a range from 10.0 to 12.0 in section 2.2.2.

Part of the input file is devoted to describe the explosion models. No explosion occurs though, so the values used are unimportant, but they have to be given in the input.
L.6 - Code input deck

PARO LT-14 ISP with 125 kg of molten metal.

4SET  Pressure Iteration Control Indicators
IB=10  Number of problem nodes
IP0PT=0  Uniform distribution of particles
FLB=2  Reflective lower boundary
FLU=2  Reflective Upper Boundary
ITMAX=50  Maximum number of pressure iterations per timestep
TTHSTAR=0.5  See C(40)
TTHFLAG=0.1  Relative convergence criterion for liquid mass eq.
EPSL=1e-5  Relative convergence criterion for vapour mass eq.
EPSD=0.5  Relative error for mass changes
EPSI=0.5  Relative error for internal energy change
EPSP=0.5  Relative error for pressure changes
ETH=1  Vapour void fraction

4GRID  Geometrical data
XMIN=0.0  Minimum x
XMAX=1.085  Drop height of jet
DX1(1)=3.085  Mesh cell size to be used (max 8)
NDX(1)=9  # of mesh cells that will use each corresponding mesh cell size
ARY1(1)=0.396  Y-axis (vertical) mesh cell cross-sectional areas
NARY1(1)=9  # of mesh cells that will use each corresponding mesh cell cross-sectional area
ARYJ(1)=0.396  Junction cell cross-sectional areas
NARYJ(1)=9  # of mesh cells that will use the junction cell cross-sectional areas

DX1(2)=3.085  Mesh cell size to be used (max 8)
NDX(2)=1  # of mesh cells that will use each corresponding mesh cell size
ARY1(2)=1.894  Y-axis (vertical) mesh cell cross-sectional areas
NARY1(2)=1  # of mesh cells that will use each corresponding mesh cell cross-sectional area
ARYJ(2)=0.396  Junction cell cross-sectional areas (was 0.3782)
NARYJ(2)=1  # of mesh cells that will use the junction cell cross-sectional areas

4INIT  Initial Conditions
UGO=0.  Vapour velocity
UL0=0.  Liquid velocity
P0(1)=5.166  Pressure
NPO(1)=10  Number of cells to use the above pressure (from bottom)
TH0(1)=0.0  Vapour void fraction (0 is totally liquid)
NTH(1)=6  Number of cells to use the above vapour void fraction
TH0(2)=0.3549  Vapour void fraction
NTH(2)=1  Number of cells to use the above vapour void fraction
TH0(3)=1.0  Vapour void fraction
NTH(3)=3  Number of cells to use the above vapour void fraction
TG0(1)=536.  Vapour temperature
TL0(1)=536.8  Liquid temperature
NTG(1)=10  Number of cells to use the above vapour and liquid temperature
GRAYO(1)=9.8  Gravity constant
NGRAY(1)=10  Number of cells to use the above gravity
TW0=536.8  Wall temperature (equal to water temp.)

4PART  Particle initial and control data
RPARN=0.05  Particle radius (means about 4.2 kg per particle)
KFUEL=2.88  Fuel thermal conductivity
NBOUN=4  Upper bound for number of particles to regroup
NPPART=1  Number of real initial particles per master particle
NPIN=1  Number of real particles injected
CP=565.0  Particle specific heat capacity.
RHOP=760.  Particle density.
FEAT=3.8205  Fuel particle heat of fusion.

TEXAS KEMA
TMELT=2840.0  Particle melting temperature.
TPIn=3073.0  Injection particle temperature.
NPARN=0  Initial total number of master particles in
problem.
NPARN=2  Increasing number of total master particles as the
coherent discrete mass begins to break up.
UPC0=0
UPC1=2.0  Injection particle velocity.
NENTRY=1  1 = coherent jet entry mode.
IFRAGMIX=1  1 = hydrodynamic fragmentation.

&BOUND SYSTEM BOUNDARY DATA
PTIN=5.1266  Pressure at the bottom boundary cell.
THOUT=1.0  Vapor volume fraction at the top boundary cell.
PFOUT=5.166  Pressure at the top boundary cell.

&RUNTIM TIME CONTROL
DT=1D-4  Initial time step.
DTMAX=1D-1  Maximum time step
TMAX=10.0  Maximum problem run time.
TPT=.0281  Time interval at which to inject particles.
TIJEND=0.805  Particle injection stopping time.
TOT=5D-2  Time interval at which to increase master particles
group number.

&OUTPUT PRINT AND PLOT OUT INDICATOR
LP=3  1 = print and plot.
TFL=0.1  Time interval for the output variables as function
of position.
DTDUMP=1D3  The time interval to dump the necessary information
for restart.
TFL15=0.01  Time interval for the output variables as functions of
time.
TFL99=0.01  Used for STARBASE graphics package.
IPR(1)=2  The cell numbers whose pressures and other needed
variables are printed out each time step.
IPR(2)=3
IPR(3)=4
IPR(4)=6
IPR(5)=8
IPR(6)=9
IPR(7)=10

&EXPL0 PARAMETERS FOR THE FRAGMENTATION MODEL
AND INITIAL DATA FOR THE TRIGGER CELL
cfr=0.0025  Proportional constant in the model.
rfrage=1.e-4  Initially estimated size of fragmented particles.
pole=3.65  Threshold pressure for film collapse.
alpha=100.  Constant used in the F factor function in the model.
alphas=.5  Void fraction above which fragmentation rate
decreases sharply.
ptrigs=2.2e7  Initial trigger pressure.
dxtrigz=2.41e-2  Position of the trigger cell.
sdxtrig=6.22e-4  Trigger cell cross sectional area.
sdxtrig=6.22e4  Junction cross sectional area between the
cell and the adjacent cell.
fittrig=2  Top boundary condition flag.
tmstrig=0.02  Maximum propagation time.
temptrigs=598.  Initial trigger cell temperature.
tpttrigs=0.001  Time interval for the printed variables as functions
of position.
tfraglim=2.e-3  Fuel fragmentation time interval.

&CONST PHYSICAL PROPERTIES AND INPUT PARAMETERS
C(5)=373.  Reference temperature
C(6)=2.586  Vapor specific internal energy at reference
temperature
C(8)=4.195  Liquid specific internal energy at reference
temperature
C(9)=940.  Microscopic density of liquid
C(11)=1.85  Reference pressure
C(13)=5.4E-2  Vapor thermal conductivity
C(14)=.60  Liquid thermal conductivity
C(20)=0.5  Volume fraction criterion of vapor and liquid
internal energy updated by adding the viscous
work and heat conduction terms.
C(21)=1. Flag of calculation of pressure expansion work in the energy equations
0 calculated out of the pressure iteration loop.
1 calculated in the pressure iteration loop.
C(23)=1.03E-4 Liquid viscosity
C(24)=0.0226 Liquid surface tension
C(25)=1.68E-5 Vapor viscosity
C(29)=22. Particle thermal conductivity
C(30)=1. 1 = fragmentation (liquid particle).
C(31)=11. Critical Weber number of fuel particle
C(32)=0.45 Particle surface tension
C(33)=0. 0 = liquid-vapor velocity non-equilibrium.
C(34)=0. Flag of the top boundary physical properties
1 = specified by input data.
C(35)=1. Not used
C(36)=1. Not used
C(37)=0. reset BETAP matrix with subr. BETAP
C(38)=1. Not used
C(39)=1. Calculate energy flux in pressure iteration loop
C(40)=1. 1 = have bubbly, transition and droplet flow regimes.
C(41)=0.1 Fraction of vapor heat capacity of the vapor existing in the vapor film.
C(42)=1D-4 Input parameter of volume fraction of a dispersed phase for the minimum drag coefficient.
C(43)=0. Flag of the liquid-vapor drag force.
0 only standard steady-state drag force
C(44)=0. Flag of liquid-vapor macroscopic heat transfer coefficient
0 calculated by the old time physical variables and interfacial area.
C(45)=0.1 Flag of vapor bubble thermal thickness
C(46)=0. Flag of the relative velocity used in the liquid-vapor drag coefficient calculation
0 using the updated liquid-vapor relative velocity
C(47)=1D-2 Input parameter of initial and minimum bubble and droplet radius.
C(48)=0. Flag of wall friction force 0 = frictionless
C(49)=0.1093 First coefficient in the time-independent linear fragmentation model
C(50)=0.0785 Second coefficient
C(51)=1.0 Third coefficient
C(52)=0.246 Fourth coefficient
C(53)=0. Input parameter of volume fraction of the minimum virtual mass force.
C(54)=1. Not used
C(55)=0. Flag of top boundary conditions, 0=determined from the program
C(56)=1.0 Input parameter describing the portion of radiation heat, from fuel to the liquid-vapor interface, that will be absorbed by the bulk liquid field.
C(57)=0. Flag of bubble and liquid droplet size
0 = calculated by three different physical
C(58)=0. Not used
C(59)=0. Vapor radiation emissivity
C(60)=0. Only for KROTOE, use 0
L.7 - Participants comments

A global comparison shows that the calculated results compare reasonably well [within an order of magnitude] with the experimental results. After about 5.5 s deviations show up.

It turned out that in the current code version the model for heat transfer through the vessel wall to the environment is turned off. In subroutine QWALL the next lines can be found:

c    do not consider the heat transfer to the wall temporarily
    iay=0

c    if (iay.eq.0) return ! a modification for hp9750

This line effectively stops the routine QWALL without calculating any heat transfer. Switching on the model by giving iay another value than zero does not solve the problem. Investigating the values calculated by QWALL for the wall temperature shows that this temperature remains the same throughout the calculation. This must lead to the conclusion that the heat transfer to the vessel and the environment is not modelled correctly.

The energy balance shows inconsistency. The net energy does not equal zero, meaning that there must be an extra energy source in the system which has not been included in the energy loss of the fuel. Chemical reactions are not modelled, so a probable explanation is that this extra term is the solidification energy from the melt. This energy is released into the system without any possibility for removal to the vessel or the environment, thus causing the pressure and temperature increase after about 5.5 s.

