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In-Pile tests in the IGR Research Reactor

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IGR Reactor

IGR reactor facility is located on the former Semipalatinsk Nuclear Test Site.

Distance from the IGR technical site up to the nearest settlement - 55 km (Paris – 5200 km, Berlin – 5000 km, Moscow – 2717 km, Dimitrovgrad – 1960 km).

IGR Reactor

The reactor first achieved criticality on June 7, 1960. The reactor first start-up was carried out on August 1, 1961.

IGR reactor is an impulse uranium-graphite thermal self-shutdown nuclear reactor of heat capacity type with graphite moderator and reflector. The reactor core represents the stack of graphite blocks assembled as columns and it has a cubic shape with a side of 1.4 m. The stack is embraced by leak-proof vessel filled up with helium located in the reactor water cooling tank. There is no special cooling system for the core. Heat released during the reactor operation is accumulated by stack and then it is gradually transferred into cooldown circuit water through the reactor casing walls.

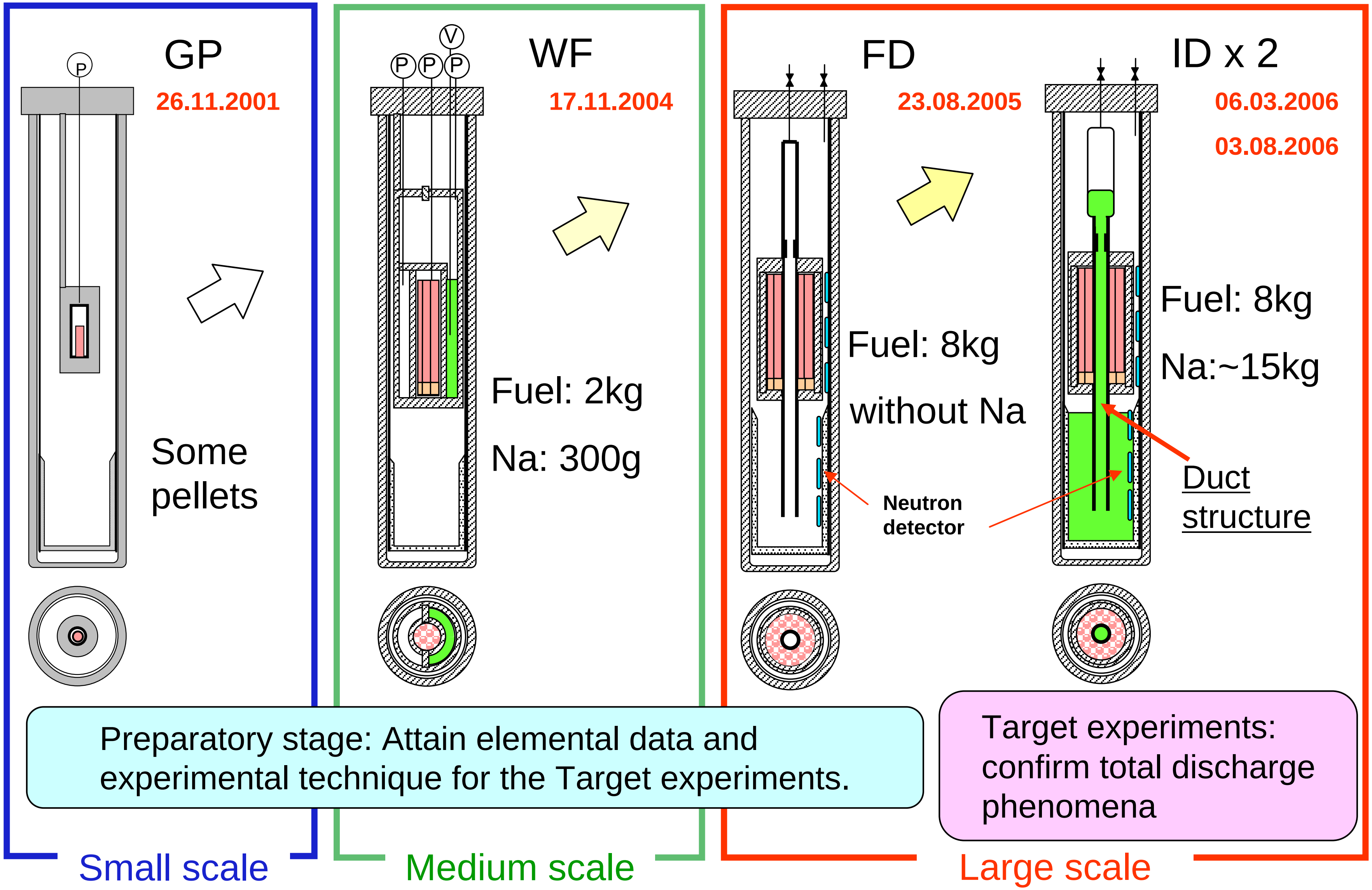
EAGLE Project

- IGR reactor has been used for the implementation of experiments under EAGLE-1 Project by the Joint Team of IAE NNC (Institute of atomic energy of National Nuclear Center of Republic of Kazakhstan), JNC (Japan Nuclear Fuel Cycle Development Institute) and JAPC (Japan Atomic Power Company as representative of Japanese electric power companies)
- This program is dedicated to show the experimental evidence for **the elimination of the re-criticality issue in the sodium cooled fast reactors**
- Useful experimental techniques for the tests with melting of ~8 kg of UO_2 have been obtained through the conduction of WF, FD, ID1 and ID2 tests implemented under EAGLE program

EAGLE In-Pile Experiments Matrix

- As a final step, three large-scale experiments with ~8kg of UO2 fuel were given. The first large-scale test (FD: Fuel Discharge) was performed with no sodium as a preparatory one for the last two ones with ~9kg of sodium. This FD test provided basic data on the key phenomena in the fuel escape scenario. The last two large-scale tests ID1 and ID2 (ID: Integral Demonstration) using IGR provided demonstrative data for the fuel-escape behaviour which can be applied for the reactor evaluation with complementary information from the out-of-pile tests.

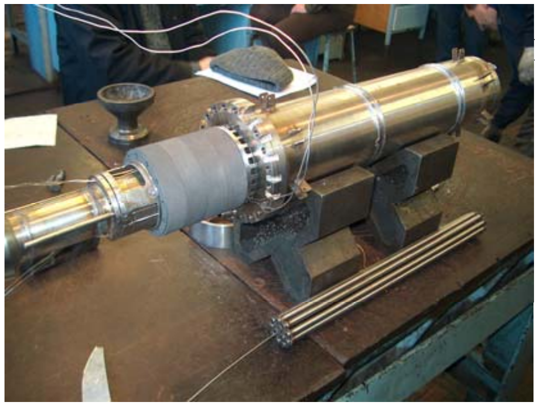
EAGLE In-Pile Experiments Matrix

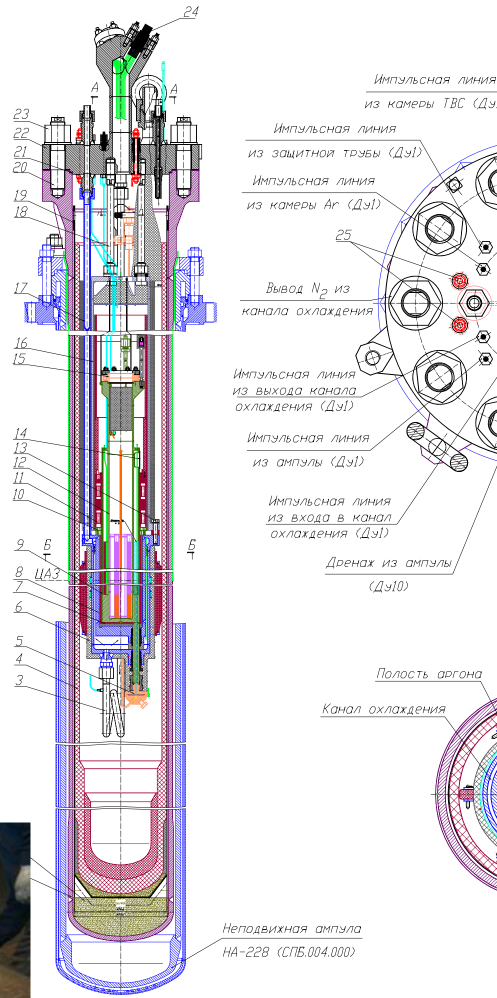


WF test section

- Inside a SS tube with outer diameter of 54 mm and wall thickness of 3 mm, 12-pins fuel assembly (FA) was installed. Each fuel pin was made of fuel pellets with 7.55 mm-diameter (with 1.5mm central hole) and SS-cladding with 9mm-diameter and 0.5mm-thickness. Main fuel column of 400mm-length was made of 4.4%-enriched UO_2 pellets of VVER-type and there installed blanket pellets (UO_2 with natural isotopic concentration) at the bottom part of 50 mm-length. The total involved UO_2 mass was 2.311kg (fuel: 2.07kg and blanket: 0.241kg respectively). There were partitions on the outer surface of SS tube and a thin (3mm) gap filled with argon gas (gas gap) and a 10 mm-thick sodium-filled channel (Na gap) were placed around the SS tube. With this setup, we could adopt common molten pool condition onto both non-sodium-cooled wall and sodium-cooled wall at the same time. With this, we could directly clarify the effect of sodium presence behind the wall.
- Such test section was installed in a pressure housing and energy insertion over melting point of UO_2 was performed by the huge neutron fluence in the central experimental channel of IGR. (Before the energy insertion by neutron flux, the whole test section was heated up to ~400°C by electric heaters.)

WF Experimental Device





WF experimental device was fabricated in NNC RK.

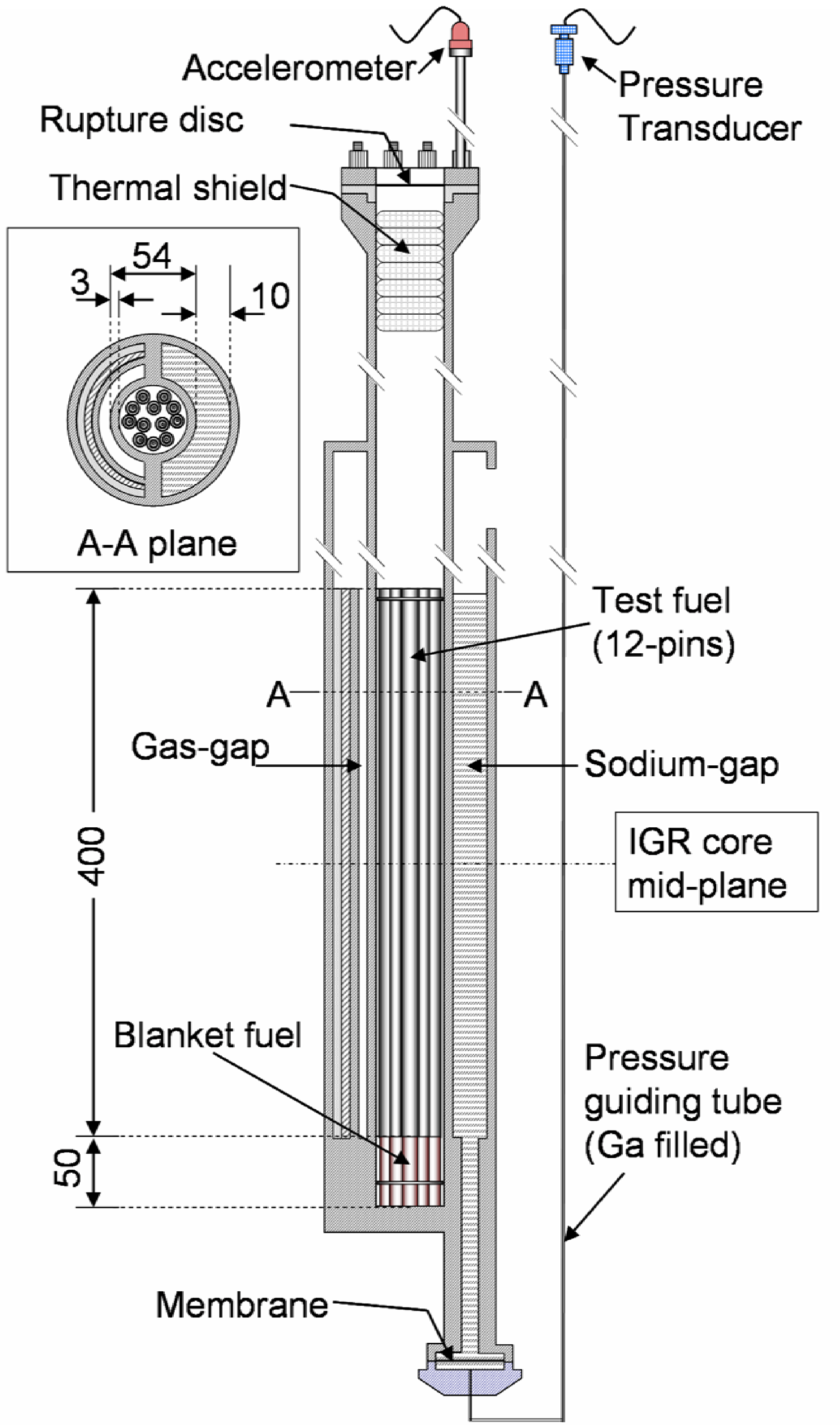
Outline of Medium Scale Experiment WF (Wall Failure)

WF device gave possibility to study interaction of the melt simultaneously with walls contacting with sodium and with Ar-gas

Objectives

- Technical confirmation for future large scale experiments
  - Nuclear heating and melting
  - Physical measurements
- Acquire wall failure data of the steel duct with sodium inside.
  - Effect of coolant sodium
  - Under the condition of high heat-flux with nuclear heating

Reduce the uncertainty of discharge timing in the accident scenario.



