Scoping Analysis on Energy Release and Core Explosion in CDA of PGSFR using CDA-ER and CDA-CEME Codes

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1. Introduction

❑ By French Institute for Radiological protection and Nuclear Safety (IRSN), the severe accident refers to an event causing significant damage to reactor fuel and resulting from more or less complete core meltdown [1].

❑ In general, the severe accident is classified by three phases.

Initiation (Pre-disassembly) Phase	- Gradual core meltdown - By the point of neutronic shutdown with an intact geometry
Transition Phase	- Fuel transition from solid to liquid phase - Fuel and clad melt to form a molten pool - Core can boil and recriticality conditions can occur
Disassembly Phase (CDA)	- Power excursion is followed until the core is disassembled - Conversion of excursion energy to work done on reactor vessel

❑ Whether CDA are potentially real events that must be considered in establishing design bases for the containment, very low probability events that can be eliminated from design basis considerations, or mechanistically unrealistic fantasies of creative analysts has been hotly debated. The answer may be design dependent [2].

❑ A numerical analysis is conducted to estimate the energy release and core expansion behavior induced by CDA in Prototype Gen-IV SFR (PGSFR). An analysis of the CDA energy release based on the Bethe-Tait method [3] is carried out and its results are used as the initial conditions for the core explosion computations.

2. Modeling for Analyzing CDA of PGSFR

❑ Calculations have been performed for analyzing CDA of PGSFR which is a 150 MWe pool type SFR and use metallic fuel, U-10Zr. The PGSFR core is designed to generate 392.1 MWth of power as shown in Fig. 1.

❑ Table I shows the calculation parameters used in the scoping analysis about CDA of PGSFR and reactor core characteristic.

❑ Fig. 2 shows the CDA scenario.

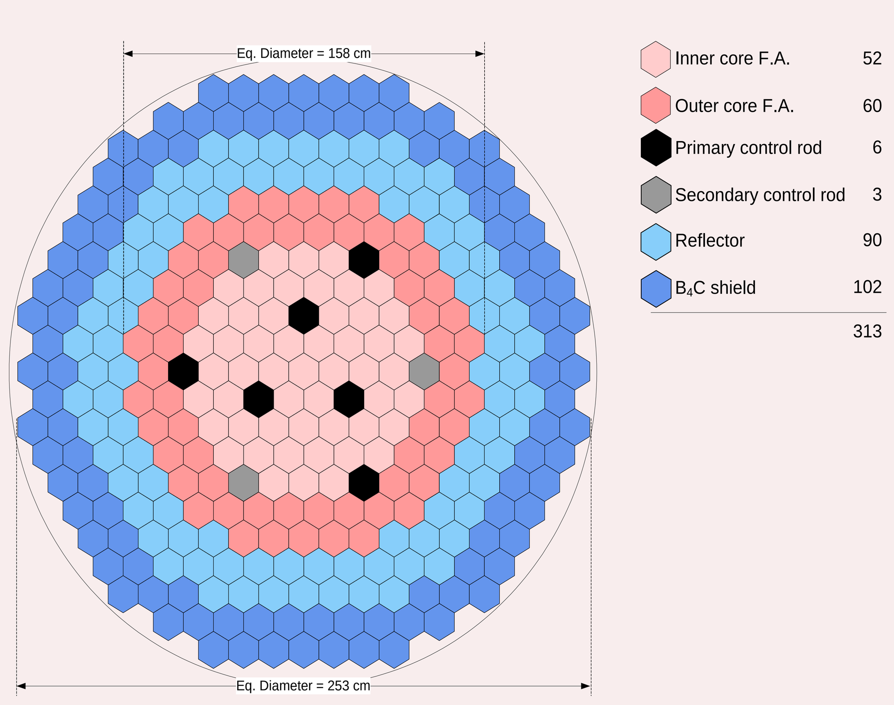

Fig. 1. Core configuration of PGSFR.