Because heat removal to the vessel and the environment is not important in the first few seconds of the fuel-coolant interaction, comparisons are valid until about 5.5 seconds. Benuzzi, (Benuzzi 1994 page 13) estimates the heat transfer to the structure after 1.44 s causing a temperature rise of 6 °C to be about 30 MJ. This roughly half the amount of energy contained in the melt. So heat transfer to the vessel cannot be neglected.

Influencing the fragmentation by letting the melt fragment more (i.e. using higher values for NGROUP) and letting the particles regroup less (high value for NBOTTOM) releases the solidification energy earlier. The sudden pressure rise does not appear under these circumstances, but the resulting net pressure will then be around 18 MPa.

The heat transfer area is a factor of about 6 below the value for the experiment. It must be noted that the heat transfer area depends strongly on the particle size. Especially the smallest particles contribute heavily to the total area. The particle size distribution is governed by the fragmentation model. A difficult to understand part of information from the TEXAS code about fragmentation is that after 3 s no fragmented particles are available in the cells, the radius of the fragmented particles goes to zero. At the same time there is still a heat transferring area from fragmented fuel. Because the thermohydraulic results compare well with the experiment, explanation is difficult.

CONCLUSIONS

The results of the TEXAS calculations compare remarkably well with the results from the experiments. Only a little bit of tuning was necessary, especially for the values describing the particle behaviour like regrouping and fragmentation. Thermohydraulic results are realistic, but since the code is one-dimensional it is difficult to compare measurements done off-axis in the experiment with the calculated result.
The solidification energy in the system is probably not accounted for in the energy balance. This energy and the lack of a model to describe the heat transfer to the TERMOS vessel and the environment cause an unlikely increase in pressures and temperatures and makes interpretation of the calculated results after 5 seconds 'real time' meaningless.

Much more model parameters can be varied, but a thorough sensitivity analysis was beyond the scope of this project. For benchmarking purposes the results are satisfying. For future use of the code, it is recommended to gain more insight in the parameters of the fragmentation models.
M. - TEXAS-Univ. of Wisconsin Calculations

M.1 - Participant Identification

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M.2 - Initial and boundary conditions

Two calculations have been performed with the TEXAS code. The reference calculation has been performed with the original fuel fragmentation model. A second calculation has been performed with a modified fuel fragmentation model. The initial and boundary conditions valid for both calculations are reported in the following table.

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>Wisconsin Univ.</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>121</td>
<td>-4</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.092</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.085</td>
<td>+0.045</td>
</tr>
</tbody>
</table>

| Water in test vessel |            |                 |            |
| Mass, Kg            | 623        | 616             | -7         |
| Depth, m            | 2.05       | 2               | -0.05      |
| Temperature (average), K | 536.8 | 537 | -1.04 |
| Subcooling at melt contact, °C | 1.2 | 0.16 | +0.2 |
| Fuel to coolant mass ratio | 0.20 | 0.196 | -0.004 |
| Total water volume, m³ | 0.798 | 0.792 | -0.006 |

| **Gas Phase** |            |                 |            |
| Composition, w% | 77 steam + 23 Argon | 100 steam | no Argon |
| Volume, m³      | 1.26       | 1.266           | +0.006     |
| Temperature, K  | 536        | 537             | +1         |
| Pressure, MPa   | 5.1        | 5               | -0.1       |

TEXAS University of Wisconsin
M.3 - Code nodalization

The nodalization was done in 41 cells as shown in the following figure.
M.4 - Comparison of calculations with the experiment

M.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome

TEXAS University of Wisconsin
Quantity: 3 - Water temperature at 400 mm
Quantity: 4, 5, not present due to I'd calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantity: 7, 8, not present due to I'd calculation
Quantity: 9 - Water temperature at 1200 mm
Quantity: 10,11 not present due to 1d calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

Experimental 0.45 s
TEXAS Wisconsin Univ. (calc. 1) 0.39 s

Quantity: 21 - Melt/Bottom contact

Experimental 0.87 s
TEXAS Wisconsin Univ. (calc. 1) 1.70 s
M.4.2 Additional calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm

Quantity: 6 - Water temperature at 800 mm, average position
Quantity: 9 - Water temperature at 1200 mm

Quantity: 12 - Mixture level

TEXAS University of Wisconsin
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time
M.5 - Code description or code models/options

The code is extensively described in the TEXAS-JRC Appendix K.5. The fragmentation of the fuel was assumed as primarily caused by RT instability. The model requires the number of the particles that are first injected as being ready for fragmentation. In this calculation, only one particle was assumed as such. The criteria used in fragmenting a particle is of "trailing edge." That is the intact particle would start breaking up when it reaches the trailing end of the already fragmented particles.
M.6 - Code input deck

Input deck for calculation a

Input deck for TEXAS for the calculation of L14

```
0
Post PARO Test L14 - Run 5 (ENTRY=0, C(4)=4.23E-3 Pa.s, C(141)=0.01)

!SET
IB=41, IPOR=0, PLB=2, FLT=2, ITMAX=5,
THSTAR=0.5, EPSL=1E-5, EPSG=3E-3, EPSD=0.5, EPSI=0.5, EPSP=0.5,
THFLAG=.01, ETH=.1 &

!GRID
XMAX=3.085,
DXX(1)=.20,  NDXX(1)=1,
DXX(2)=.10,  NDXX(2)=32,
DXX(3)=.30,  NDXX(3)=7,
DXX(4)=.10,  NDXX(4)=1,
ARYI(1)=.396,  NARIY(1)=36,
ARYI(2)=.0163,  NARIY(2)=1,
ARYI(3)=.387,  NARIY(3)=3,
ARYI(4)=.0163,  NARIY(4)=1,
ARJ(1)=.396,  NARJ(1)=36,
ARJ(2)=.0163,  NARJ(2)=2,
ARJ(3)=.387,  NARJ(3)=3,
ARJ(4)=.05,  NARJ(4)=1 &

!INIT
UGO=6, ULO=0, PO(1)=5e6, NPO(1)=41,
THO(1)=0, NTH(1)=10, TNO(2)=2, NTH(2)=22,
TGO(1)=537, TLO(1)=537, NPG(1)=41,
GRAO(1)=9.8, NGRV(1)=41, TNOV(2)=537.

!PART
TLLMS=121,
NEB=1,
NPAR=1, KFUEL=2.89, NBOTTOM=1,
MPAR=1, MPIN=1, RP=565, RHOP=8000,
TFH=3.62D5, TMELT=2840,
TPIN=3073, NPAR=1, NGROUP=1, PP=3.2, ENTRY=0,
RGRF(1)=0.04573, FVGRF(1)=0.095, UPGRF(1)=0.87, TIPNRF(1)=3073,
RGRF(2)=0.04573, FVGRF(2)=0.095, UPGRF(2)=2.09, TIPNRF(2)=3073,
RGRF(3)=0.04573, FVGRF(3)=0.095, UPGRF(3)=2.78, TIPNRF(3)=3073,
RGRF(4)=0.04573, FVGRF(4)=0.353, UPGRF(4)=3.00, TIPNRF(4)=3073,
RGRF(5)=0.04573, FVGRF(5)=0.156, UPGRF(5)=2.83, TIPNRF(5)=3073,
RGRF(6)=0.04573, FVGRF(6)=0.663, UPGRF(6)=2.52, TIPNRF(6)=3073,
RGRF(7)=0.04573, FVGRF(7)=0.663, UPGRF(7)=1.96, TIPNRF(7)=3073,
RGRF(8)=0.04573, FVGRF(8)=0.663, UPGRF(8)=0.80, TIPNRF(8)=3073 &

!BOUND
PIN=5D6, THOUT=1.0, POUT=5D6 &

!RUNTIM
TPT=.0278, TJEND=1.0, TGT=5D-2, TMAX=6.0,
DT=1D-5, DTMAX=1D-3 &

!OUTPUT
IPR=3, TPL=.1, TPL99=.1, TPL15=.1,
IPR(1)=37, IPR(2)=28, IPR(3)=32, IPR(4)=20, IPR(5)=12,
IPR(6)=8, IPR(7)=4, IPR(8)=2 &

!EXPL0
&

!CONST
C(4)=4.23E-3,
C(5)=537, C(6)=2.597E6, C(8)=1.14E6, C(9)=778, C(11)=5E6,
C(13)=5.4E-2, C(14)=.60, C(23)=1.63E-4, C(24)=.0226, C(25)=1.8E-5,
C(20)=.05, C(21)=.1,
C(29)=.22, C(30)=.1, C(31)=.20, C(32)=.045, C(33)=.0, C(34)=.0,
C(35)=.1, C(36)=.1, C(37)=.0, C(38)=.1, C(39)=.1, C(40)=.1,
C(41)=.1, C(42)=100.04, C(43)=.0, C(44)=.0, C(45)=.1, C(46)=.0, C(47)=1D-3,
C(48)=.1, C(49)=.1093, C(50)=.0.0786, C(51)=.0, C(52)=.246,
C(60)=.0, C(54)=.1, C(55)=.0, C(56)=.1, C(57)=.0, C(58)=.0, C(59)=.0,
C(61)=.0,
```

TENSA University of Wisconsin
\[ C(62) = -0.5, \quad C(63) = 6.0, \quad C(64) = 0.0, \quad C(65) = 5.75, \]
\[ C(66) = 3, \quad C(67) = 0, \quad C(68) = 260.0, \quad C(69) = 375.0, \]
\[ C(70) = 3, \quad C(71) = 0, \quad C(72) = 260.0, \quad C(73) = 375.0, \]
\[ C(74) = 2, \quad C(75) = 0, \quad C(76) = 4.5, \quad C(77) = 9.5, \]
\[ C(78) = 4, \quad C(79) = 0, \quad C(80) = 260.0, \quad C(81) = 310.0, \]
\[ C(82) = 4, \quad C(83) = 0, \quad C(84) = 260.0, \quad C(85) = 310.0, \]
\[ C(86) = 4, \quad C(87) = 0, \quad C(88) = 260.0, \quad C(89) = 310.0, \]
\[ C(90) = 4, \quad C(91) = 0, \quad C(92) = 260.0, \quad C(93) = 310.0, \]
\[ C(94) = 4, \quad C(95) = 0, \quad C(96) = 260.0, \quad C(97) = 310.0, \]
\[ C(98) = 0. \]
\[ C(100) = 0.0, \]
\[ C(101) = 0.0, \]
\[ C(102) = 0.05, \quad C(103) = 3.083E-8, \]
\[ C(104) = 150.0, \quad C(105) = 91.22, \quad C(106) = 2.0, \]
\[ C(119) = 0.066, \quad C(120) = 9.0D - 10, \]
\[ C(141) = 0.01, \]
\[ C(143) = 1.066 \text{ 4} \]

**Input deck for calculation b**

The input deck for 'b' is identical except the IENTRY is to be set as 2.
M.7 - Participants comments

In order to replace the experimental criteria such as the "trailing edge" as used in this calculation, a more physical model is to be pursued. The model current being developed and tested assumes that the fragmentation is caused by RT, KH and BL. With these three mechanisms, it is possible to model the fragmentation physically without specifying the starting fragmented particles and the criteria for the fragmentation as used in this calculation of L14.