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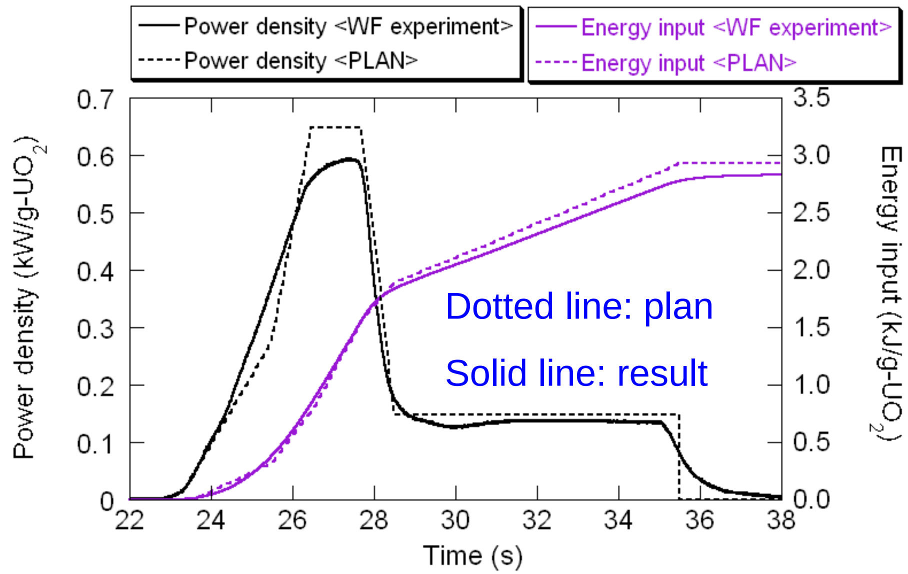
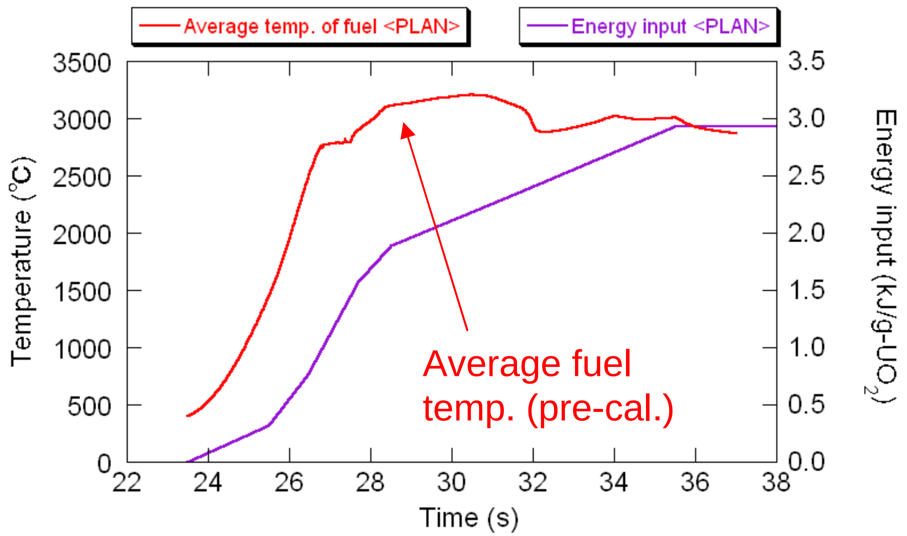
Heating Condition of the Fuel

- **Approximately the planned power diagram was realized**
  (The planned power history has been selected based on the pre-calculations using SIMMER-III and IV code)

- **Based on the pre-calculation, the attained molten-fuel temp. must be 3100~3200 deg.C**
  (This point could be confirmed by PTE in detail in the future)



Power diagram (plan and result)

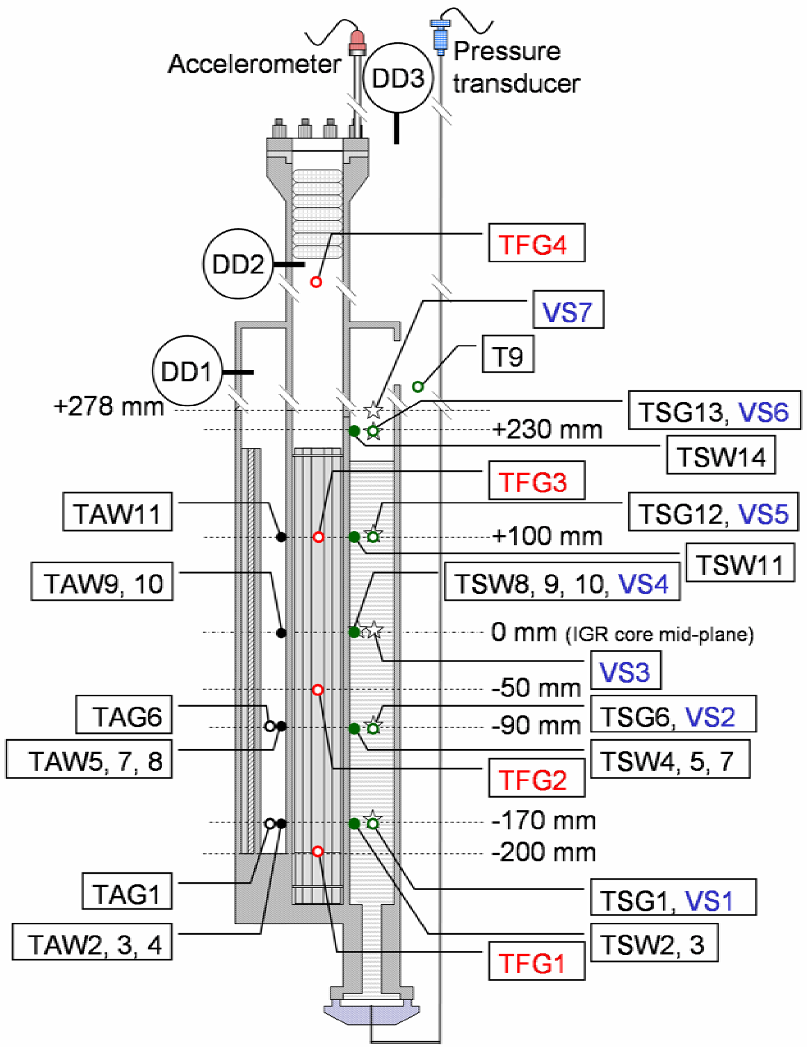


Fuel temperature history (by pre-calculation)

Measurements in the WF Test Section

- One of the purposes of WF test was to check functional effectiveness of all the measuring devices which were used in the target large scale tests. There installed a lot of measuring sensors including chromel-alumel (CA)-type and tungsten-rhenium (WRe)-type thermocouples, pressure transducers for gas and sodium, an accelerometer and void sensors. Thermocouples were installed for the purpose of measuring thermal state of test fuel. Pressure transducers and an accelerometer were installed to observe wall-failure induced pressure and acoustic events. Void sensors were installed to observe boiling and/or voiding of sodium which was assumed to occur depending on the wall-failure mechanism.
- Four WRe-thermocouples were arranged at the center of FA along the axis direction (TFG). Nine (7 CA-type and 2 WRe-type - TAW) thermocouples were fixed on the wall facing the gas gap and ten (8 CA-type and 2 WRe-type - TSW) thermocouples were fixed on the wall facing the Na-gap. These were fixed by either bandage with small SS-patch or soldering with CuZn-based material. The soldering was adopted intending to enhance thermal contact between thermocouple's hot-junction and wall surface and to measure wall surface temperature as ideal as possible. In the middle of each gap, CA-type thermocouples were arranged (TAG in gas-gap and TSG in NA-gap)

Measurements in the WF Test Section



TFGs: WRe thermocouples placed in fuel assembly cavity,

TAGs: CA thermocouples placed in gas-gap,

TAWs: thermocouples fixed on gas-side outer surface of SS-tube

(TAW4, 7, 10 are WRe-type and the others are CA-type),

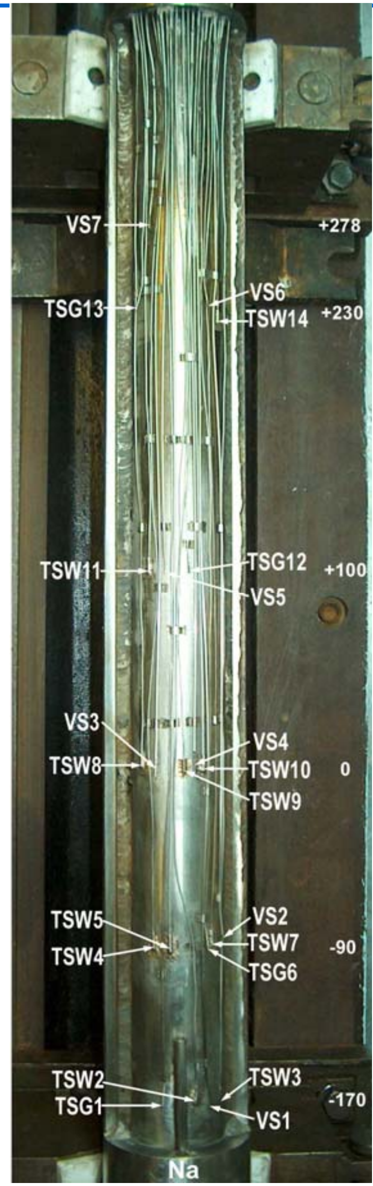
TSGs: CA thermocouples placed in Na-gap,

TSWs: thermocouples fixed on Na-side outer surface of SS-tube

(TSW4, 7 and 10 are WRe-type and the others are CA-type)

VSs: Void sensors (Sensing part is placed middle position of Na-gap except VS4.

VS4 is placed near the SS-tube surface.)



