Report to the Sasakawa Peace Foundation

Passive Safety Features and Severe Accident Scenarios of the small metal-fueled fast reactor system

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1. Estimate of passive reactivity shutdown

The capability of passive reactivity shutdown in response to ATWS events are estimated based on an equation of quasi-static reactivity balance taking into account favorable inherent reactivity feedback effects granted as privileges of small-scale metal-fueled fast reactors.

2. Assessment of Severe Accident (SA) scenarios

Typical SA scenarios are represented according to speculation based on available information about metallic fuel under SA conditions and experiences of CDA (Core Disruptive Accident) assessment of MOX fueled reactors.

3. Discussions

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Approach

- ✓ In order to enhance the safety on small-scale SFR(Sodium cooled Fast Reactor), inherent reactivity feedback effects privileged to reduce the power as the coolant temperature rises under the accident conditions should be utilized.
- ✓ The passive reactivity shutdown capability to prevent core damage in response to the following ATWS events has been estimated using the equation of quasi-static reactivity balance provided by Wade and Fujita, ANL[1].
  - ➢ ULOF：Unprotected loss of primary flow
  - ➢ UTOP：Unprotected control rods withdrawal
  - ➢ UTOP-ULOF：UTOP with pump trip caused by interlock sequence
  - ➢ ULOHS: Unprotected abnormality in secondary and BOP system

$$(P-1)A+(P/F-1)B+\delta T_{in}C+\Delta\rho_{ext}=0$$

P, F = normalized power and flow, respectively

δT_{in} = change from coolant inlet temperature in normal full-power state (℃)

$\Delta\rho_{ext}$ = externally imposed reactivity (¢)

A = net (power/flow) reactivity decrement (¢)

B = power/flow coefficient (¢ /100% power/flow)

C = inlet temperature coefficient of reactivity (¢ /℃)

[1] D.C.Wade and E.K.Fujita, “Trends vs. Size of Passive Reactivity Shut down and Control Performance,” NSE,103,PP182-195(1989)

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Methodology

- ✓ Taking into account reactivity effects driven by GEM activation for ULOF and limited by rod-stop for UTOP/UTOP-ULOF, outlet coolant temperature in an asymptotic state has been estimated for each event by following the equations below.
  - ➢ ULOF/UTOP-ULOF: $(A-\Delta\rho_{GEM}+\Delta\rho_{TOP})/B * \Delta Tc + Tout\_ini$
  - ➢ UTOP: $\Delta\rho_{TOP}/-C + Tout\_ini$
  - ➢ ULOHS: $(A+B)/C - \Delta Tc + Tout\_ini$

  $\Delta\rho_{GEM}$: Reactivity inserted by GEM activation (¢)
  $\Delta\rho_{TOP}$: Reactivity inserted by control rod withdrawal (¢)
  ΔTc : coolant temperature rise at normal full power operate state (℃)
  Tout_ini : outlet coolant temperature at normal full power operate state (℃)

- ✓ In order to estimate the capability of core damage prevention, the criteria has been tentatively assumed to be 650℃ where the integrity of metallic fuel and primary coolant boundary can be ensured even for relative long term.

Conditions for A, B and C

- ✓ Regarding fuel axial expansion reactivity coefficient (α_e) included in the term of A depending on whether fuel is free of the cladding (α_e goes in A) or is stuck to the cladding (α_e do not go in A), α_e is assumed so as to give conservative results.
  - ➢ For ULOF and ULOF-UTOP cases, α_e goes in A.
  - ➢ For UTOP and ULOHS cases, α_e does not go in A.
- ✓ Regarding radial expansion reactivity coefficient included in the term of B, those kinds of reactivity such as radial expansion and control rod driveline/reactor expansion are not taken into account at the current study because of projected large uncertainties and the difficulty of validation under various burnup conditions.

A(¢) = (Fuel Doppler + fuel axial expansion) × ΔTf
B(¢) = (Fuel Doppler + fuel axial expansion + sodium density in the core region + structure
+ 2 × (sodium density in the upper gas plenum region + ~~radial expansion~~))×ΔTc/2
C(¢ /℃) = Fuel Doppler + fuel axial expansion + sodium density in the core region + structure
+ sodium density in the upper gas plenum region + core support plate expansion
ΔTf (℃) : increment in average fuel temperature relative to average coolant temperature
ΔTc (℃) : coolant temperature rise at normal full power operate state

1. Estimate of passive reactivity shutdown Results

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Results

- The result suggests that to introduce both GEM and rod stop enables us to prevent core damage in response to the ATWS events.
  - ✓ Even if radial expansion reactivity is taken into account in the term of B, core is expected to be damaged without both of GEM and rod stop in the case of UTOP-ULOF. Therefore, design measures are needed to attain passive reactivity shutdown state.