Table I. Calculation Parameters and Core Characteristic

Net plant power	150 MWe / 392.1 MWth
Net plant efficiency	38.25 %
Specific power of fuel	52,012.65 W/kg
Enrichment	19.2 %
Reactor type	Pool
Core configuration	Radially heterogeneous
Active core height	900 mm
Core diameter	2,530 mm
Assembly pitch	136.36 mm
Fuel form	U-10Zr
Fuel pins per assembly	217
Inlet / Outlet temperature	390 / 545 °C
Fuel burnup	66.1 GWd/MT (74.2 / 57.2)
Neutron lifetime	$3.29 \cdot 10^{-7}$ s
Delayed neutron fraction	0.0067
Fuel mass	7,538.55 kg
Density of solid fuel	15,900 kg/m^3
Radius of spherical core	0.79 m
Vessel Radius	4.277 m

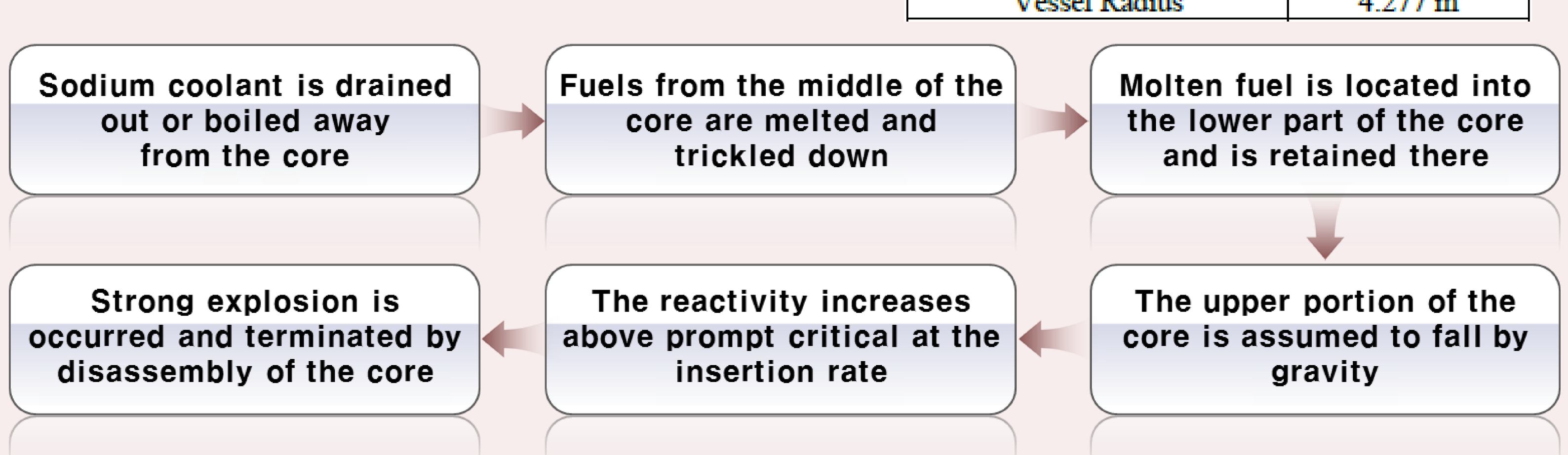

Fig. 2. CDA scenario.

❑ Table II shows molten fuel mass, reactivity insertion, reactivity insertion rate and delayed neutron fraction in each accident conditions. The reactivity insertion rate is calculated using the height and time from active fuel region to lower part of the core as shown in Fig. 3.

❑ The reactivity insertion and time that the upper portion of the core is assumed to fall by gravity are calculated conservatively. So, the calculated reactivity insertion rate is conservative. Also, the delayed neutron fraction is used conservatively.