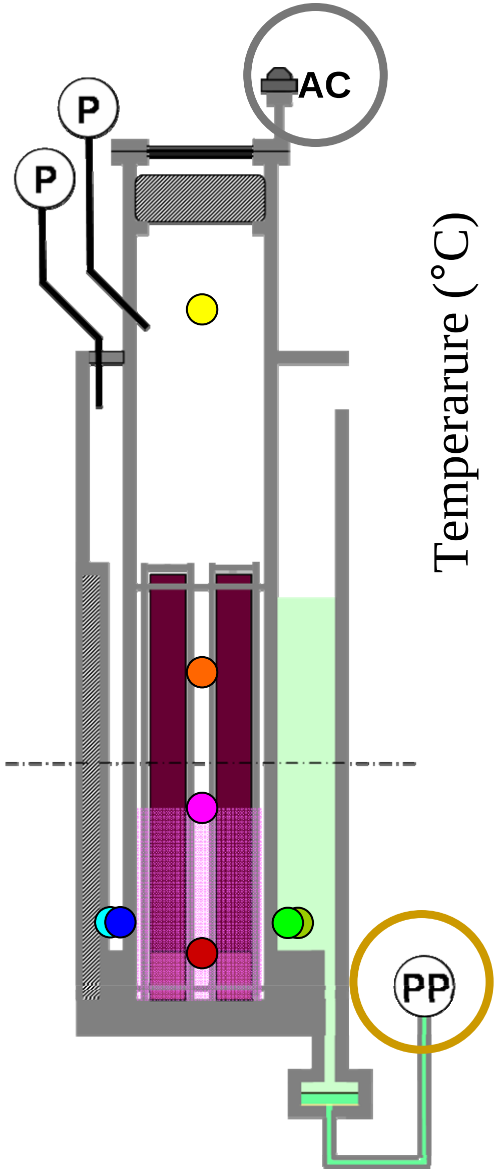
Measurements in the WF Test Section

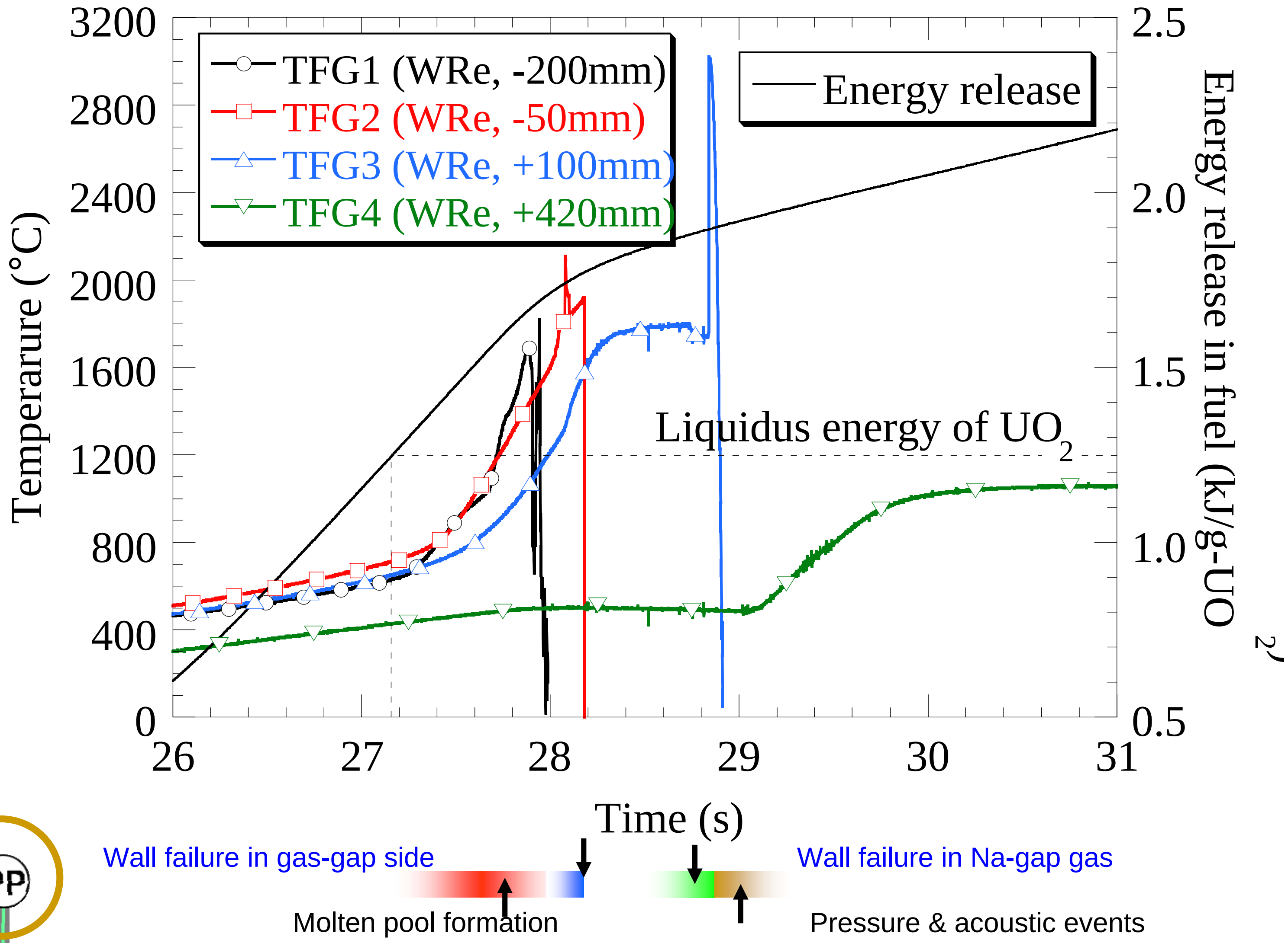
- Each gas pressure in the FA cavity, gas-gap and Na-gap was measured by pressure transducers placed outside of the core region, with which the each cavity was connected by long pipe-line (with 0.96mm I.D. and length of ~3m), intending to avoid irradiation effects on transducers.
- A special device with a gallium-filled pressure transmission tube (~5m) was installed for the purpose of detecting liquid-phase pressure in sodium which supposed to be generated when the high-temperature molten fuel was mixed with sodium (the mixing means that the molten fuel penetrated SS-tube wall) and FCI occurred. A thin membrane was placed between sodium and gallium at the lowest part of sodium. As a pressure transducer, strain-gauge-type one was used.
- A piezoelectric-type accelerometer with a wide pass bandwidth (0.1-25000Hz) was placed on top flange of the SS-tube in order to detect acoustic signals of sodium boiling and/or FCIs. The accelerometer was fixed to the flange using a waveguide rod to avoid the thermal effect on the piezoelectric device.
- The Chen-type void sensors (VS) were installed in the Na-gap. Six sensors were arranged at the mid of Na gap and one was fixed near the SS-tube wall surface (at the place 2mm apart from the surface). Not only the voltage signals of void sensors but also the supplied currents were measured in order to check the electric circuit's integrity during the transient.
- Data were sampled every 0.04msec for sodium pressure measurement and accelerometer, every 0.5msec for void sensors and every 36msec or 2msec for thermocouples (for the thermocouples, two independent data recording systems were used) respectively.

Results

- The signals of the different types of the transducers gave the possibility to identify the basic parameters and events **such, as** . . .

Molten Pool Formation





such, as the time range of the molten pool formation…

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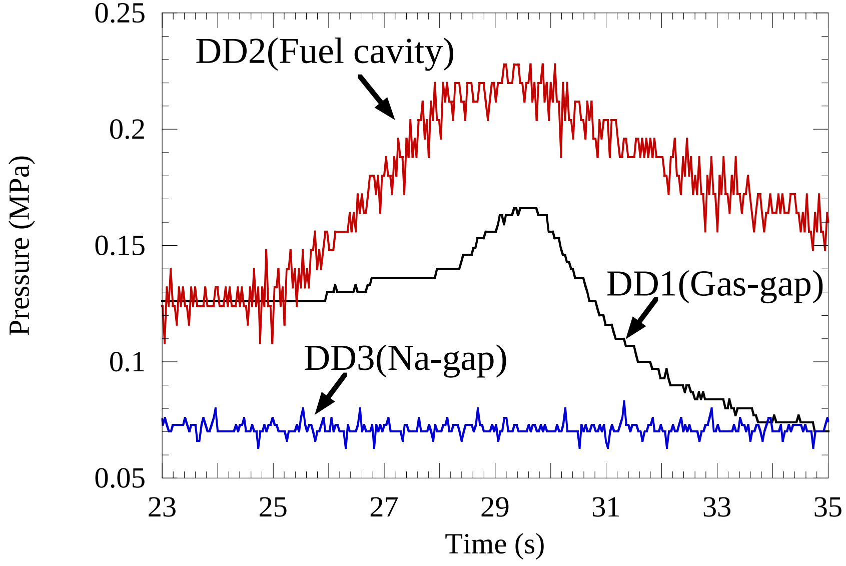
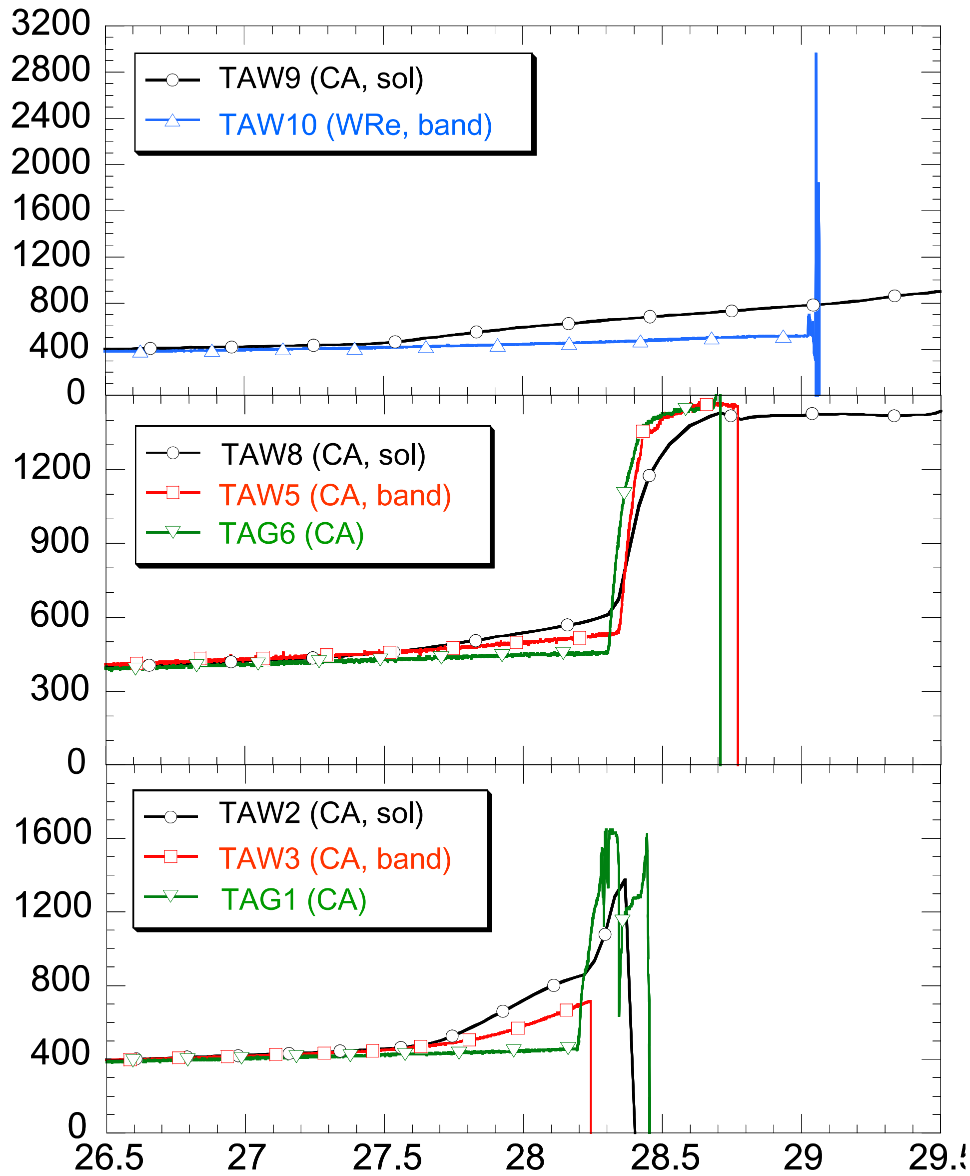
Wall Failure in the Gas-gap Side





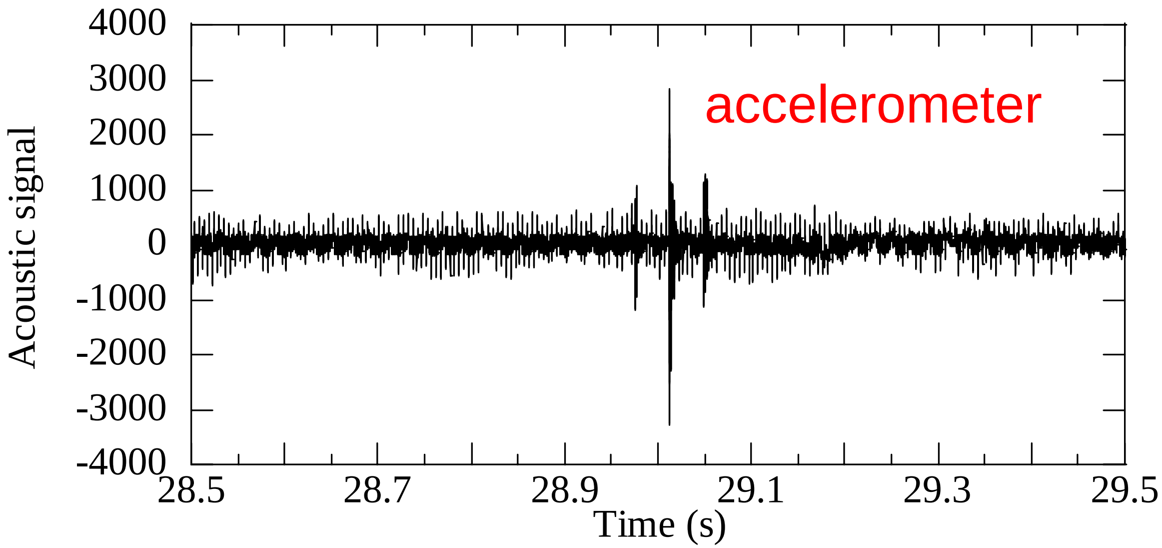
The failure of 3mm-thick SS-tube wall facing gas-gap is thought to have occurred in the lower region (near -170mm level) at about ~28.2s.