* RT = Raleigh-Taylor Instability
KH = Kelvin-Helmholtz Instability
BL = Boundary Layer stripping
N. - THIRMAL-SKI-ANL Calculations

N.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Statens Kärnkraftinspektion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>Wiktor Frid</td>
</tr>
<tr>
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<td>SKI S-106 58 Stockholm Sweden</td>
</tr>
<tr>
<td>Tel:</td>
<td>0046-8-698 8400</td>
</tr>
<tr>
<td>Fax:</td>
<td>0046-8-661 9086</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:wictor@ski.se">wictor@ski.se</a></td>
</tr>
</tbody>
</table>

N.2 - Initial and boundary conditions

Two calculations have been performed with the THIRMAL-1 code.
The first calculation (a) was performed with the suggested inlet velocity and the suggested physical properties.
The second calculation (b) was performed with the suggested inlet velocity and THIRMAL-1 code calculated physical properties (melt surface tension 0.52 N/m).
The initial and boundary conditions valid for both calculations are reported in the following table.

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>SKI-ANL</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>-</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>-</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>gravity</td>
<td>gravity</td>
<td>-</td>
</tr>
<tr>
<td>DP delivery</td>
<td>1.04</td>
<td>1.04</td>
<td>-</td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>623</td>
<td>623</td>
<td>-</td>
</tr>
<tr>
<td>Depth, m</td>
<td>2.05</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536.8</td>
<td>-</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>1.5</td>
<td>+0.3</td>
</tr>
<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.796</td>
<td>-.002</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>77 steam + 23 Argon</td>
<td>-</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.26</td>
<td>-</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536</td>
<td>-</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td>-</td>
</tr>
</tbody>
</table>
N.3 - Code nodalization

The nodalization characteristics are:

30 nodes and 30 junctions (initial condition: 20 nodes and 20 junctions for water pool).

The nodalization drawing is reported in Figure 1.
N.4 - Comparison of calculations with the experiment

N.4.1 Base calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm
Quantity: 4, 5, not present due to 1d calculation

Quantity: 6 - Water temperature at 800 mm, average position
Quantity: 7, 8, not present due to 1d calculation
Quantity: 9 - Water temperature at 1200 mm
Quantity: 10,11 not present due to Id calculation

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

Experimental  0.45 s
THIRMAL SKI-ANL  0.39 s

Quantity: 21 - Melt/Bottom contact

Experimental  0.87 s
THIRMAL SKI-ANL  0.96 s
N.4.2 Additional calculation

Quantity: 1 - Pressure

Quantity: 2 - Temperature in the steam dome
Quantity: 3 - Water temperature at 400 mm

Quantity: 6 - Water temperature at 800 mm, average position

THIRMAL SKI-ANL
Quantity: 9 - Water temperature at 1200 mm

Quantity: 12 - Mixture level
Quantities: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time
N.5 - Code Description or code models/options

(1) FRAGMENTATION:

(a) BOUNDARY LAYER STRIPPING AT THE JET LEADING EDGE;

(b) SMALL WAVE INSTABILITY (BY SHEAR FORCE) EROSION ALONG THE MELT JET SURFACE;

(c) LARGE WAVE INSTABILITY (BY VARICOSE OR SINUOUS WAVE) BREAKUP OF THE MELT JET; AND

(D) SECONDARY BREAKUP OF MELT SEGMENT FORMED BY LARGE WAVE INSTABILITY BY HYDRODYNAMIC WITH R-T INSTABILITY AS WEBER NUMBER GREATER THAN 12.

(2) HEAT TRANSFER:

(a) COVER COMPLETE HEAT TRANSFER REGIME INCLUDING FILMING, NUCLEATE BOILING, TRANSITION BOILING, FORCED CONVECTION & NATURAL CONV.

(b) FILM BOILING HEAT TRANSFER: WITTE SATURATED FORCE CONVECTION FILM BOILING HEAT TRANSFER COEF. + DHIR'S SUBCOOLING CORRELATION

(3) STEAM GENERATION/CONDENSATION:

(a) IS FULLY IMPLICITLY CALCULATED BY HEAT BALANCE AT THE VAPOR/WATER INTERFACE WITH THE ASSUMPTION THAT THE INTERFACE TEMP. IS EQUAL TO THE VAPOR SATURATION TEMP.

(b) A QUASI-STEADY STATE VAPOR FILM ALONG THE MELT JET SURFACE IS CALCULATED INCLUDING ALL OF THE EFFECTS (i.e., DRAG FORCE CAUSED BY ERODED MELT DROPLET AND WATER DROPLETS).

(4) NUMERICAL SOLUTION:

(a) ONE-DIMENSIONAL WATER POOL WITH VAPOR/WATER/MELT MIXING ZONE WHICH IS VARIED WITH TIME & WATER POOL HEIGHT;

(b) LAGRANGIAN MELT STREAM;

(c) LAGRANGIAN MELT DROPLET/PARTICLES.
N.6 - Input Deck

Calculation (a) Input Deck

THRMAL-1 FARO ISP-39 Problem with Reference Conditions
$ CARD 2:
$ $ 099999
$ CARD 3:
$ NODEPOOL, NODEGAS, NJETMAX, NGROUP, ITIME
$ 20 10 51 552124001
$ CARD 4
$ COMPUTATIONAL OPTIONS INDEX
$ 2 2 1 1 1 1 3 0 2 2 0 1 0 1
$ CARD 5:
$ $ CARDS 5-5D: COMPUTATIONAL CONTROL PARAMETERS
$ $ CARD 5:
$ NPRINT, NLUT, NLFT
$ 1 1 1
$ CARD 5A:
$ PRINT FREQUENCIES
$ 100 200 2.00E00 1.00E01
$ CARD 5B:
$ MAJOR PLOT FREQUENCIES
$ 1 200 300.000
$ CARD 5C:
$ MINOR PLOT TIMES (s)
$ 0.500E00 0.900E00 1.50E00 2.50E00
$ CARD 5D:
$ INITIAL TIME(S), MAXIMUM CALCULATION TIME (S),
$ TIME STEP (S), MINIMUM CALCULATION TIME STEP (S)
$ 0.0E00 3.00E00 0.00E-00 0.00E-01
$ CARD GROUP 5E
$ ICONV, ICONVK, ICONVE, ICONVD, ICONVU
$ 10 2 10 10 5
$ CARD GROUP 5F
$ EPS, EPSS, EPSU
$ 1.0E-3 1.0E-3 1.0E-3
$ CARDS 6-8: CONTAINMENT GEOMETRY & INITIAL CONDITIONS
$ CARD 6:
$ CONTAINMENT GEOMETRY DATA:
$ HEIGHT (M) OF MELT RELEASE LOCATION (USUALLY AT TOP OF SYSTEM),
$ HEIGHT (M) OF STRUCTURE PLATE;
$ VOLUME (M**3) OF FREE-GAS SPACE;
$ AREA (M**2) OF STRUCTURE IN THE FREE-GAS SPACE.
$ 3.0900 3.0900 1.26000 2.715700
$ CARD 7:
$ CONTAINMENT INITIAL CONDITIONS: CONTAINMENT PRESSURE(MPA), GAS TEMP (K),
$ STRUCTURE TEMPERATURE (K), AND STRUCTURE EMISSIVITY.
$ 0.510E01 536.80E00 536.80E00 0.60E00
$ CARD 7A:
$ INITIAL PRESSURE (MOLE) FRACTION OF STEAM, ARGON, & HYDROGEN
$ 0.681400 0.118400 0.00E00
$ CARD 8:
$ INITIAL WATER POOL CONDITIONS:
$ WATER POOL DEPTH (M), WATER POOL RADIUS (M),
$ WATER TEMPERATURE (K), & INITIAL VAPOR VOLUME FRACTION
$ 2.0500 0.3500 536.80E00 0.00E00
$ CARD 9:
$ MIXING ZONE CONDITIONS:
$ SWEDD OUT DROPLETS/PARTICLES ARE CARRIED AWAY BY THE STEAM FLOW
$ AND MAY REENTER THE WATER POOL MIXING/INTERACTION ZONE

THRMAL SKI-ANL
CARDS 10-11: MELT RELEASE CONDITIONS
CARDS 10-10A: MELT SOLIDUS & LIQUIDUS TEMPERATURES (K)
2830.02E00 2850.00E00
2830.08E00 2850.00E00 1693.00E00 1723.00E00

CARD 11:
CONTINUOUS MELT RELEASE INTERVAL, SINGLE JET, TEN TIME STEPS TO LUMP MELT
RELEASE CONDITIONS, FIVE TIME STEPS TO GENERATE A NEW PARTICLE GROUP,
950 TIME STEPS STORED IN ABLATION OUTPUT FILE PORT:12
1 1 10 5 950 0 3

CARD 11A:
MELT RELEASE PARAMETERS
MELT RELEASE TIME(S), MELT TEMPERATURE(K)
MELT STREAM RADIUS (M), DECAY HEAT SOURCE(J/S)
0.00E00 0.950E00 3073.00E00 0.00E0 4.600E-2 0.0800 0.00E00 0.00E00

CARD 11B:
TWO CONSTITUENTS AND NO MINIMUM MELT RELEASE RATE
NOTE: NO COMMENT CARDS BETWEEN CARDS 11B AND 11C

CARD 11C:
METAL
INDEX: CONSTITUENT INDEX: CONSTITUENT
1 Zr 8 ZrO2
2 Fe 9 FeO
3 Cr 10 Fe3O4
4 N1 11 Cr2O3
5 B 12 NiO
6 U 13 B2O3
7 B4C 14 UO2
8 24.676
15 99.504
16 AL2O3