Table II. Molten Fuel Mass, Reactivity Insertion, Reactivity Insertion Rate and Delayed Neutron Fraction in Each Accident Conditions

	Inner core (52/52)	Inner core (52/52) + Outer core (30/60)	Whole core (52/52 + 60/60)
Molten fuel mass (kg)	3500.04	5519.30	7538.55
Reactivity insertion ($)	29.18 ±0.45 (29.63*)	35.64 ±0.47 (36.11*)	39.25 ±0.47 (39.72*)
Reactivity insertion rate ($/s)	63.43	77.30	85.03
Delayed neutron fraction	0.00713 ±0.00011 (0.00702*)	0.00716 ±0.00013 (0.00703*)	0.00695 ±0.00013 (0.00682*)

* : the conservative value

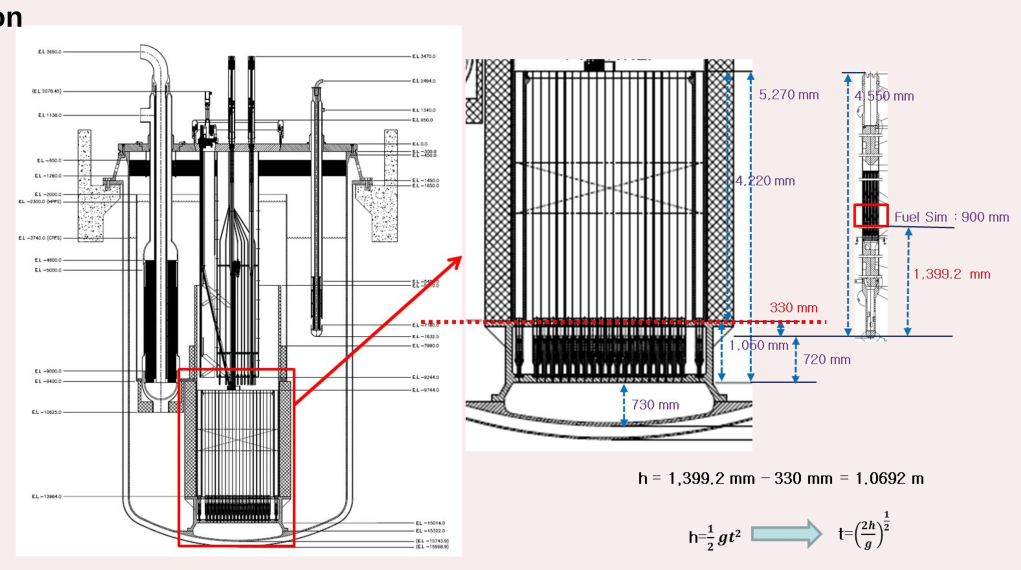

Fig. 3. Height and time from active fuel region to lower part of the core.

3. Analysis Results

❑ Energy Release and Pressure Behavior using CDA-ER Code

- A numerical analysis was conducted to estimate the energy release and pressure behavior induced by CDA in PGSFR. A numerical code, CDA-Energy Release (ER), which is based on the Bethe-Tait method was developed to calculate the energy release and pressure during CDA. The influences of Doppler effect on the power excursions were also estimated.

- Fig. 4 shows the calculated results of energy release and pressure behavior induced by CDA with Doppler effect in PGSFR when whole cores were melted (100 $/s). The analyzed maximum energy release and pressure were 6.65 GJ and 3.39 GPa, respectively. When Doppler effect is considered in this situation, 14.74 % of the maximum energy release and 29.23 % of the maximum pressure are decreased.