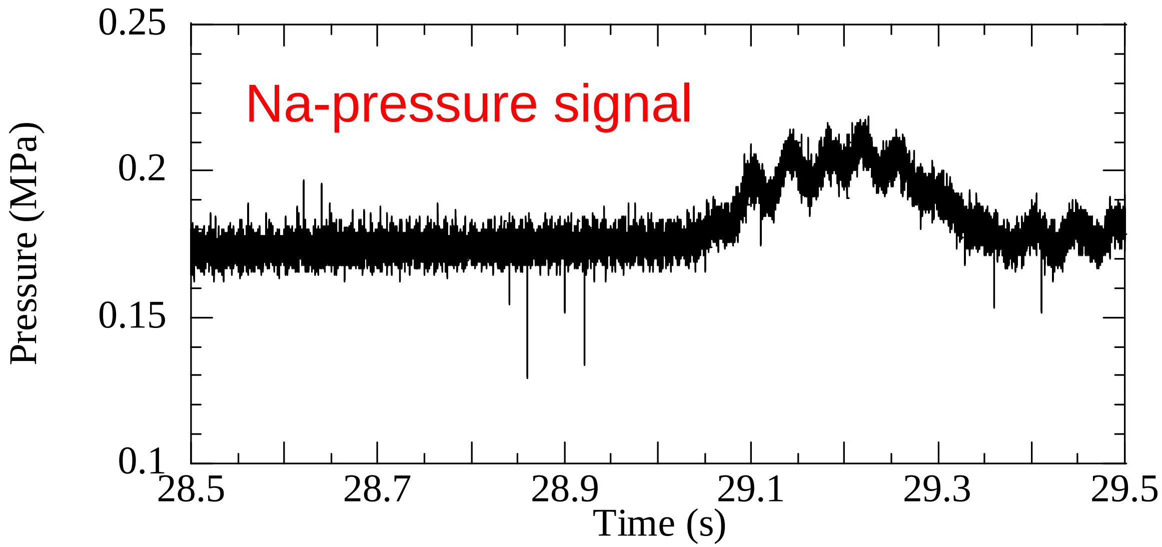
The pressure increasing rates of fuel cavity and gas-gap changed at around 28.2s. It suggests that the fuel cavity and gas-gap was connected spatially and hot-gas release from fuel cavity to the gap occurred at around 28.2s.

such, as the time of the failure of SS-tube wall facing gas-gap…

Wall Failure in the Na-gap Side

The acoustic signal spikes (measured 3 times; 28.976s, 29.012s and 29.049s respectively) and sodium-pressure increase by 0.5MPa (started from 29.04s) are thought to be a result of rather mild fuel-coolant interactions (FCI)





such, as the rather mild fuel-sodium interaction (FCI)…

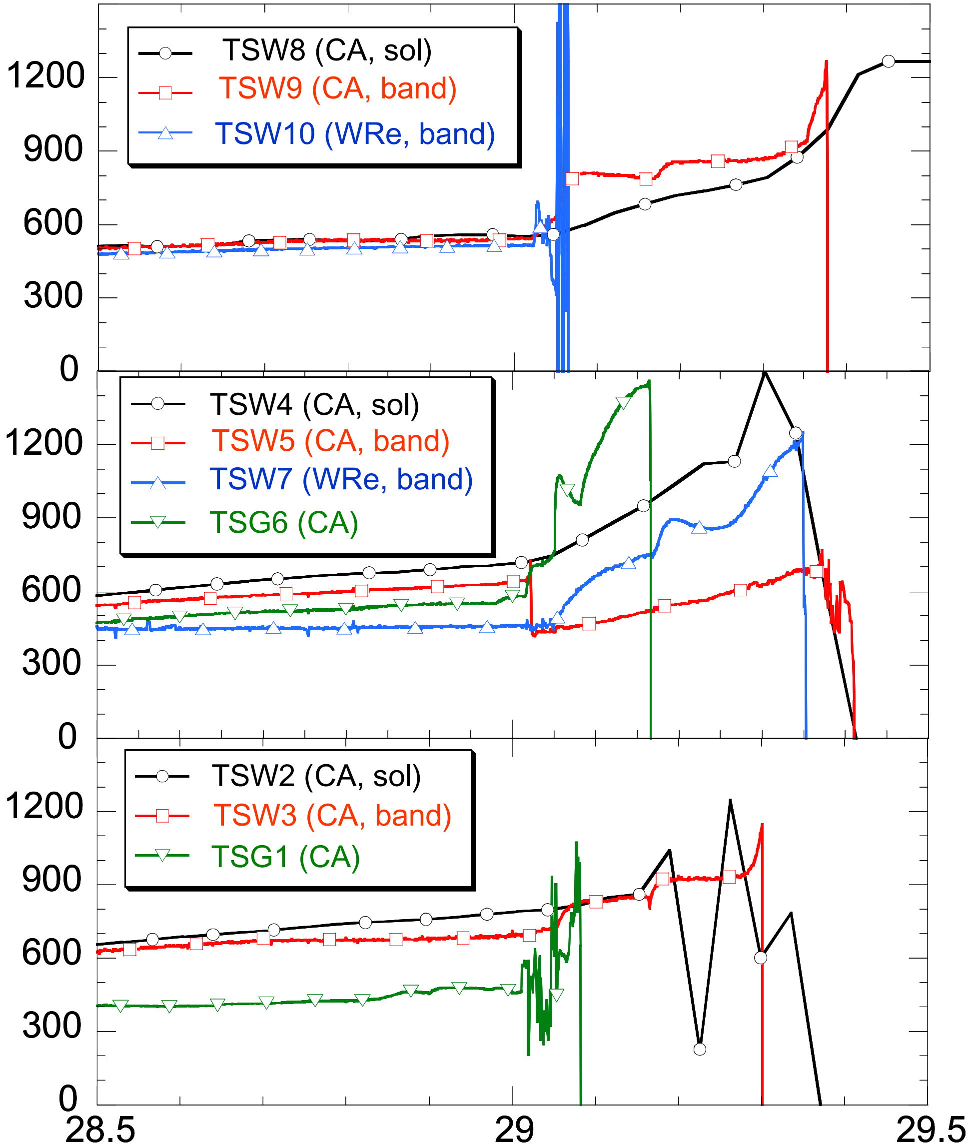
Wall Failure in the Na-gap Side

It is pointed out that the sodium-temperatures TSG1 and TSG6 began to increase beyond wall temperatures and TSG6 indicated temperature above sodium boiling point at 29.05s. .

WRe-thermocouple TSW10 was broken as a result of hot material's entering into the gap.

The initial failure position seems to have been in the lower region, because the wall temperature TSW2 at ~29s was the highest over any other signals of thermocouples fixed on the wall surface.

such, as the time of entering of the melt into the Na-gap …

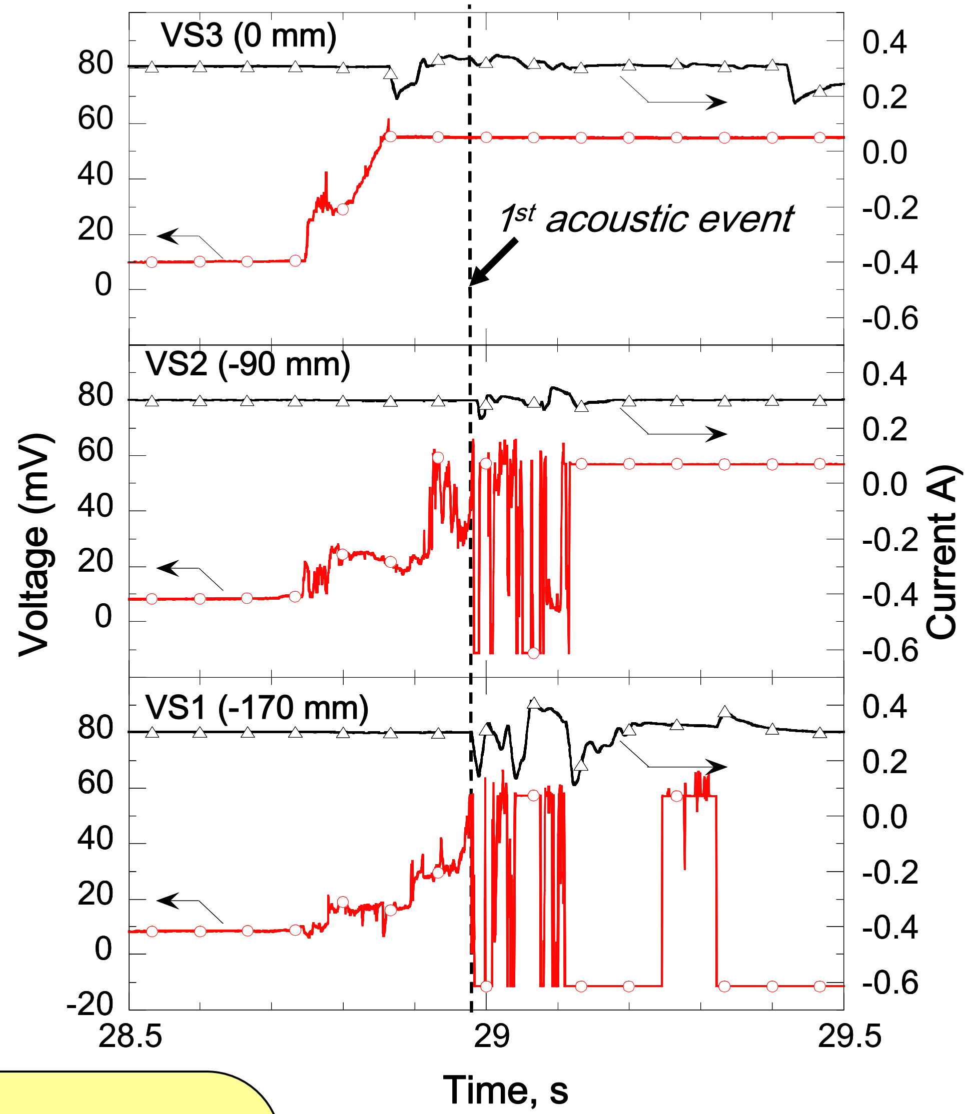


Wall failure in the gas-gap happened soon after pool formation (27.2…28.2 s).
As for Na-gap, it was 1sec after the pool formation.

Sodium Condition

The timing of the first acoustic event (28.976s) is the first contact between hot material and sodium .

The void sensors which were placed in sodium gave signals increase corresponding to void formation at around 28.74…28.89 s (VS1, VS2, VS3, VS4 and VS5).