CARD 13:
STEAM TABLE RANGE
100 201 100 0 50.00E00 0.000E00 0.500E00 0.000E00 10.00E00

CARD 14-22:
USER FLEXIBILITY
INCLUDE CARDS 14-22 ONLY IF IUSER=1

CARD 14:
USER'S INDEX
IBLS,IXH,ILWAVE,ICD,ICPV68,ICFLUXBGD,ISTM,ISTO
0 1 0 1 0 0 0 0

CARD 16:
KELVIN-HELMHOLTZ INSTABILITY INPUT, INCLUDE ONLY IKX=0
1.00E00 1.00E00 1.00E00 1.50E00

CARD 17:
LARGE WAVE INSTABILITY INPUT, INCLUDE ONLY ILWAVE=1
1.00E00 1.00E00 2.00E00 1.00E00

CARD 19:
VAPOR TEMPERATURE COEFFICIENT, INCLUDE ONLY ICPV68=1
0.68E00 0.25E00 0.500E00
0 0 0 0 0
160.00E00 0.25E00 201.00E00
2 2 2 2 11
0

Calculation (b) Input Deck

THIRMAL-1 FARO ISP-39 Problem with Reference Conditions

CARD 2:
NEW JOB OR RESTART JOB
099999

CARD 3:
NODEPOOL, NODEGAS, NJETMAX, NGROUP, ITIME
20 10 51 552124001

CARD 4:
COMPUTATIONAL OPTIONS INDICE
^VARICOSE&SIMIOUS LARGE WAVES
2 2 1 1 0 1 1 1 3 0 2 2 0 1 0 1

CARD 5:
SNPRINT, NPLT, NPLT
1 1 1

CARD 5A:

THIRMAL SKI-ANL
$ PRINT FREQUENCIES
100 200 2.00E00 1.00E01
$ CARD 5B:
$ MAJOR PLOT FREQUENCIES
1 200 300.000
$ CARD 5C:
$ MINOR PLOT TIMES (S)
0.5000E00 0.9000E00 1.50E00 2.50E00
$ CARD 5D:
$ INITIAL TIME(S), MAXIMUM CALCULATION TIME (S), TIME STEP (S), MINIMUM CALCULATION TIME STEP(S)
0.0000 3.0000E00 0.001E-00 0.005E-01
$ CARD GROUP 5E
ICONV, ICONVK, ICONVE, ICONVD, ICONVU
10 2 10 10 5
$ $ CARD GROUP 5F
EPSF, EPSG, EPSU
1.0E-3 1.0E-3 1.0E-3
$ $ CARDS 6-9: CONTAINMENT GEOMETRY DATA & INITIAL CONDITIONS
$ CARD 6:
$ CONTAINMENT GEOMETRY DATA:
HEIGHT (M) OF MELT RELEASE LOCATION (USUALLY AT TOP OF SYSTEM),
HEIGHT (M) OF STRUCTURE PLATE;
VOLUME (M^3) OF FREE-GAS SPACE;
AREA (M^2) OF STRUCTURE IN THE FREE-GAS SPACE.
3.0900 3.0900 1.26000 2.715700
$ CARD 7:
$ CONTAINMENT INITIAL CONDITIONS: CONTAINMENT PRESSURE (MPA), GAS TEMP (K),
STRUCTURE TEMPERATURE (K), AND STRUCTURE EMITTIVITY.
0.5100E01 536.80E00 536.80E00 0.60E00
$ CARD 7A:
$ INITIAL PRESSURE (MOLE) FRACTION OF STEAM, ARGON, & HYDROGEN
0.981400 0.118600 0.000000
$ CARD 8:
$ INITIAL WATER POOL CONDITIONS:
WATER POOL DEPTH (M), WATER POOL RADIUS (M),
WATER TEMPERATURE (K), & INITIAL VAPOR VOLUME FRACTION
2.0000 0.355000 536.80E00 0.0000
$ CARD 9:
$ MIXING ZONE CONDITIONS:
SWEPPT OUT DROPLETS/ Particles ARE CARRIED AWAY BY THE STEAM FLOW
AND MAY REENTER THE WATER POOL MIXING(INTERACTION) ZONE
2
$ CARDS 10-11: MELT RELEASE CONDITIONS
$ CARDS 10-10A: MELT SOLIDUS & LIQUIDUS TEMPERATURES (K)
2830.00E00 2850.00E00
2830.00E00 2850.00E00 1693.00E00 1723.00E00
$ CARD 11:
$ CONTINUOUS MELT RELEASE INTERVAL, SINGLE JET, TEN TIME STEPS TO LUMP MELT
RELEASE CONDITIONS, FIVE TIME STEPS TO GENERATE A NEW PARTICLE GROUP,
950 TIME STEPS STORED IN ABLATION OUTPUT FILE FOR..12
1 1 10 5 950 0 0
$ CARD 11A: MELT RELEASE PARAMETERS
$ MELT RELEASE TIME(S), MELT TEMPERATURE(K), MELT STREAM RADIUS (M), DECAY HEAT SOURCE(J/S)
0.00E00 0.9500E00 3073.00E00 0.00 4.600E-02 0.00E00 0.00E00 0.00E00
$ CARD 11B:
$ TWO CONSTITUENTS AND NO MINIMUM MELT RELEASE RATE
$ (NOTE: NO COMMENT CARDS BETWEEN CARDS 11B AND 11C)
$ METAL
$ OXIDE
$ CARDS 11C: MELT COMPOSITIONS & MASS FLOW RATE (KG/S)
$ INDEX:
CONSTITUENT INDEX CONSTITUENT
1 2r 8 2r02
3 Fe 9 Fe0
4 Cr 10 Fe203
4 Ni 11 Fe304

THIRMAL SKI-ANL
<table>
<thead>
<tr>
<th>Card</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>5</td>
<td>B</td>
</tr>
<tr>
<td>6</td>
<td>U</td>
</tr>
<tr>
<td>7</td>
<td>B4C</td>
</tr>
<tr>
<td>8</td>
<td>24.876</td>
</tr>
<tr>
<td>9</td>
<td>99.504</td>
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</table>

$ CARD 13: STEAM TABLE RANGE
100 201 100 0 50.0E00 0.000E00 0.500E00 0.000E00 10.00E00
$ CARDS 14-22: USER FLEXIBILITY
$ INCLUDE CARDS 14-22 ONLY IF USER=1

$ CARD 14: USER'S INDEX
$ IBLS, IKH, ILWAVE, ICD, ICPV68, IQFLUXBED, ISTM, ISTO
0 2 1 0 1 0 0 0

$ CARD 16: KELVIN-HELHOLTZ INSTABILITY INPUT, INCLUDE ONLY IKH>0
1.0E00 1.0E00 1.0E00 1.0E00

$ CARD 17: LARGE WAVE INSTABILITY INPUT, INCLUDE ONLY ILWAVE=1
1.0E00 1.0E00 2.0E00 1.0E00

$ CARD 19: VAPOR TEMPERATURE COEFFICIENT, INCLUDE ONLY ICPV68=1
0.68E00 0.25E00 0.500E00
0 0 0 0 0
160.0E00 0.25E00 201.0E00
2 2 2 2 1 1
0

THIRMAL SKI-ANL
N.7 - Participants Comments

Comments to calculation (a)

(1) The THIRMAL-1 calculated results for the ISP-39 problem with the referenced melt release conditions and initial/boundary conditions compared well with most of the experimental data (i.e., pressure history, energy to steam/water, steam/water temperature, total fragment mass & size). There is a difference of the swell pool level between the data and THIRMAL-1 predicted results. This is mainly because the THIRMAL-1 code is one-dimensional code which overpredicts the level swell of the water pool and also resulted in the oscillation of THIRMAL-1 code calculated quench rate. However, the overall trend of the THIRMAL-1 code calculated quench rate is consistent with the data.

(2) The total fragment mass of 113 Kg calculated by the code is higher than the data of 105 Kg. The THIRMAL-1 code calculated median fragment size is 3.7 mm which is smaller than the data (4.8 mm). This difference is caused by the higher melt erosion rate of small wave calculated by the code which resulted in less melt mass break-up into melt segments due to large waves. This may be attributed to the higher swell water level calculated by the code.

Comments to calculation (b)

(1) The THIRMAL-1 calculated results for the ISP-39 problem with the referenced melt release conditions and THIRMAL-1 melt surface tension compared well with most of the experimental data (i.e., pressure history, energy to steam/water, steam/water temperature, total fragment mass & size). There is also a difference of the swell pool level between data and THIRMAL-1 results. This is mainly because the THIRMAL-1 code is one-dimensional code, which overpredicts the level swell of the water pool and also results in the oscillation of THIRMAL-1 calculated quenching rate. However, the overall trend of the THIRMAL-1 code calculated quench rate is consistent with the data.