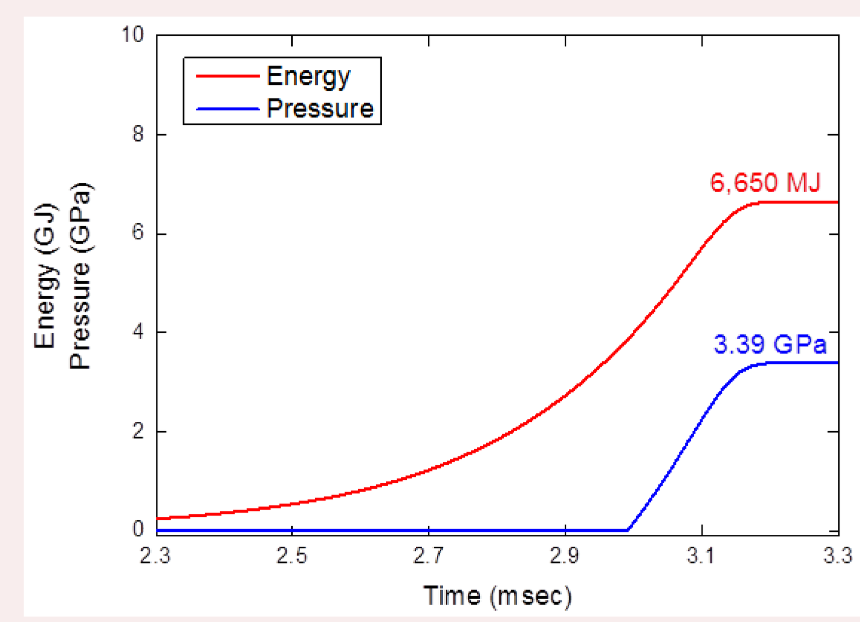

Fig. 4. Energy release and pressure behavior induced by CDA with Doppler effect in PGSFR when whole cores were melted (conservatively 100 $/s).

❑ Mechanical Energy using CDA-CEME Code

- Hydrodynamic and thermodynamic computations are performed using the code developed, CDA-Core Explosion Mechanical Energy (CEME) in this work for the simulated CDA's condition.

- Fig. 5 shows the calculated results of the energy distributions during 0.015 seconds after the explosion with Doppler effect in PGSFR when whole cores were melted (100 $/s). The total energy is calculated to be 1.31 GJ. At 0.01 s, the kinetic energy of the sodium is 1.29 GJ, while the expansion work and internal energy of the bubble are 15.9 MJ and 2.10 J, respectively.

- Fig. 6 show the expansion work in PGSFR according to the degree of core melting. The more the degree of core melting is, the larger the expansion work are when Doppler effect is considered.

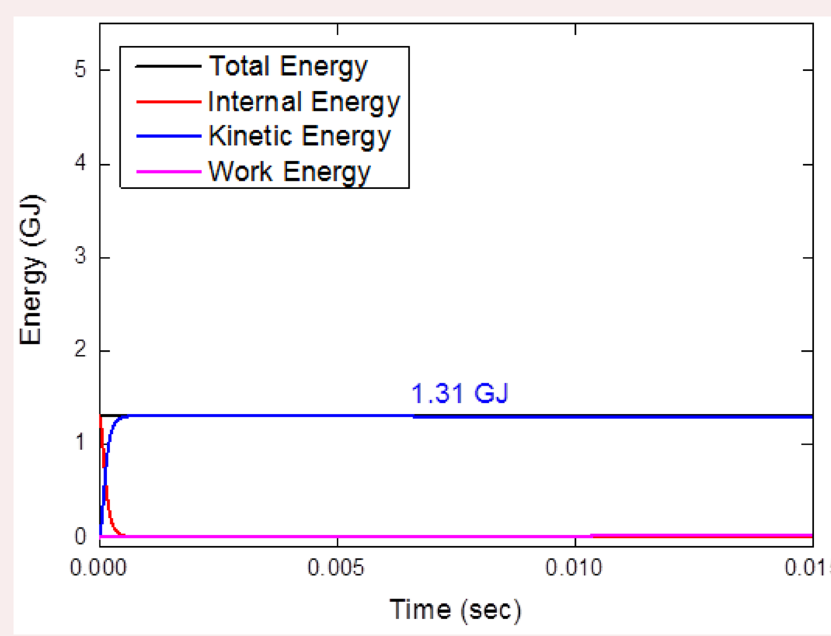

Fig. 5. Energy distributions during 0.015 seconds after the explosion with Doppler effect in PGSFR when whole cores were melted (conservatively 100 $/s).