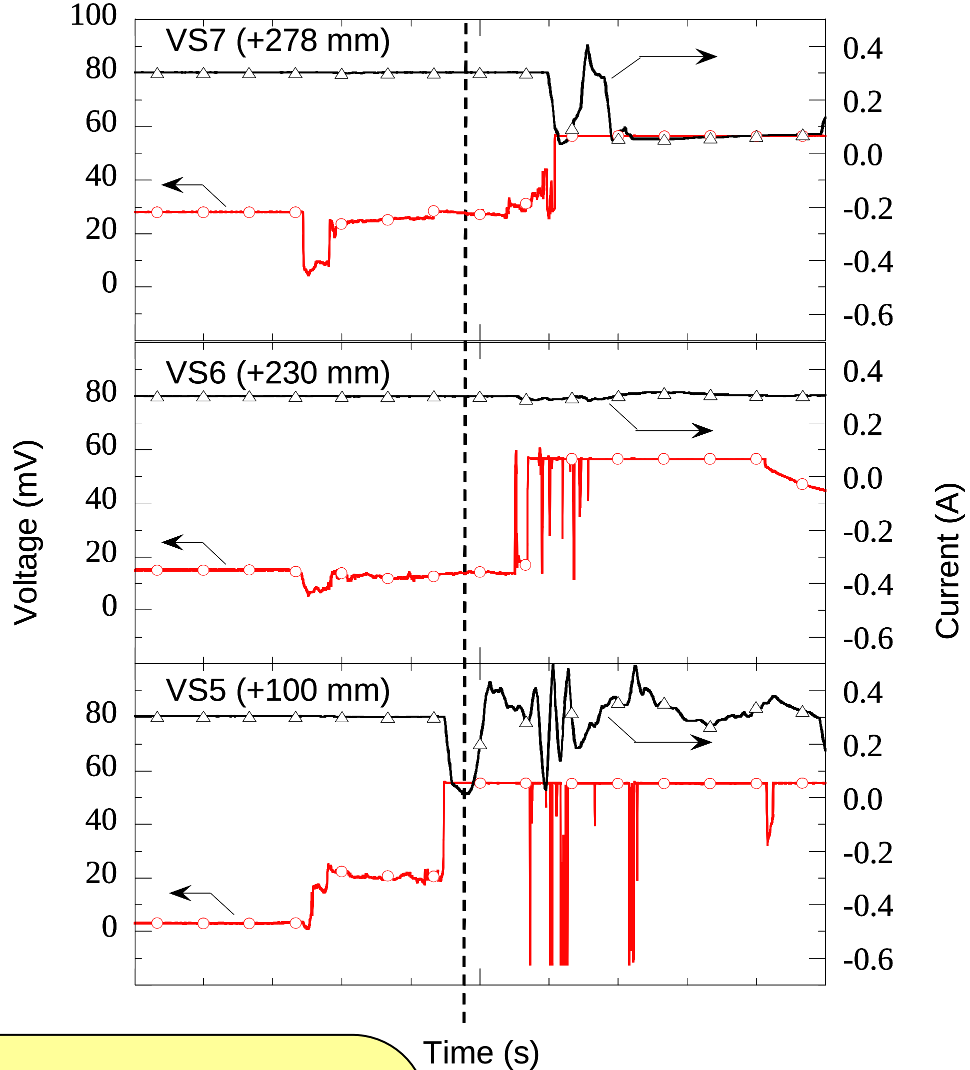


such, as the void formation in the sodium …

Sodium Condition

- VS6 and VS7 sensors, which were placed above sodium surface initially, gave signal decrease corresponding to arrival of liquid sodium at 28.74s to 28.78s respectively. This void-sensor response is suggesting sodium boiling before the wall failure.

- The possible sodium boiling, if any, was only seem local one



such, as the sodium boiling before the wall failure …

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Heat Flux from the Molten Pool

Calculated method:

In order to evaluate heat flux from the molten pool to the inner surface of wall, we conducted heat transfer calculations using TAC2D code taking the structural geometry of thermocouples into account.

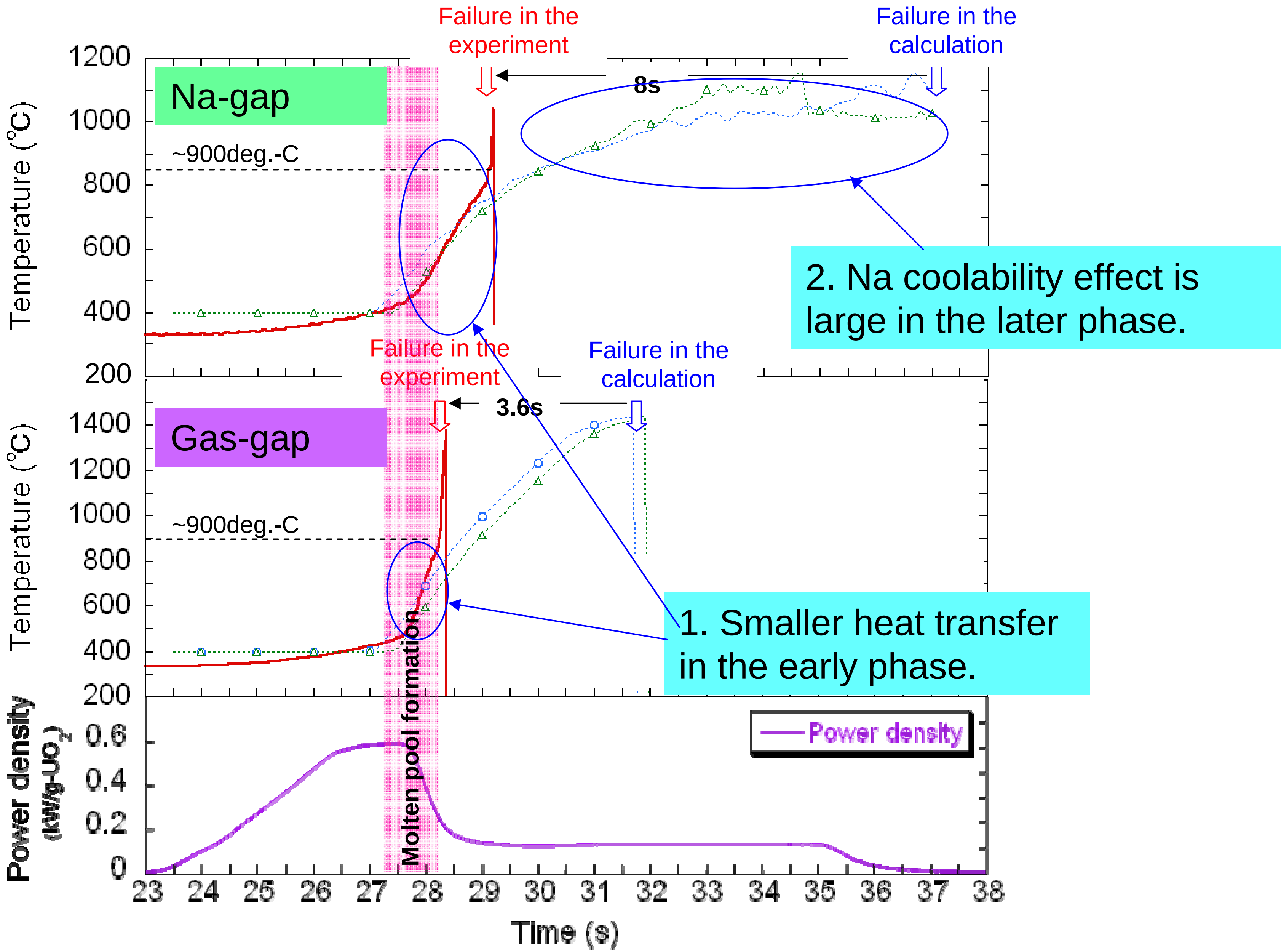
The heat flux onto the wall were parametrically changed (by changing temperature and thermal conductivity in the pool, hypothetically) and searched for a heat flux value with which TAW2 thermocouple's trend could be simulated.

Result:

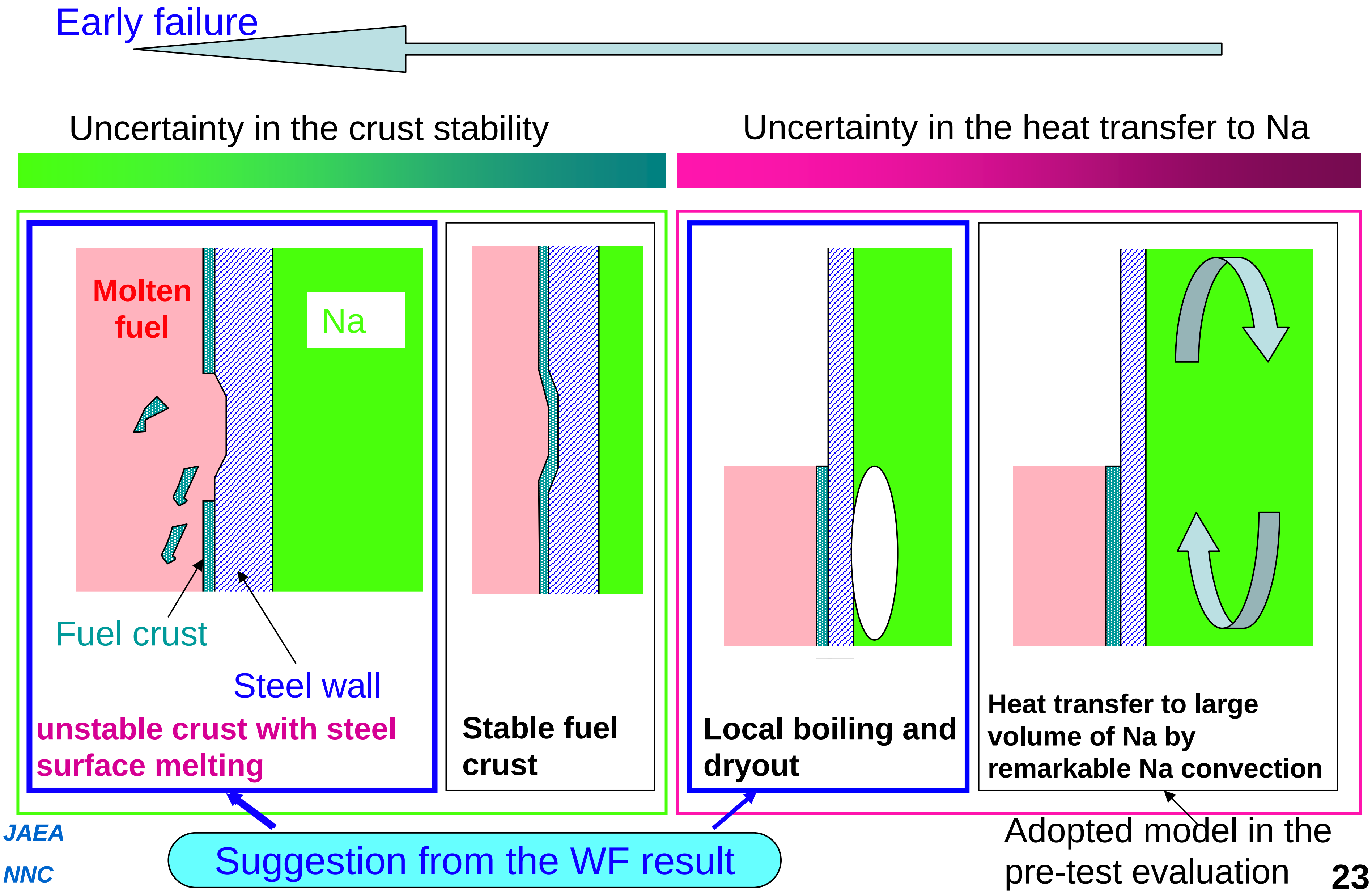
As a result from calculations, heat flux of ~20MW/m^2 from molten-pool to the wall surface was obtained (has similarity to SCARABEE tests BE+3, BF3).

such, as the heat flux from the molten pool to the SS-wall …

Comparison with Pre-calculation



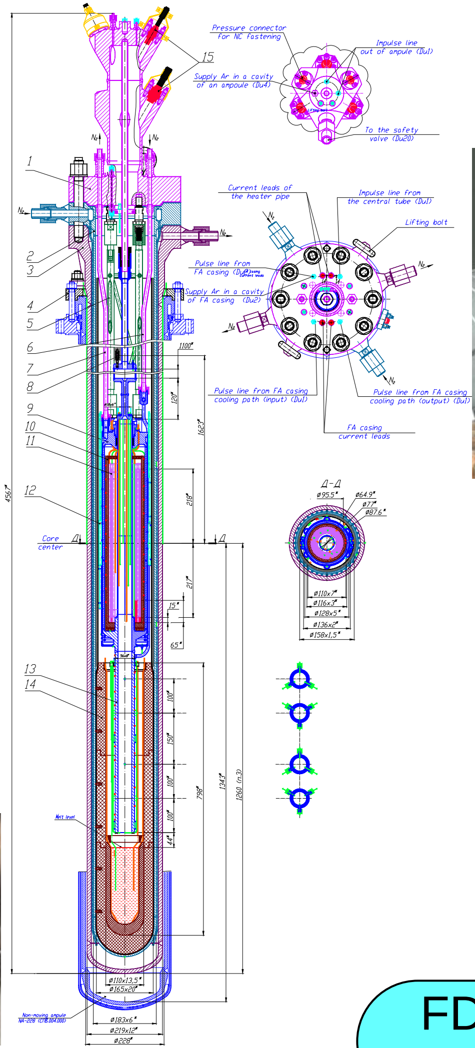
Uncertainty Before the Test in the Timing of Na-cooled Wall Failure and Suggestion from the WF-Test Results

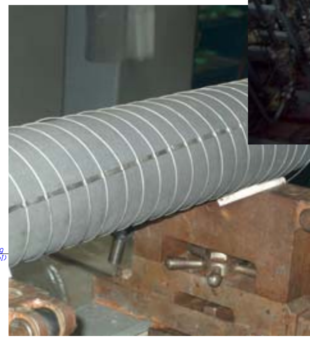


FD/ID Test Section

- The FD and ID test sections were designed so that they have the same structure except for the difference of absence (FD) or presence (ID) of sodium (in the inner duct model and lower trap). Another difference between FD and ID was in the material of which the trap was made. Graphite was used in the FD test while SS was used in the ID test as the trap material. The common test conditions between FD and ID are as follows. The inner duct model with 40mm of inner diameter and 2mm-wall thickness was installed vertically through the jacket structure, and 75-pin fuel assembly with 450mm-height (the fuel mass was about 8 kg totally) was placed in the jacket surrounding annularly around the inner duct model. BN350-type pellets with 17%-enriched UO_2 were used as the test fuel to be melted. Upper part of the inner duct was connected to an expansion tank with a thin pipe (inner diameter: 6mm, length: 120mm) between them. Such test section was confined in double-wall power housing and inserted into the central experimental channel of IGR core. The whole test section was heated up to around 300~400°C and energy insertion over the melting point of UO_2 (up to about 3000°C) was performed by the high neutron flux from IGR core.