(2) The total fragment mass of 116 Kg calculated by the code is higher than the data of 105 Kg. The THIRMAL-1 code calculated median fragment size is 4.2 mm which is closer to the data (4.8 mm) than the calculated results in calculation (a). The difference between data and predictions is also caused by higher erosion rate by small wave, which resulted in less melt mass break-up into melt segments by large waves. This may be attributed to the higher swell water level calculated by the code.
O. - VAPEX-EREC Calculations

O.1 - Participant Identification

<table>
<thead>
<tr>
<th>Organisation:</th>
<th>Research &amp; Engineering Centre of Nuclear Plants Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Person(s):</td>
<td>Oleg Melikhov</td>
</tr>
<tr>
<td>Address:</td>
<td>EREC</td>
</tr>
<tr>
<td></td>
<td>Bezymyannaya 6</td>
</tr>
<tr>
<td></td>
<td>Electrogorsk</td>
</tr>
<tr>
<td></td>
<td>Moscow Region</td>
</tr>
<tr>
<td></td>
<td>Russia 142530</td>
</tr>
<tr>
<td>Tel:</td>
<td>007-9643 31679</td>
</tr>
<tr>
<td>Fax:</td>
<td>007-9643-32322</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:bulat@erec.msk.ru">bulat@erec.msk.ru</a></td>
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</table>

O.2 - Initial and boundary conditions

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<thead>
<tr>
<th></th>
<th>EXPERIMENT</th>
<th>EREC</th>
<th>Difference</th>
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<tbody>
<tr>
<td><strong>Melt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td>80 UO₂ + 20 ZrO₂</td>
<td></td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>125</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3073 ± 50</td>
<td>3073</td>
<td>+0.008</td>
</tr>
<tr>
<td>Delivery nozzle diameter, m</td>
<td>0.092</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>DP delivery</td>
<td>gravity</td>
<td>gravity</td>
<td></td>
</tr>
<tr>
<td>Free fall in gas, m</td>
<td>1.04</td>
<td>1.04</td>
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</tr>
<tr>
<td><strong>Water in test vessel</strong></td>
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</tr>
<tr>
<td>Mass, Kg</td>
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<td>613</td>
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</tr>
<tr>
<td>Depth, m</td>
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<td>-0.01</td>
</tr>
<tr>
<td>Temperature (average), K</td>
<td>536.8</td>
<td>536</td>
<td>-0.8</td>
</tr>
<tr>
<td>Subcooling at melt contact, °C</td>
<td>1.2</td>
<td>1.83</td>
<td>+0.63</td>
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<tr>
<td>Fuel to coolant mass ratio</td>
<td>0.20</td>
<td>0.204</td>
<td>+0.004</td>
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<tr>
<td>Total water volume, m³</td>
<td>0.798</td>
<td>0.785</td>
<td>-0.013</td>
</tr>
<tr>
<td><strong>Gas Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition, w%</td>
<td>77 steam + 23 Argon</td>
<td>100 steam</td>
<td>no Argon</td>
</tr>
<tr>
<td>Volume, m³</td>
<td>1.26</td>
<td>1.264</td>
<td>+0.004</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>536</td>
<td>536</td>
<td></td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>5.1</td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>
0.3 - Code nodalization

A 2d axisymmetric numerical scheme has been used. The grid dimension is 7x47. The grid is regular in both directions. Heat transfer to the vessel wall has been used in calculations. All the gaseous volumes have been modelled by means of appropriate increasing of the dome height. The nodalization is shown below.
O.4 - *Comparison of calculations with the experiment*

**Diagram 1:**
- **Y**Y**Y** VAPEX1 PRESSURE
- **XXX** L14B PT.150.0115

**Quantity:** 1 - Pressure

**Diagram 2:**
- **XXX** L14B TS.000.2800.200
- **YYY** L14B TS.180.2800.200
- **ZZZ** VAPEX1 TS

**Quantity:** 2 - Temperature in the steam dome

**VAPEX EREC**
Quantity: 3 - Water temperature at 400 mm axial, 0 mm radial position

Quantity: 4 - Water temperature at 400 mm axial, 150 mm radial position
Quantity: 5 - Water temperature at 400 mm axial, 330 mm radial position

Quantity: 6 - Water temperature at 800 mm axial, 0 mm radial position
Quantity: 7 - Water temperature at 800 mm axial, 150 mm radial position

Quantity: 8 - Water temperature at 800 mm axial, 330 mm radial position

VAPEX EREC
Quantity: 9 - Water temperature at 1200 mm axial, 0 mm radial position

Quantity: 10 - Water temperature at 1200 mm axial, 150 mm radial position
Quantity: 11 - Water temperature at 1200 mm axial, 330 mm radial position

Quantity: 12 - Mixture level
Quantity: 13, 14 - Energy to steam, Energy to liquid, Total energy

Quantity: 15 - Quenching rate
Quantity: 16 - Fragmented mass versus time, compared with the experimental final value: 105 kg

Quantity: 18 - Heat transfer surface versus time, compared with the final estimate: 33.2 m²
Quantity: 19 - Jet leading edge position versus time

Quantity: 20 - Melt/Water contact

- Experimental: 0.45 s
- VAPEX EREC: 0.431 s

Quantity: 21 - Melt/Bottom contact

- Experimental: 0.87 s
- VAPEX EREC: 0.93 s
0.5 - Code description or code models/options

The code is based on three-fluid model (liquid coolant, vapour coolant, melt droplets). Coolant dynamics description is based on the Eulerian 2D axisymmetric governing equations. Melt droplets are described with Lagrangian approach.

Two flow regimes are considered for two-phase coolant dynamics (hubbly flow regime and droplet flow regime). Realisation of each regime depends on a value of void fraction (boundary value is 0.7).

Fuel droplets-liquid heat transfer is determined by radiation and film boiling (Epstein-Hauser correlation). Vapour generation is calculated in accordance with heat flux from liquid to interface (convective heat transfer). Melt droplet fragmentation is determined by critical Weber number (We=12).

In the presented calculations the inlet melt has been described by droplets of initial diameter 2 cm. This value is evaluated using Weber criterion above.
### O.6 - Code input deck

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid dimension</td>
<td>7x47</td>
</tr>
<tr>
<td>Time step, s</td>
<td>2x10^4</td>
</tr>
<tr>
<td>Radial cell size, m</td>
<td>0.05</td>
</tr>
<tr>
<td>Initial melt temperature, K</td>
<td>3073</td>
</tr>
<tr>
<td>Initial water temperature, K</td>
<td>536</td>
</tr>
<tr>
<td>Initial steam temperature, K</td>
<td>536</td>
</tr>
<tr>
<td>Initial steam pressure, Mpa</td>
<td>5.1</td>
</tr>
<tr>
<td>Specific heat of melt, J/kgK</td>
<td></td>
</tr>
<tr>
<td>liquid</td>
<td>565</td>
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<tr>
<td>solid</td>
<td>445</td>
</tr>
<tr>
<td>Melt fusion heat, J/kg</td>
<td>0.362x10^6</td>
</tr>
<tr>
<td>Melt density, kg/m^3</td>
<td></td>
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<td>liquid</td>
<td>7960</td>
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<tr>
<td>solid</td>
<td>9430</td>
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<tr>
<td>Melt surface tension, N/m</td>
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<td>Melt liquid/solid temperature, K</td>
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<td>liquid</td>
<td>2850</td>
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<tr>
<td>solid</td>
<td>2830</td>
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</table>

VAPEX EREC
O.7 - Participants comments

The calculation reproduced the main features of the experiment. Differences are due to some model simplifications and uncertainties. The absence of coherent melt jet model leads to overestimates of melt fragmentation and vessel pressurisation. The absence of debris bed model is one of the reasons for differences between the calculation and the test. Simplified melt droplets fragmentation model in fact excludes a consideration of fragmentation kinetics.

Regular calculation grid does not permit to accurately simulate processes nearby the degraded melt jet.

Future developments of the VAPEX code will take into account the problems above and will permit to achieve better modelling of quenching processes.
P. - ACCURACY QUANTIFICATION BY THE FFT METHOD

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P.1 Introduction

The assessment process of large thermal-hydraulic codes aims principally at verifying the quality of code predictions against experimental data gathered mainly by tests performed in plant simulators (i.e. quantifying the code accuracy), since direct assessment is not possible due to the lack of suitable measurement in Nuclear Power Plants (NPP). The reliability of these predictions, adopted for safety analyses, depends on many factors involving code features and user's experience.

On the other hand, to estimate the applicability of a code in predicting a transient, one must verify that the experimental data used for qualifying code models are representative of the phenomena expected in the plant and, subsequently that the used code is able to reproduce qualitatively and quantitatively these data.

A methodology suitable to quantify code accuracy has been developed at the University of Pisa (DCMN). It is an integral method using the Fast Fourier Transform (FFT) in order to represent the code discrepancies in the frequency domain. Several applications of this method have been already carried out analysing calculations related to primary system tests [1],[2]. This methodology is an indispensable tool in the frame of the UMAE (Uncertainty Methodology based on Accuracy Extrapolation), that allows the evaluation of uncertainties in predicting transient scenarios in NPPs through the extrapolation of accuracy data obtained in small-scale facilities.

P.2 FFT Method Description

A fundamental property of the Fourier Transform is that we can analyse a particular relationship from a completely different viewpoint, without any lack of information with respect to the original one. When using functions sampled in digital form, the FFT can be used, i.e. an algorithm that computes more rapidly the discrete Fourier Transform. To apply this algorithm, functions must be identified by a number of values, which is a power of 2. Thus, if the number of points defining the function in the time domain is \( N = 2^m \), the FFT gives the transformed function defined in the frequency domain by \( 2^m + 1 \) values associated to the frequencies \( f_n = n/T, \quad (n=0,1,...,2^m) \), in which \( T \) is the time duration of the sampled signal.

The accuracy quantification of a code calculation is based on the amplitude of the FFT of the experimental signal and of the difference between this one and the calculated trend. In particular, the method characterises each calculation through two values:

- a dimensionless average amplitude

\[
AA = \frac{\sum_{n=0}^{2^m} |\Delta F(f_n)|}{\sum_{n=0}^{2^m} |F_{\exp}(f_n)|}
\]

- a weighted frequency

\[
WF = \frac{\sum_{n=0}^{2^m} |\Delta F(f_n)| \cdot f_n}{\sum_{n=0}^{2^m} |\Delta F(f_n)|}
\]

The most significant information is given by AA, which represents the relative magnitude of discrepancy deriving from the comparison between the addressed calculation and the corresponding experimental trend. The WF factor emphasises whether the error has more relevance at low or high
frequencies, and depending on transient, high frequency errors can be less important than low frequency ones (in other words, analysing thermalhydraulic transients, better accuracy is generally represented by low AA values at high WF values, [2]).

Trying to give an overall picture of the accuracy of a given calculation, average indexes of performance are obtained by defining:

\[(AA)_{tot} = \sum_{i=1}^{N_{aa}} (AA)_i \cdot (wf)_i\]

\[(WF)_{tot} = \sum_{i=1}^{N_{aa}} (AA)_i \cdot (wf)_i\]

with

\[\sum_{i=1}^{N_{aa}} (wf)_i = 1\]

where \(N_{aa}\) is the number of analysed parameters and \((wf)_i\) are weighting factors introduced to take into account the different importance (from the viewpoint of safety analyses) of each parameter, and its reliability of measurement. Briefly, each \((wf)_i\) includes the following contributions:

- "experimental accuracy": experimental trends of thermalhydraulic parameters are characterised by a more or less sensible uncertainty due to:
  - intrinsic characteristics of instruments;
  - method of the measurement;
  - different evaluation ways necessary to compare experimental measurements and the code calculated results;
- "safety relevance": particular importance is given to the accuracy evaluation of code calculations concerned with those parameters (such as pressure, peak clad temperature, etc.) which are relevant for safety and design.