CASE	Passive shutdown design measures	Asymptotic outlet temperature (℃)
ULOF	Only inherent core feature	670
	GEM: -27 ¢ (1 unit)	500
UTOP-ULOF	Rod stop :+25 ¢	820
	Rod stop :+25 ¢ GEM: -54 ¢ (2 units)	490
UTOP	Only inherent core feature Full one CR withdrawal: +250 ¢	990
	Rod stop :+25 ¢	560
ULOHS	Only inherent core feature	430

- **Design the core not leading to CDA when ATWS occurs by the passive safety feature of small metal fueled core**

Even though, CDA should be assumed for application for a license

How to select initiating event candidates to evaluate the CDA consequences

a. Assumption of Multiple-failure situation beyond ATWS
b. Over-estimate the uncertainty of physical phenomena in the evaluation ATWS sequence
c. Assuming CDA not to determine the initiating events

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◇ ULOF+ Loss of GEM negative reactivity function:

Based on “a. assumption of multiple-failure”

and moreover assuming over-estimate uncertainty based on “b.”

(The sudden loss of flow event (caused by sudden loss of all pumps driving force) without SCRAM that may be the most severe condition as ULOF is not selected, because EMPs would not be installed)

◇ UTOP +Loss of “Rod stop” limiting reactivity function:

Based on “a. assumption of multiple-failure”

◇ UTOP-ULOF +Loss of “Rod stop” limiting reactivity function and pump trip*:

Based on “a. assumption of multiple-failure”

* UTOP sequences are described as E/T in later slide

Evaluation of ULOF type event sequence

Assuming the loss of the GEM function and conservative reactivity

Event 1 Fuel cladding failure occurs one after another in several hours because of long-term high temperature condition

Event 2 Gradual eutectic reaction between fuel and cladding leads to core melt-down without power burst (negative void reactivity)

This is one of the typical event sequences of small metal-fueled CDA

Gradual meltdown after settling at high temperature

The possibility of the large mechanical energy generation would be very small because of the small reactivity insertion rate

Event 3 Molten fuel moves down from the core region along with the eutectic reaction proceeding

Event 4 Fuel retention by the core catcher and PAHR (IVR) success

Some CDA sequences of UTOP described in the following Event-Tree as shutdown failure type after SCRAM signal for abnormal power increasing

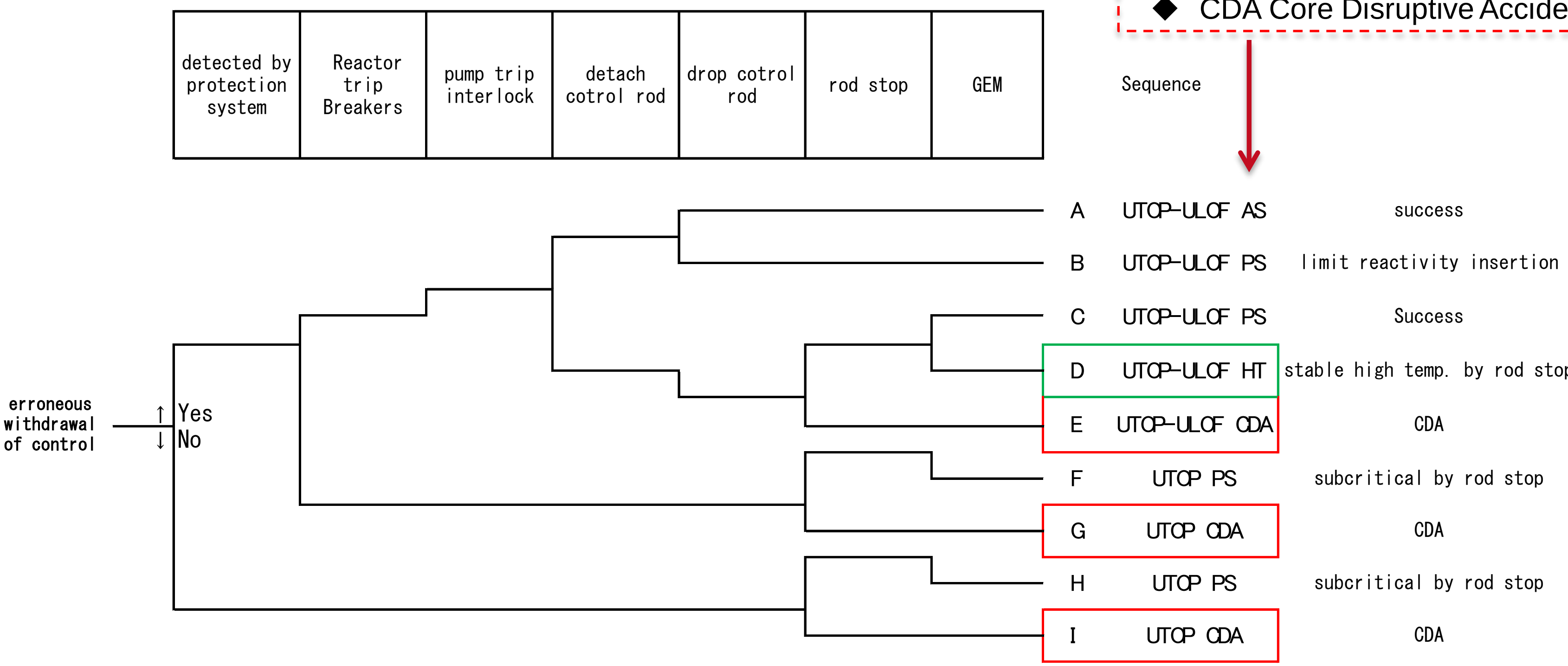
Seq.D Gradual meltdown after settling at high temperature (similar to the ULOF type sequence)