FD/ID Experimental Device





FD and two ID experimental devices were fabricated in NNC RK.

Outline of Large Scale Dry-Test (FD test)

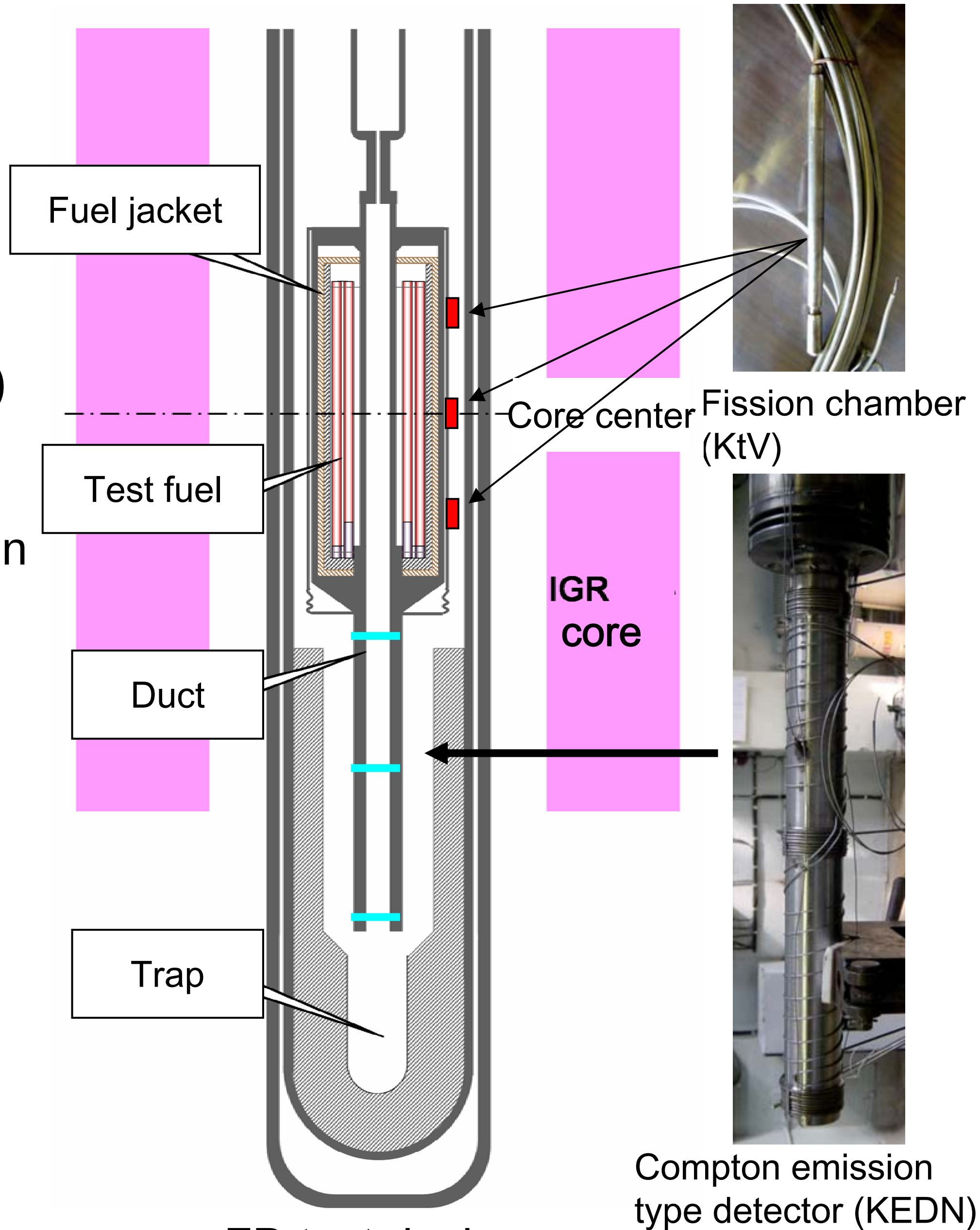
Objectives

- Confirm 8kg-scale fuel melting technique
  - Fission heating
  - Fuel motion measurement
- Discharge data (without sodium)
  - Energy release same as that of future ID test : simulating high power FA condition of the core in CDA condition.
  - Minimized pressure difference.
  - Comparison data for ID tests.

Tested fuel

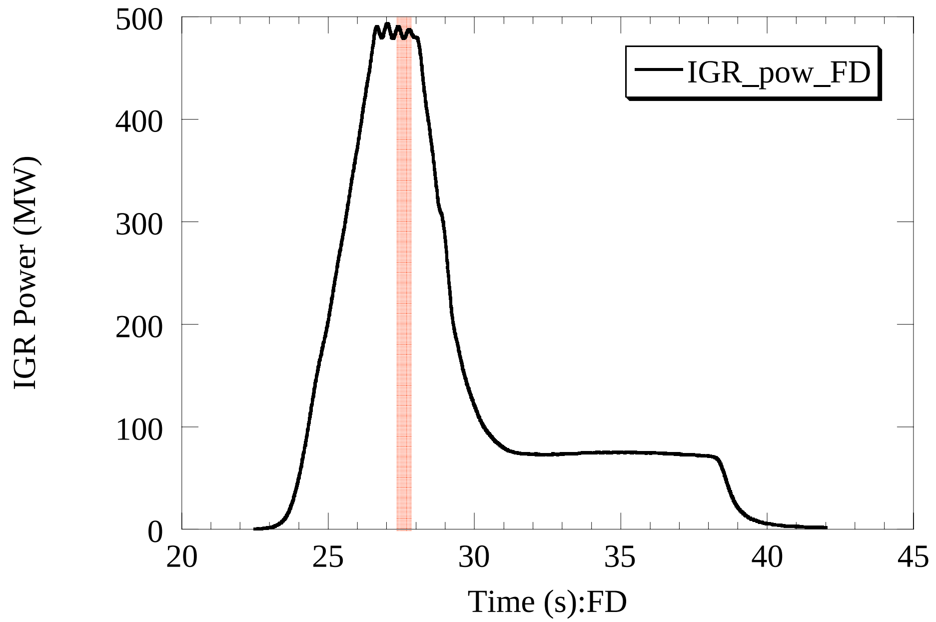
- BN-350 fuel pins
- 17% enriched UO_2

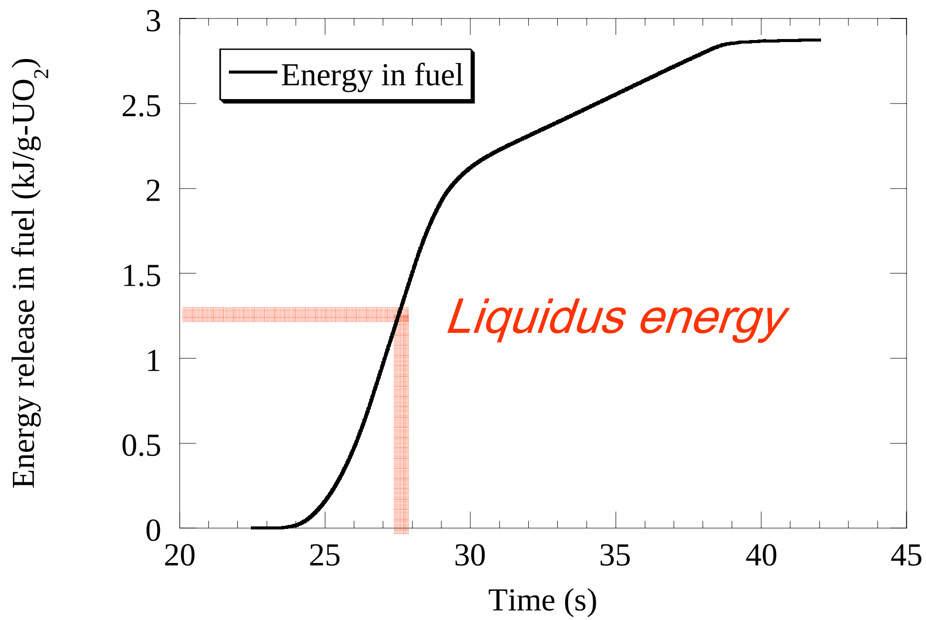
(Length: ~435mm, 75pins)



FD test device

Heating Condition





IGR power transient

Energy release in the test fuel (initial temperature: 400 deg.C)

Heating condition of FD test is similar to WF ones.