Last, a further contribution in the definition of the weighting factors is given by a factor which normalises the AA value calculated for the selected parameters with respect to the AA value calculated for primary side pressure. This factor has been introduced in order to consider the physics relations existing between different quantities (i.e. fluid temperatures and pressures must be characterised by the same order of error).

So doing, the weighting factor of the j-th parameter is defined as:

\[(wf)_j = \frac{(w_{exp})_j \cdot (w_{saf})_j \cdot (w_{norm})_j}{\sum_{j=1}^{N_{aa}} (w_{exp})_j \cdot (w_{saf})_j \cdot (w_{norm})_j}\]

where

- \(w_{exp}\) is the contribution related to the experimental accuracy;
- \(w_{saf}\) is the contribution expressing the safety relevance of the addressed parameter;
- \(w_{norm}\) is the normalisation factor referring to the AA evaluated for the primary pressure.

This introduces some degree of engineering judgement that can be partly reduced by a proper and unique definition of the weighting factors.

### P.2.1 Implementation of the methodology

Being available experimental and calculated trends of the parameter to be analysed, the application of the FFT method implies the following steps:
- selection of analysis time window;
- determination of the number of points;
- determination of the cut frequency value;
- selection of the set of weights.

The choice of the time windows is mainly related to the qualitative accuracy evaluation, and focuses on the identification of the various transient phases, to allow more realistic comparison of involved physical phenomena and corresponding code models.

Since the FFT algorithm requires that functions are identified by a number of values, equally spaced, which is a power of 2, an interpolation generally is necessary to satisfy this requirement.

Supposing that available data are characterised by an adequate sampling frequency, the fulfilment of the Sampling Theorem is required to avoid distortion of sampled signals.

If we select \( N = 2^{m+1} \) points, the maximum frequency of FFT transformed functions is given by:

\[
f_{\text{max}} = \frac{2^m}{T_d} = \frac{f_s}{2}
\]

where
- \( T_d \) is the transient time duration,
- \( f_s \) is the sampling frequency.

In other words, it is meaningless to choose a number of points giving, in terms of FFT analysis, a frequency greater than the maximum one achievable adopting a certain \( f_s \). On the other hand, some information could be lost using a too low number of points.

Then, a cut frequency value, which has to be considered in evaluating the AA and WF factors, has been introduced to filter spurious contributions, generally negligible (e.g. slopes added to interpolated signals, as an effect of the performed linear interpolation). This value is obviously related to the frequencies characterising the addressed parameters and the available data.

Last, a delicate point is the choice of the weighting factors. The terms \( (W_{\text{exp}})_j \) and \( (W_{\text{ad}})_j \) in the previous equations have to be assigned using engineering judgement, starting from measuring and safety considerations. A set of weights suitable to the analysis of typical thermalhydraulic parameters has been set up for typical quantities of thermalhydraulic calculations. These values have been determined as a consequence of the identification and the analysis of all significant elements concurring to establish this difference of importance.

P.2.2 Accuracy evaluation ranking

The most suitable quantity to define an acceptability criterion is the AA factor evaluated for each analysed quantity by the FFT method. The accuracy of the addressed code calculation can be characterised by means of the following criterion:

\[(\text{AA})_{\text{tot}} < K\]

where \( K \) is an "acceptability factor" valid for the whole transient. Lower is the \( (\text{AA})_{\text{tot}} \) value, better is the accuracy of the analysed calculation (i.e. the code prediction capability and acceptability is higher).

Furthermore, the \( (\text{AA})_{\text{tot}} \) value should not exceed the unity in any part of the transient (for a generic quantity, \( \text{AA}=1 \) means a calculation affected by a 100% error). Due to this requirement, the accuracy evaluation should be performed at different steps during the transient, to verify whether this condition is not satisfied in any phase of it.

As a consequence, acceptable values of \( K \) are included within the interval \((0+1)\). With reference to the experience gathered from all previous applications of this methodology to the analysis of LOCA transient predictions, it has been noted that results in the range:
1) \((AA)_{tot} < 0.3\) characterise very good predictions;
2) \(0.3 < (AA)_{tot} < 0.5\) characterise good code calculations;
3) \(0.5 < (AA)_{tot} < 0.7\) characterise poor code predictions;
4) \((AA)_{tot} > 0.7\) characterise very poor code calculations.

Taking into account these considerations, \(K=0.4\) has been chosen as reference threshold value identifying good accuracy of such calculations.

The same criterion has been used to evaluate codes capability in the single parameter prediction; clearly, in this case the AA factor is the one evaluated for the addressed parameter. In particular, an acceptability factor \(K=0.1\) has been fixed for the error in primary system pressure, for applications to LOCA transients.

It should be noted that the FFT based methodology does not allow the identification of the origin of the error (i.e. user effect, wrong initial condition nodalization model deficiency, etc.) \(^1\).

**P.3 Accuracy Evaluation for ISP-39**

All the fifteen calculations submitted to the ISP 39 have been considered for the quantification of the accuracy.

The activity has been conducted in the following way:

a) a qualitative accuracy evaluation has been made including engineering (subjective) judgement in the selection of suitable parameters and in the identification of unsuitable calculation results;
b) application of the FFT based method including the comparison between all measured and calculated trends;
c) the step a), including the obtained results, had no impact on the FFT application;
d) the knowledge and the consideration of the importance of the involved physical phenomena has been kept to a minimal and necessary level to minimize the impact of subjective judgement.

Participants have been labelled from 1 to 15 according to the alphabetic list order provided by the Host Organisation (Table 1, including the Directory of participants). Participants using 2-D models have been distinguished from participants using 1-D models, specifically considering the larger number of temperatures predictable by 2-D models. However qualitative accuracy evaluation has been completed making reference to "0-D" quantities; in this case, the distinction between 1-D and 2-D models was not necessary.

In the "Standard" application of the FFT based method, three phenomenological windows have been considered according to the indications from the Host Organisation. The related time spans have also been used for deriving qualitative accuracy judgements.

The results of the investigation ("Standard" application) are given in three tables (Table 2, Table 3, Table 4) including all the participants and in three additional tables (Table 5, Table 6, Table 7) including only the participants using 2-D models. Finally, Table 10 and Table 11 show the final ranking of the calculations based upon the "Standard" application of the FFT.

A further application of the FFT based method is documented in P.3.3. P.3.3 dealing with a phenomenological window (single time span) selected by the Host Organisation. This essentially coincides with the second Ph. W. selected in the "Standard" application. The related results are reported in Table 12 and Table 9. This also needed a shift of calculated results to match the beginning

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\(^1\): Most of these aspects are dealt with in the frame of the UMAE (which uses the FFT method to evaluate code accuracy), where criteria have been fixed to minimise the influence of all of the above with the exception of the error sources intrinsic to the code like numerical and models deficiencies.
of the selected phenomenological window (see Table 8) and an additional qualitative evaluation that is discussed in the same sect. P.3.3.

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Table 1 - Identification of the participants in OECD/CSNI ISP39.

P.3.1 Qualitative accuracy evaluation - Standard

The first step in the qualitative accuracy evaluation was the identification of phenomenological windows (Ph.W.). Three Ph.W. were distinguished (Table 2, Table 3, Table 4 and Table 5, Table 6, Table 7):

I. from time 0 to time 0.45 s; i.e. the time when the melt touches the liquid level;

II. the period between 0.45 and 1.42 s, i.e. the quenching phase, when all the melt is submerged;

III. the period between 1.42 and 4.5 s when the corium transfers most of its energy to the liquid water.

The qualitative accuracy evaluation consisted in ranking the comparison between measured and calculated values related to six among punctual values and time trends relevant into the transient. These are labelled as A, B, C, D, E and F in Table 2, Table 3, Table 4 and Table 5, Table 6, Table 7, where the relevant Ph.W. is identified, too:

- A = time of the first contact between melt and liquid;
- B = time of first contact between melt and bottom of the liquid full tank;
- C = pressurisation of the pool open space during the Ph. W. I;
- D = pressurisation of the pool open space during the Ph. W. II;
- E = pressurisation of the pool open space during the Ph. W. III;
- F = Energy release from the melt to the liquid.

The following should be noted in relation to the choice of the parameters A to F:

• the parameters A to E are directly measured and are affected by small errors (i.e. experimental error much less than the difference between measured and calculated values);
the parameters C, D and E are assumed as relative values (this means that the calculated values of pressure have been "forced" to match the experimental values at the beginning of the Ph.W.);

the parameter F has been introduced owing to its importance in the overall understanding of the transient scenario.

The qualitative accuracy is necessary owing to the non-linear response of the FFT-based method, specifically when the discrepancies between measured and calculated trends are too high. In addition, this step better emphasises the occurrence of compensating errors and constitutes an independent (with respect to the FFT-based method) judgement tool. In a methodological sense, the qualitative accuracy evaluation can be intended as similar to the chi-square method widely adopted to screen statistical databases.

The results of the qualitative accuracy evaluation are reported in the first part of Table 2, Table 3, Table 4 and Table 5, Table 6, Table 7. It might be noted that 5, 3 and 4 calculations do not pass the qualitative examination in the Ph.W. I, II and III, respectively. An error compensation can be envisaged for those calculations that pass the qualitative accuracy screening in the Ph.W. III but not in the Ph.W. I or II (the same can be repeated with reference to Ph.W. II and I).

It should be noted that only 5 calculations have been judged qualitatively correct during all the three phases (or Ph. W.).