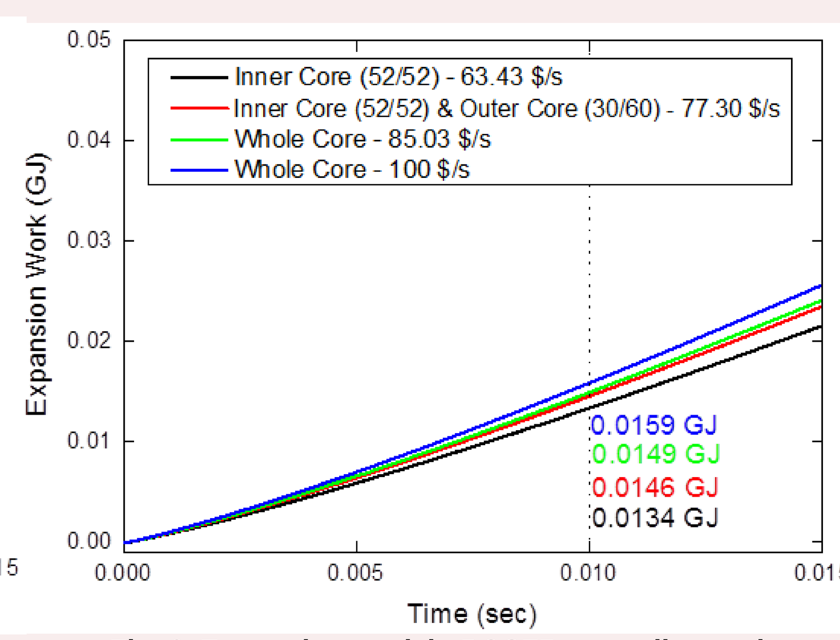

Fig. 6. Expansion work in PGSFR according to the degree of core melting with Doppler effect.

4. Conclusions

❑ A numerical analysis is conducted to estimate the energy release, pressure behavior and core expansion behavior induced by CDA of PGSFR using CDA-ER and CDA-CEME codes.

❑ Conservatively, the calculated results of energy release and pressure behavior induced by CDA without Doppler effect in PGSFR when whole cores were melted (100 $/s) were 7.80 GJ and 4.79 GPa, respectively. With Doppler effect, the analyzed maximum energy release and pressure were 6.65 GJ and 3.39 GPa, respectively.

❑ The calculated results of the core expansion behavior during 0.015 seconds after the explosion without Doppler effect in PGSFR when whole cores were melted (100 $/s) were as follows: The total energy is calculated to be 1.85 GJ. At 0.01 s, the kinetic energy of the sodium is 1.83 GJ, while the expansion work and internal energy of the bubble are 19.5 MJ and 1.01 J, respectively. With Doppler effect, the total energy is calculated to be 1.31 GJ. At 0.01 s, the kinetic energy of the sodium is 1.29 GJ, while the expansion work and internal energy of the bubble are 15.9 MJ and 2.10 J, respectively.

❑ Though this scoping analysis is calculated to very conservative method and has a large difference from the point of view of a practical approach, it seems to give basic insight into the worst case in CDA of PGSFR.

REFERENCES

[1] IRSN-2007/83, Research and Development with regard to Severe Accidents in Pressurised Water Reactors: Summary and Outlook, 2007.

[2] A. J. Brunett, A Methodology for Analyzing the Consequences of Accidents in Sodium-Cooled Fast Reactors, A Master's Thesis, The Ohio State University, 2010.

[3] H. A. Bethe, J. H. Tait, An Estimate of the Order of Magnitude of the Explosion when the Core of a Fast Reactor Collapses, UKAEA-RHM, Vol. 56, 1956.