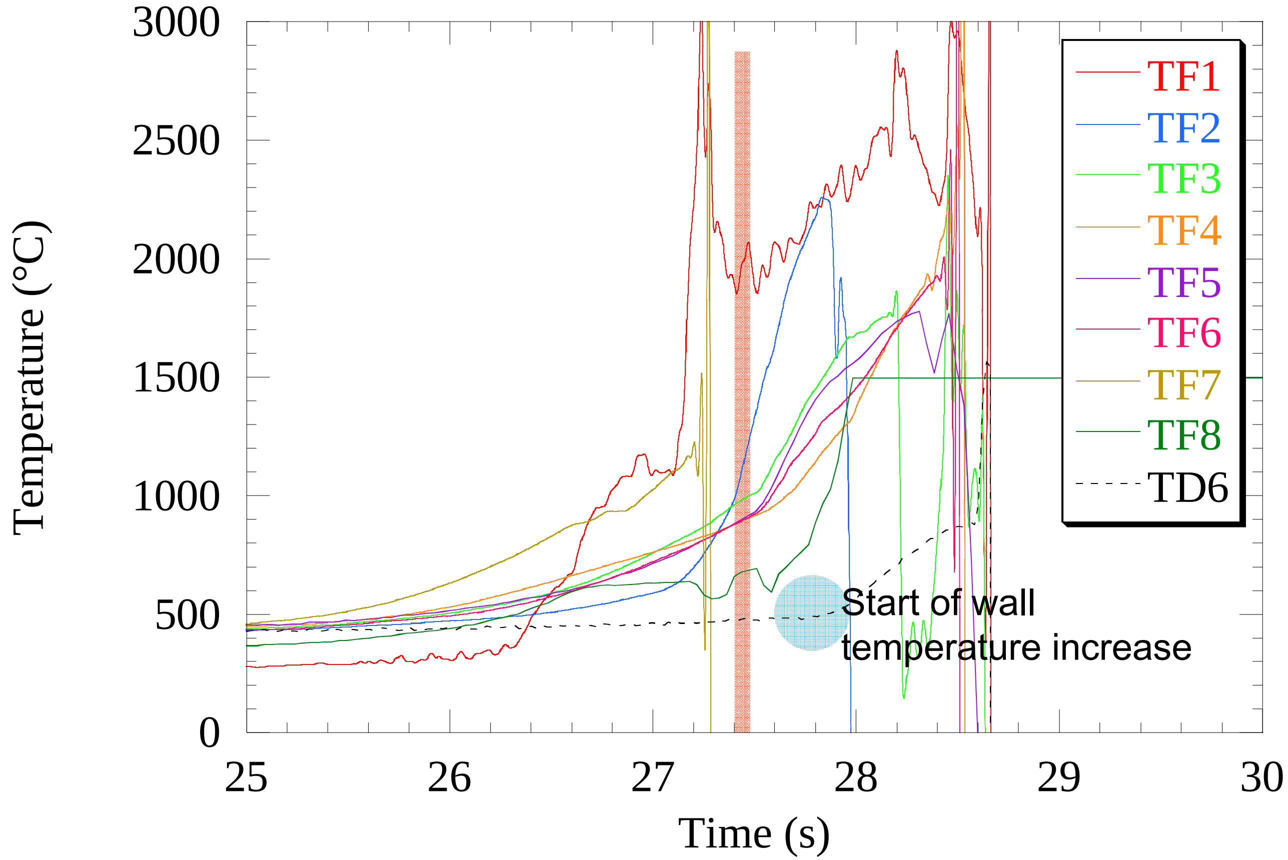
Results

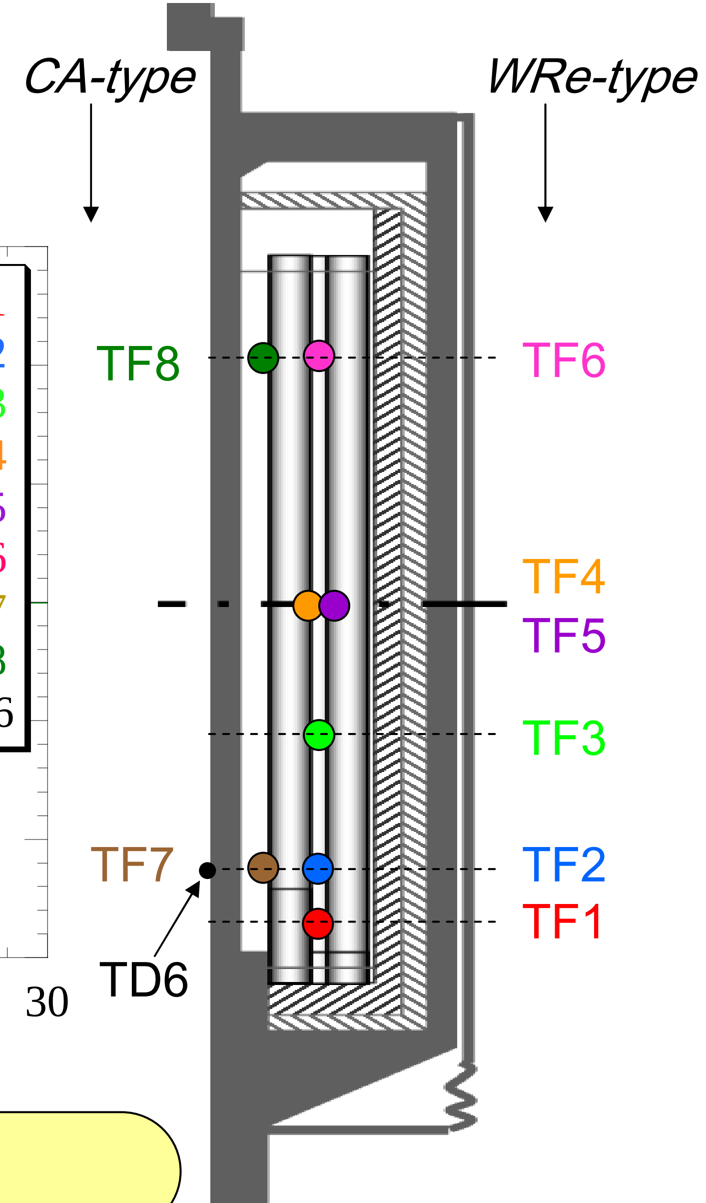
- Results of experiments FD and IDs are not published yet, only preliminary results therefore are below shown (the first presentation will be at Korea-Japan Symposium on Nov.26-29, announcement at URL; http://home.kaeri.re.kr/nthas5).

Melting of the Test Fuel

- As strong suggestion of fuel melting in the fuel jacket, the temperature of inner-duct wall started to increase continuously at ~27.8s. This timing was roughly coincided with the time at which the liquidus condition of UO2 was reached in the estimated energy insertion.

Melting of the Test Fuel



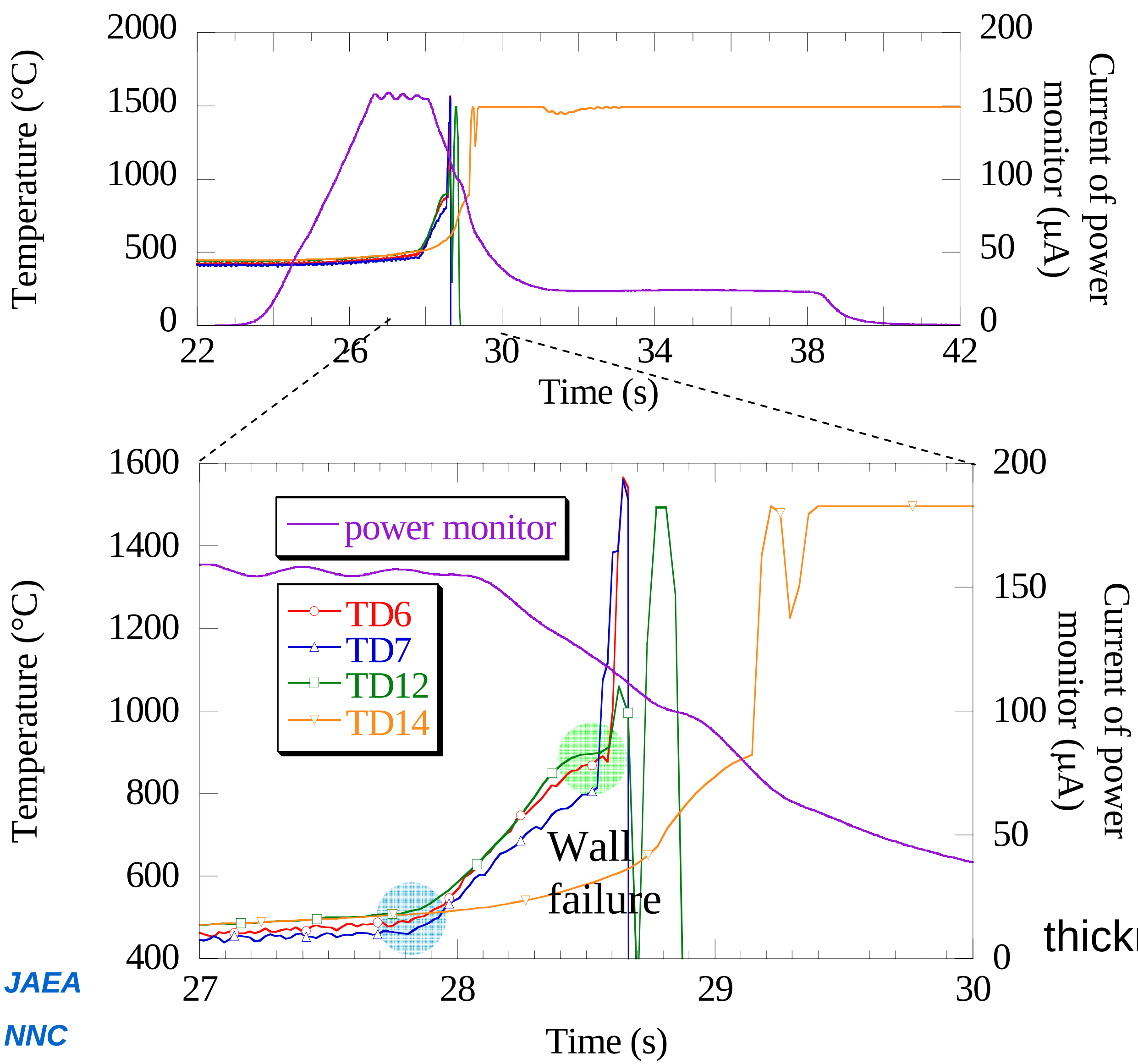


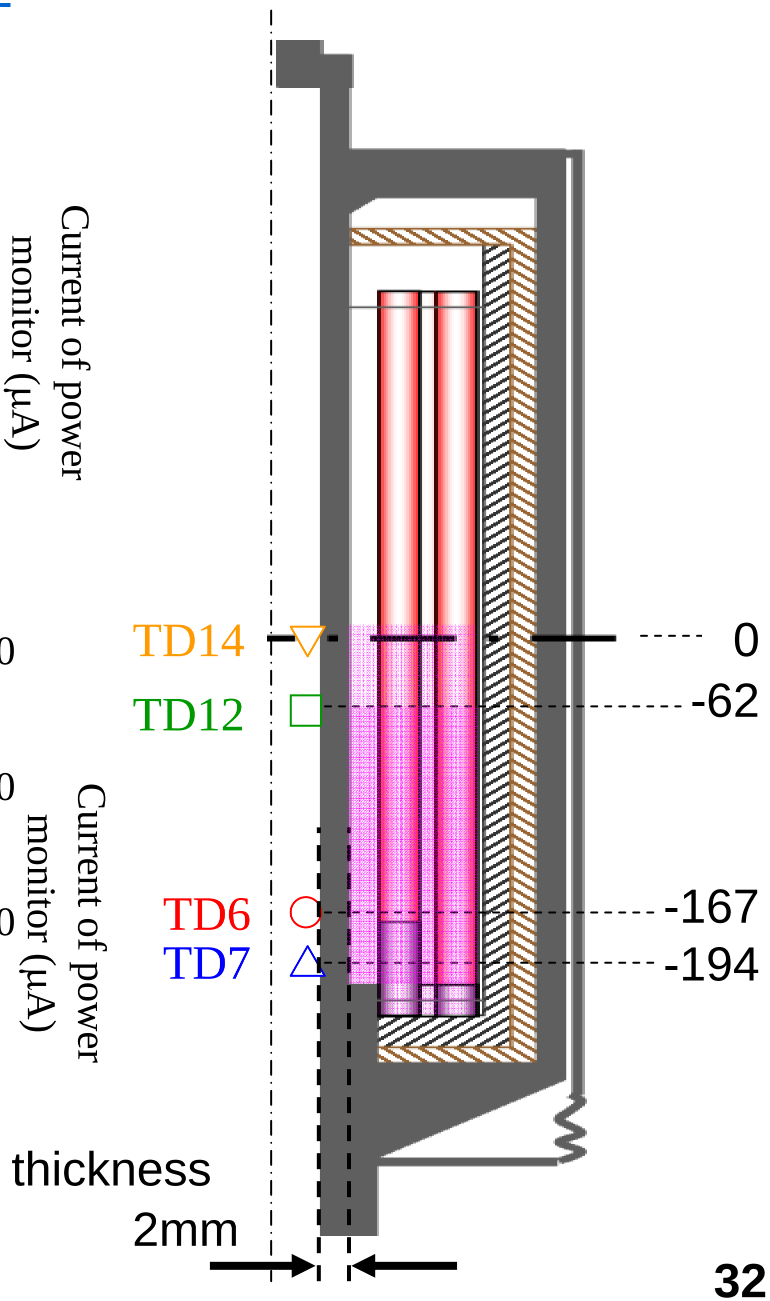
Melting occurred near the target timing

Duct Wall Failure

- Temperature increasing rate at TD6 and TD7 positions (inner surface of the duct wall) in 27.8~28.5s suggested that there was about 10MW/m2 of high heat flux from the molten-fuel pool to the wall. After this temperature increase, very high temperature over the melting point of SS (~1400°C) was measured and failure of the thermocouples occurred. Therefore, it was estimated that the wall failure occurred at 28.5s that was ~0.7s after the beginning of probable molten pool-wall heat transfer.