No impact of the qualitative evaluation upon the quantitative evaluation step is considered: the qualitative evaluation allowed a better understanding of the results produced by the application of the FFT-based method; these are the only ones considered in the final ranking of the calculations (Table 9 and Table 10 related to the 1-D and 2-D qualitative evaluations of accuracy, respectively).
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**CAUTION:**
- PMED bar
- T °C
- LTC m
- ENERTOT MJ

*consistent with available time trend*  
*calculated temperature remains constant; the same applies to participants 7, 8, 9, 12 and 14*  
*the best 2-D calc. without (-); w.f. definition in Ph.W. I*

**QUALITATIVE ACCURACY**

**QUANTITATIVE ACCURACY**

*Parentheses: number of dashes in qualitative accuracy*
*Derived quantity*
*Directly measured quantity*
Calculation not satisfying minimal qualitative accuracy requirement
# Inconsistency found in available experimental data
x w.f. - weighting factors: these are processed in the standard way of the FFT method

Table 2 - Application of the FFT based method to ISP39 (1D & 2D codes); Ph.W. I
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<td>.024</td>
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<td>.024</td>
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<td>.042</td>
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</tbody>
</table>

**Notes:**
- Parentheses: number of dashes in qualitative accuracy
- Derived quantity
- Directly measured quantity
- Calculation not satisfying minimal qualitative accuracy requirement
- w.f. - weighting factors: these are processed in the standard way of the FFT method

Table 3 - Application of the FFT based method to ISP39 (1D & 2D codes); Ph.W. II
<table>
<thead>
<tr>
<th>QUALITATIVE ACCURACY: 1-D</th>
<th>QUALITATIVE ACCURACY</th>
<th>QUANTITATIVE ACCURACY</th>
</tr>
</thead>
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</tr>
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<tr>
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</tr>
<tr>
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<td>15</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES**

A,B,C,D,E,F: THESE ARE COMPARISONS BETWEEN MEASURED AND CALCULATED QUANTITIES, PUNCTUAL VALUES (A,B) OR TIME TRENDS (C,D,E,F)

CAUTION: PMED bar
         T °C
         LTC m
         ENERTOT MJ

<table>
<thead>
<tr>
<th>1.</th>
<th>069</th>
<th>22</th>
<th>21</th>
<th>2.2</th>
<th>2.1</th>
<th>1.7</th>
<th>w.f.x</th>
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<td>.055</td>
<td>.114</td>
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<td>.070</td>
<td>.065</td>
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<td>.063</td>
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<td>.234</td>
<td>-</td>
<td>.059</td>
<td>.035</td>
<td>.049</td>
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<td>.080</td>
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<td>.099</td>
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<tr>
<td>TAVG 2000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

§ Parentheses: number of dashes in qualitative accuracy

* Derived quantity

o Directly measured quantity

- Calculation not satisfying minimal qualitative accuracy requirement

x w.f. - weighting factors: these are processed in the standard way of the FFT method

The best 2-D calc. without (-); w.f. definition in Ph.W. 111

Table 4 - Application of the FFT based method to ISP39 (1D & 2D codes); Ph.W. 111
| Ph. W. | 2D* | MODEL TYPE | CALCULATION IDENTIFICATION | EXCLUDED DUE TO | MELT-LIQUID CONTACT TIME | MET-BOTTOM CONTACT TIME | PGM & GEOMETRY | TIME | STATE | ENERGY-RELEASE | ENERGY | THERMOCOUPLING | THERMOCOUPLING | TW-000,000.000 | TW-270,000.150 | TW-000,000.150 | TW-000,000.150 | TW-000,000.150 | TW-000,000.150 | TW-000,000.150 | TW-000,000.150 | TW-000,000.150 | AA- |
|-------|-----|------------|---------------------------|----------------|--------------------------|------------------------|-----------------|-----|------|---------------|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-------|
| 1     | 2   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -              | -              | -      | 0.999 |
| *     | 3   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -              | -      | 0.17  |
| *     | 4   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | 0.048 |
| *     | 5   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | 0.09  |
| *     | 6   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | 0.05  |
| *     | 7   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 8   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 9   | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 10  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 11  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 12  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 13  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 14  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |
| *     | 15  | -          | -                         | -              | -                        | -                      | -               | -   | -    | -             | -      | -              | -              | -              | -              | -              | -              | -      | -     |

Table 5 - Application of the FFT based method to ISP39 (2D codes); Ph.W. I

* All Tw multiplied by 1E3
* Derived quantity
* Directly measured quantity
* Calculation not satisfying minimal qualitative accuracy requirement
** As far as possible
Table 6 - Application of the FFT based method to ISP39 (2D codes); Ph.W. II
<table>
<thead>
<tr>
<th>QUALITATIVE ACCURACY</th>
<th>QUANTITATIVE ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derived quantity</td>
<td>Directly measured quantity</td>
</tr>
<tr>
<td>Calculation not satisfying minimal qualitative accuracy requirement</td>
<td>As far as possible</td>
</tr>
</tbody>
</table>

Table 7 - Application of the FFT based method to ISP39 (2D codes); Ph.W. III
P.3.2 Quantitative accuracy evaluation - Standard

The application of the FFT based method implies the selection of relevant quantities and, if the case, of phenomenological windows. Six quantities (all of these must be time trends), again proposed by the Host Organization (ref. [6]), were selected as basis for comparing the performances of all the 15 calculations submitted to ISP 39 (Table 2, Table 3, Table 4) and nineteen quantities (all time trends) were selected for comparing the performances of the 2-D models (Table 5, Table 6, Table 7) alone.

The lists of seven and of nineteen times trends are shown in Table 2, Table 3, Table 4 and Table 5, Table 6, Table 7: their labels are self explanatory. The first group (seven time trends) is assumed to fully identify the transient scenario; the second group (nineteen time trends) is assumed to characterize the 2-D behaviour of the melt.

The use of the FFT based method included the following steps that were repeated in each Ph. W.:

- run of the FFT program related to each of the time trends (one experimental set of data and one calculated set of data properly homogeneized in relation to time step);
- the FFT program has been run 3 times for each calculation starting from 0. s to the end of the phenomenological windows I, II and III (i.e. 0.45 s, 1.42 s and 4.5 s, respectively); a meaningful consideration of the beginning of each Ph.W. in the FFT method, implies a time shift of the calculated trends that can be defined on the basis of any of the 6 selected time trends; in order to avoid this additional step of engineering judgement, it was decided to run the FFT starting each time from 0. s;
- identification of the best calculation, among those adopting 2-D models, in relation to PMED: this was used as reference one to "normalize" (see Chapt. 4.) the results of accuracy of the other quantities;
- definition of the weighting factors (w.f.) on the basis of the above step; these were introduced in the "standard formula" for weighting factors adopted in the FFT based method (Chapt. 4.);
- evaluation of the $AA_{tot}$ (Average Accuracy) of the calculations considering all the quantities properly normalized.

These steps are at the basis of the results documented in Table 2, Table 3, Table 4 and Table 5, Table 6, Table 7. A number of additional notes are included in these tables that are considered self-explanatory. The quantity $1/WF$ (i.e. the reverse of the Weighted Frequency of the accuracy) has not been directly considered in the present framework; however, $1/WF$ data are reported in the Appendices 1 and 2, showing the direct output of the FFT based method.

The ranking of the 15 submitted calculations has been made on the basis of the $AA_{tot}$ achieved in the Table 2, Table 3, Table 4 (i.e. all participants together) and in the Table 5, Table 6, Table 7 (i.e. only the participants using 2-D codes). The results are given in the Table 9 and Table 10. The following can be noted:

- in each of the three phenomenological windows only participants passing the qualitative accuracy step are listed;
- the bottom part of the table essentially shows that each "bad" qualitative judgement is supported by a "bad" result coming from the quantitative evaluation (application of the FFT based method);

- the four participants, i.e. nos. 1, 2, 3 and 15, (the participant no. 7 is not in this list because no data are available from this calculation related to the Ph.W. III) characterized by not having any dash for qualitative accuracy, are the best ones resulting from quantitative accuracy (1-D analysis, Table 2, Table 3, Table 4; an exception is represented by participant no. 8. This demonstrates the tight interaction between qualitative and quantitative accuracy statements;

- the best and the worst $AA_{tot}$ values, among those considered acceptable in the Ph. W. I, II and III, increase with time;
the data and the participants ranking in Table 10 (2-D quantitative accuracy evaluation results),
appear consistent with the information in Table 9 and;

when the terms error compensation are introduced (e.g. Table 2, Table 3, Table 4), related to an
assigned comparison measured-calculated data base, it is meant that a "bad" agreement in one part
of the transient transforms into a "good" agreement later in time, or that, during the same time
span, a "bad" and a "good" agreement related to two independent (or nearly independent)
quantities coexist (e.g. during an assigned Ph.W. the pressure is well predicted but the level is
badly predicted). And in depth study would be needed to characterize the origin of the error
compensation, like wrong modelling, wrong nodalization, wrong boundary conditions or code user
choices, or combination of these; such a study could not be carried out in the present framework
and was not among the related objectives.

P.3.3 Qualitative and quantitative accuracy evaluation - Consideration of a
Phenomenological Window

The Ph.W II characterized in sect. P.3.1 (from experimental data analysis, the period between 0.45 and
1.42 s, i.e. the quenching phase, when all the melt is submerged and the potential for steam explosion
achieves the maximum value), was selected by the Host Organization, ref. [7]. A quantitative
evaluation of code calculation results was requested making reference only to the phenomena occurring
during such time span.

In order to achieve the above objective, the following procedure was adopted:

1. experimental data only are selected to identify the Ph.W. (in the same way as in sect. P.3.1) and
Ph.W. II was chosen, i.e. period 0.45 to 1.42 s in the actual experiment;

2. the time instants 0.45 and 1.42 s were set to 0. and to 0.97 s, respectively in the Special Ph.W.
(SPh.W. in the following);

3. selection of a minimum number of quantities relevant for the SPh.W.;

4. in relation to each participant, shifts of calculated results were introduced to match the beginning of
the SPh.W:

   a) time shift common to each quantity, (X axis), based on the difference between measured
   and calculated values of the time of MWC (Metal Water Contact), see also below;
   b) quantity shift, (Y axis), different for each quantity, based on the difference between
   measured and calculated value of each of the variables selected at the item 3. at the beginning
   of the SPh.W., see also below;

5. qualitative accuracy evaluation, considering the "new" comparison between experimental and shifted-
calculated trends;

6. quantitative accuracy evaluation and derivation of final judgements.