Duct Wall Failure





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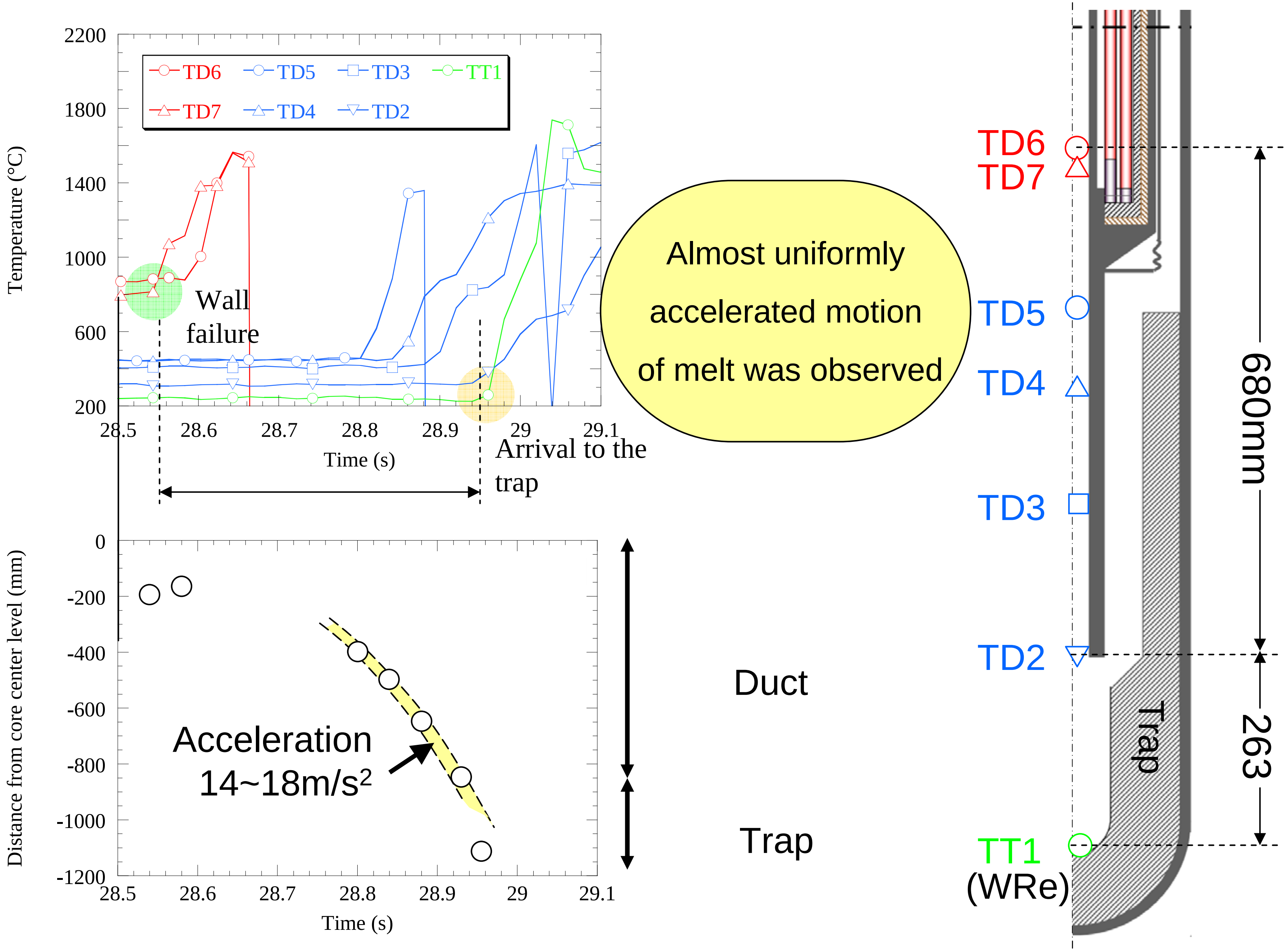
Melt Discharge through the Duct (Movement of the Tip)

- Sudden temperature rise up to over 1400°C measured at each position suggests molten fuel contact with the hot-junction of thermocouple (their tips of hot junctions have been put 5mm inside the duct). Based on this, we could roughly estimate a leading-edge velocity in the duct as 3.5m/s (average in the duct) and an acceleration as 14~18m/s2 exceeding the gravitational constant. The pressure difference between fuel jacket and trap area at the time of duct-wall failure was 0.025MPa in the FD test. It was understood that such a small pressure difference was enough to conquer the drag force with the help of gravity.

Melt discharge through the duct (movement of the tip)



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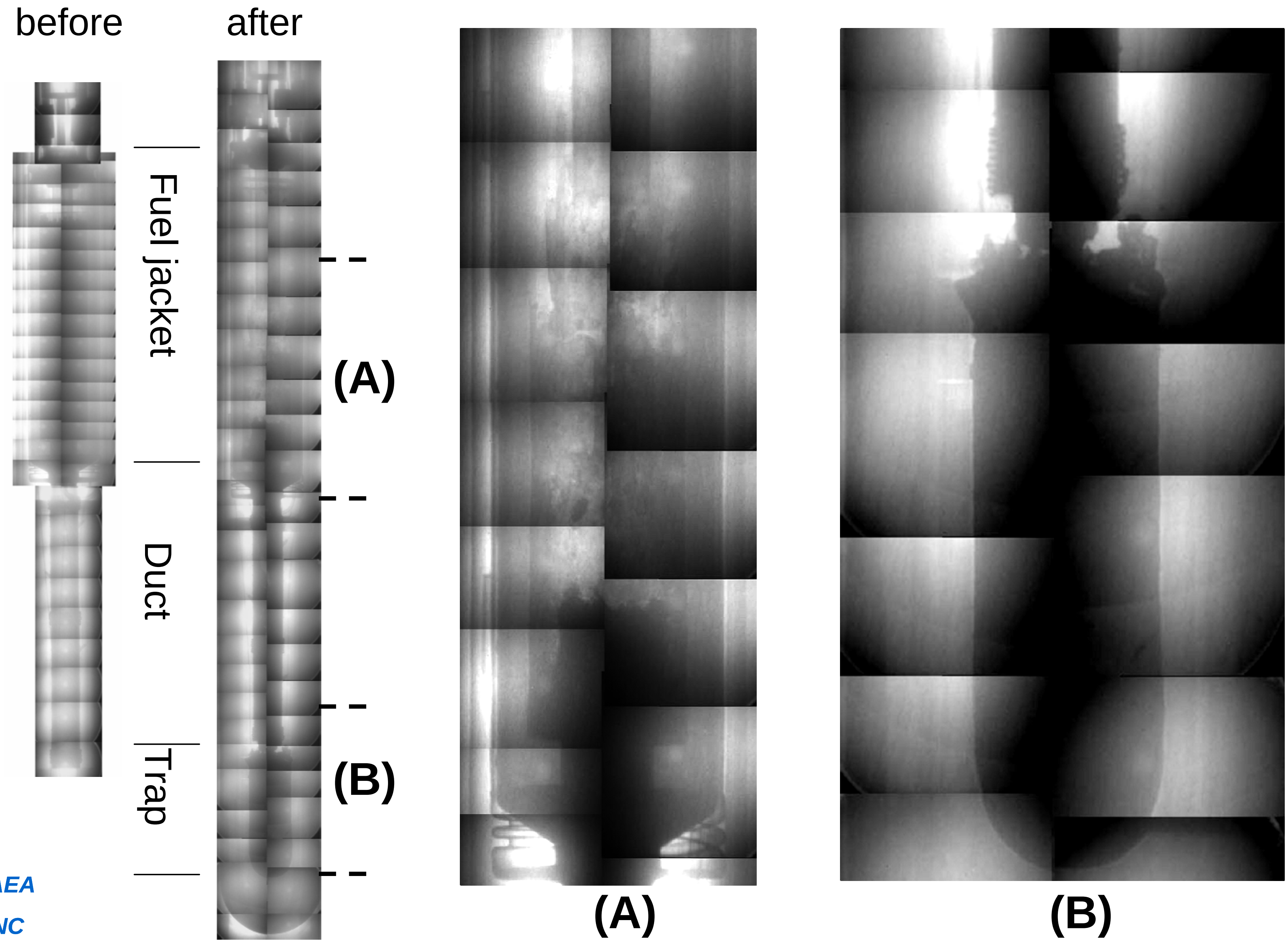
X-ray Observation Results

- The resulted material distribution after the test and discharged mass into the trap will be clarified in the planned destructive investigations, though, X-ray translucent photograph after the test has shown that the main part of the molten material (except for a small amount of solidified crust in the bottom part of the jacket) escaped out from the fuel jacket and certain amount of that accumulated inside the trap.

X-ray Observation Results



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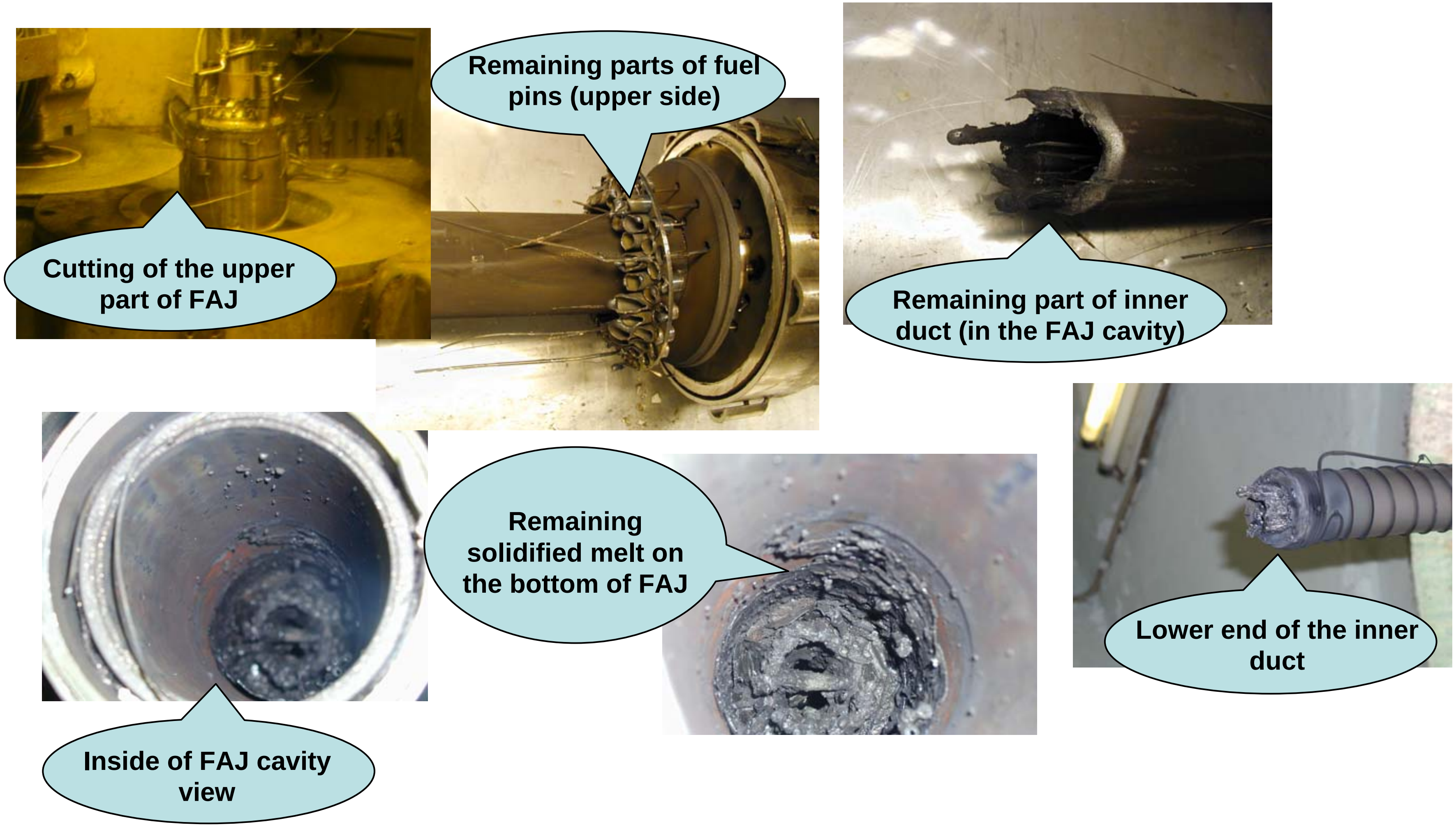
PTE of Fuel Assembly Jacket of FD Device



There is almost no fuel inside FAJ cavity of FD device.

Summary

- The conduction of EAGLE in-pile tests made great progress on the experimental techniques which include power control with large amount of mobile molten fuel, application a lot of measurement means for control and registration of test parameters, safety treatment of sodium and so on
- These experiments show that there is possibility of the conduction of new tests with the purpose to study of Core Damage Accidents, for example, to study of the melt fuel-structure materials interaction.
- In the IGR reactor it is possible to melt the fuel, transfer the melt into the trap, where the residual energy can be imitated.
- The trap can be made of investigated structure materials - for example, made of the steel of the vessel or of the concrete of the core-catcher. It will be possible to study the interaction in the condition of the residual energy influence.
- It possible to carry out the post-test examination (PTE) with study of the next structure materials parameters: phase composition and its modification; lattice parameters; structure (by optical method); elemental composition; hardness; density

Summary

- One of the possible application of in-pile experiment is the investigation of lower head (of RPV) cooling under the severe accident condition with core melting. Because of necessity to discuss of such experiments planning details it is reasonable to carry out the possible Project into two stages:

- First - “Planning of the in-pile test to study of the melted corium-construction materials interaction in the condition of the residual energy influence” (Results – clarification of the objective through the calculation pre-analysis, design of the experimental equipment, description of the main technologies of preparation and conduction of the test, time schedule. Cost – 70 000…100 000 US dollars. Timing of orders – nine month …one year).

- Second – “Manufacturing of the experimental device and equipments. Necessary preparation test conduction. Main tests preparation and conduction. Results analysis” (conditional title). Preliminary estimated cost (based on the experience of the EAGLE Project) is 500 000US dollars (should be discussed). Timing of orders – twenty four month (should be discussed).

- Possible collaborator – was not discussed.