In relation to the step no. 3, the following quantities were selected: pressure, thermal energy to the
fluid, average pool water temperature at position 400, average pool water temperature at position 1200.
No difference was made in this context, between 1-D and 2-D code results. 
In order to comply with the step no 4., the Table 8 was built-up. With reference to each participant
(first column), the needed time shifts (the same for all the quantities) and quantity shifts are the
differences between the participants related values and the experimental value (first row of Table 8). It
must be noted that the end-up of this process is the availability of "new" calculation results, in principle
independent from the original ones. The advantage is the possibility to focus the qualitative and
quantitative comparison upon phenomena of interest in the SPh.W.
Table 8 - Time and quantities shift for the accuracy quantification in the SPh.W.

<table>
<thead>
<tr>
<th>EXP</th>
<th>$t_{MWC}$ (s)</th>
<th>$PMED_{MWC}$ (bar)</th>
<th>$ENERTOT_{MWC}$ (MJ)</th>
<th>$TAVG_{400_{MWC}}$ (°C)</th>
<th>$TAVG_{1200_{MWC}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>51.21</td>
<td>0.923</td>
<td>263.87</td>
<td>264.16</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>50.52</td>
<td>0.230</td>
<td>263.86</td>
<td>263.86</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
<td>51.11</td>
<td>0.129</td>
<td>264.41</td>
<td>264.87</td>
</tr>
<tr>
<td>4</td>
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<td>0.117</td>
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<td>264.38</td>
</tr>
<tr>
<td>5</td>
<td>0.21</td>
<td>52.63</td>
<td>0.670</td>
<td>263.69</td>
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<tr>
<td>6</td>
<td>0.28</td>
<td>52.87</td>
<td>0.809</td>
<td>265.24</td>
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<td>7</td>
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<td>0.073</td>
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<td>8</td>
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<td>0.175</td>
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<td>0.067</td>
<td>262.86</td>
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</tr>
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<td>12</td>
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<td>0.210</td>
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<td>263.64</td>
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<td>264.00</td>
</tr>
<tr>
<td>15</td>
<td>0.39</td>
<td>51.13</td>
<td>0.180</td>
<td>263.64</td>
<td>263.64</td>
</tr>
</tbody>
</table>

The above result made necessary a new qualitative analysis (step no. 5.), conducted considering the same requisites discussed under sect. P.3.1. The results of this step are given in Table 12 together with those pertaining to the quantitative evaluation.

The results of the evaluation are given in Table 12 and Table 9. The following comments and evaluations apply (rough results of FFT application in Appendix 3).

The qualitative evaluation is carried out on the basis of the "new comparisons that are shown in Figs. 5.1 to 5.4. In particular, the parameters G, H, I, J, are identified in the table; they cover the entire SPh.W. and coincide with the four quantities selected. No shifted calculation result could be excluded from observing Fig. 1 and Fig. 2, but shifted calculations results of participants 7, 8, 11, 13, and 15 in Fig. 3, are not suitable for quantitative accuracy evaluation; the same is valid for shifted calculation results of participant 7 in Fig. 4.

The best 2-D calculation was selected, in the same way as in the "Standard" application, to derive the weights for the FFT. Again, this resulted to be the participant 7. This result was kept notwithstanding the unacceptable qualitative rank that this participant (Table 12) got for parameters I and J.
Fig. 1 - OECD/CSNI ISP39: Comparison between measured and shifted calculated trends during the SPh.W., system pressure.

Fig. 2 - OECD/CSNI ISP39: Comparison between measured and shifted calculated trends during the SPh.W., energy to the fluid.
Fig. 3 - OECD/CSNI ISP39: Comparison between measured and shifted calculated trends during the SPh.W., liquid temperature at position 400.

Fig. 4 - OECD/CSNI ISP39: Comparison between measured and shifted calculated trends during the SPh.W., liquid temperature at position 1200.

The final classification of participants is given in Table 9. Several possibilities can be exploited to combine the results of the "Standard" and the SPh.W. applications of the FFT based method to the ISP 39. Firstly, it was decided to use only the data of the Ph.W. II (1-D Quantitative). Secondly, the objective of this comparison (i.e., between the two FFT applications) was defined as identifying the sub-ensemble of calculations that fulfill simultaneously the acceptability requisites of both the FFT applications. Considering the above, qualitative accuracy statements were considered as reported in Table 9. The sub-ensemble of participants fulfilling all the accuracy statements, are listed in the last column of Table 9. These are participants 4, 1, 10, 2, and 3.
<table>
<thead>
<tr>
<th>Ranking</th>
<th>&quot;Standard&quot; application with qualitative accuracy statement considered</th>
<th>SP.W application with qualitative accuracy statement (its own and standard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1</td>
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</tr>
<tr>
<td>9</td>
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</tr>
</tbody>
</table>

Table 9 - Final classification of participants in the OECD/CSNI ISP39 (all participants, 1D-QUANTITATIVE): SP.W.

P.4 Conclusions

A detailed evaluation of the results submitted for OECD/CSNI ISP 39 by fifteen participants, has been carried out in this report. The FFT based method, widely utilized for assessing the results of thermalhydraulic system codes calculations, is at the basis of the evaluation.

The "engagement" into the experiment phenomenology and into the adopted codes structures and modelling capabilities, have been purposely kept at the minimum suitable level, in order to achieve judgements not biased by previous knowledge of code limitations or inaccuracies in measuring the phenomena. The suggestions and the necessary interactions with the ISP 39 Host Organization counterbalanced the above situation.

The first conclusions is deserved to the overall comparison activity: even an apparently simple physical event (i.e. the contact of molten material with liquid water) is affected by a variety of conditions that make difficult its predictability; in other terms, quantities like total energy transferred to the water are difficult to be theoretically evaluated, being affected by conditions like assumed heat transfer area and coefficient, time of metal to liquid contact (therefore, viscosity of the molten material), etc.

The second conclusion is connected with the time trends of the error in comparing calculated and measured quantities. Compensating errors are unavoidably present in any transient calculation and may have a physical basis: i.e. during a blowdown, an overprediction of critical flowrate at the transient beginning leads to the underprediction of pressure later in the transient and, necessarily, to the underprediction of mass flowrate at the same time; the error changes its sign. The same may happen in this experiment making reference to the entire transient and to the energy released from the hot material to the liquid pool.

Qualitative accuracy evaluations and subdivisions into phenomenological windows allow the consideration of the above problem and constitute a necessary support to what is called quantitative accuracy analysis.

In general terms, it must also be considered that errors in modelling or nodalization inadequacies or errors/uncertainties in setting up boundary conditions, might combine to produce a good agreement between calculated and experimental data. A depth and complete analysis to exclude such a possibility has not been performed and was not among the objectives of this study.

The purpose of a Standard Problem (OECD ISP) is not necessarily to achieve the best comparison with the available experimental data; examples of pursued goals when participating to an ISP activity are to
optimize the use of the code (including optimization of code use guidelines, nodalization qualification, etc.), to qualify the user, to characterize model deficiencies, to exchange opinions with other experts in the same area, to identify areas for further research. Considering the above, the FFT results should not be used to discriminate good and poor participants or calculations: its best use can be finalized by the producer of the calculations (i.e. the code user). In order to emphasize this item, only numbers have been reported in the previous chapter and hereafter to characterize a calculation or an ISP participant. The third set of conclusions is specific to the present analysis and is devoted to the results obtained from the two applications of the FFT referred in the text as "Standard" and "Special Phenomenological Window" (SPh.W.), respectively. Five sub-sets of conclusive remarks can be distinguished:

a) Ph.W. I - Standard application, all the calculations
Participants producing the best results are, (Table 9), 7, 15, 6, 8, 1, 13, 3 and 2. Differences among quantitative accuracy values are relatively minor; this suggests giving small importance to the relative ranking.

b) Ph.W. II - Standard and SPh.W. applications, all the calculations
Essentially, the use of the SPh.W. allowed the possibility of an additional check of the same data base, introducing new conditions for the acceptability of the calculations. The double screening process led to the identification of five calculations, (Table 9), satisfying all the acceptability requirements: these are 4, 1, 10, 2 and 3. Calculations 15, 8 and 7 should be added if the assumptions needed for the SPh.W. applications are not acceptable (see Table 8). It might be noted that calculations 4 and 10 do not appear under item a); error compensation (see the discussion under sect. P.3.2) can be envisaged in these two cases. The phenomena occurring in this time period are evaluated as having the highest importance by the Host Organization.

c) Ph.W. III - Standard application, all the calculations
The test conditions achieve (or are going to achieve) stationary values during this time span. Calculations 3, 15, 2, 1, 10 and 8 resulted the best. All of these are also rated at the top level from the item b).

d) Ph.W. II and III - Standard application, 2-D codes calculations
A specific analysis was carried out including the application of the FFT based method to the 2-D codes calculations. This implied the use of a larger number of quantities taken as basis of the FFT method. For the sake of simplicity, only the results of the Ph.W. II and III are considered here (Table 10). Calculations 3, 15, 8, and 10 confirmed to be the best in the Ph.W. III; limiting the evaluation to the Ph.W. II, calculations 4 and 5 must be added to the last ones.

e) Overall evaluation
Looking at the above results it can be concluded that calculations 3, 15, 10 and 8 produce results that are the most close to the experimental data, especially if one considers the entire transient (all the three Ph.W.) and the 2-D codes subset; calculations 1 and 2 should be added if all codes are considered. The ensemble of calculations having the top rank in the first two Ph.W. includes the above six ones and calculation 7. All these results must be taken with the caution coming from the here reported considerations.

The performed study confirmed the capabilities of the FFT based method in ranking generic calculations results. The use of the method is more and more powerful when more and more applications are completed addressing the comparison between measured and calculated trends that characterize the same phenomena. This is the case in the system thermohydraulics area, where acceptability values for current codes calculation results could be fixed. In this sense, the present application to the study of corium-water interaction, must be considered as a pilot one.

P.5 References


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* Participant to be excluded owing to unacceptable qualitative accuracy in previous Ph. W.

Table 10 - Final classification of participants in the OECD/CSNI ISP39 (1D - QUANTITATIVE)
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Table 11 - Final classification of participants in the OECD/CSNI ISP39 (2D - QUANTITATIVE)
Table 12 - Application of the FFT based method to ISP39 (1D & 2D codes); SPh.W.