Max temp. 820°C based on the estimate with quasi-static reactivity balance as described previously

Seq.E,G,I CDA

Especially, Seq. E UTOP-ULOF type CDA

- AS SCRAM
- PS Shutdown by safety features
- HT Stable high temperature
- CDA Core Disruptive Accident



Typical event sequence of CDA in small metal-fueled core

UTOP-ULOF or UTOP type

Event 1 Fuel and cladding temperature increase (power increase/loss of flow)

Event 2 Fuel melt (maintaining cladding integrity)

Fuel melting starts at the top of the core region in case of reactivity insertion rates of control rod withdrawal.

Event 3 Extrusion phenomena (leading to negative reactivity feedback specific to metal-fuel)

Event 4 Cladding failure

Event 5 Molten fuel release into the coolant channel and upward fuel dispersion from the core region

! Coolability of intact fuel pins could be maintained if molten fuel was released into the upper plenum.

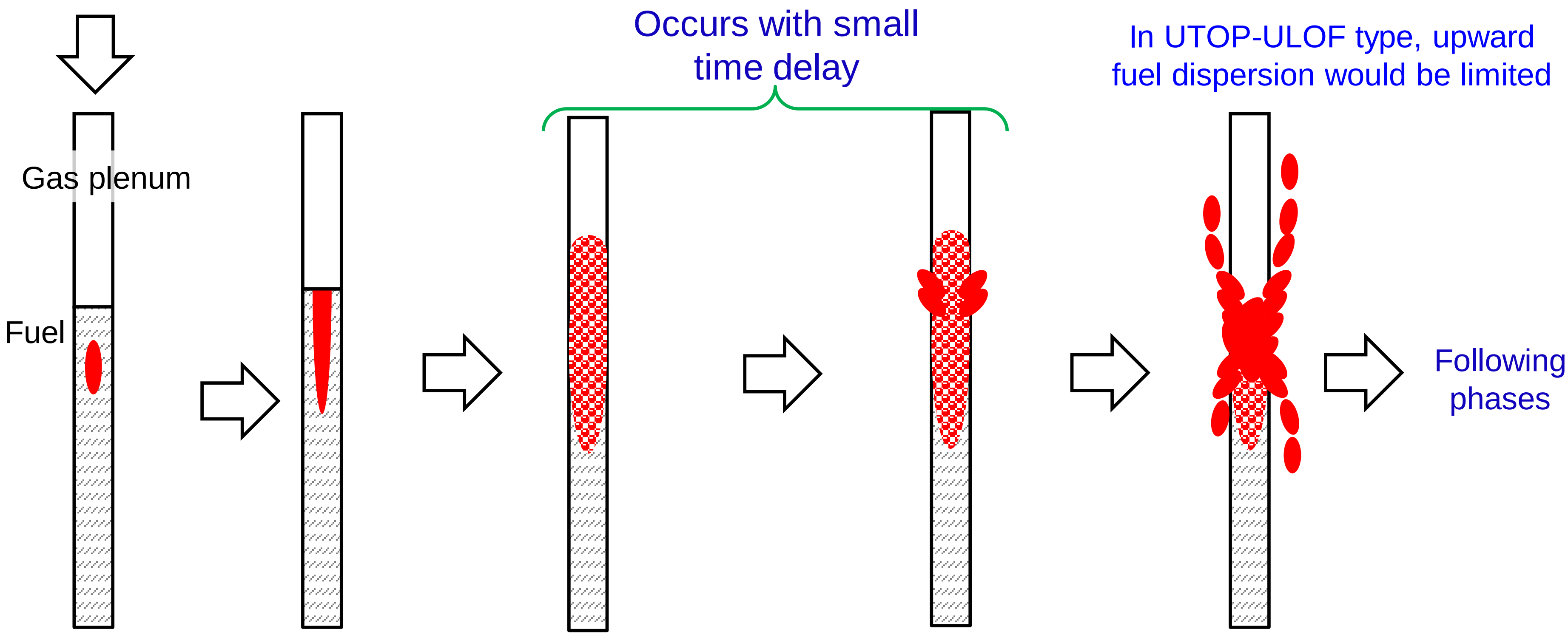
! Coolability depends on the blockage rate if molten fuel froze in the pin bundle at the upper core region .

Event 6 Subcritical core state resulting from the negative reactivity insertion due to extrusion and fuel dispersion overcoming the reactivity insertion caused by control rod withdrawal

Event 7 Post accident heat removal phase and in-vessel retention (PAHR)

2. SA scenarios Typical event sequences (2/4)

Event 1 **UTOP or UTOP-ULOF initiating event**



Fuel melt

Extension of molten fuel region

Event2

Extrusion Negative reactivity effect

Event3

Cladding failure and FP gas release

reactivity due to core voiding is small

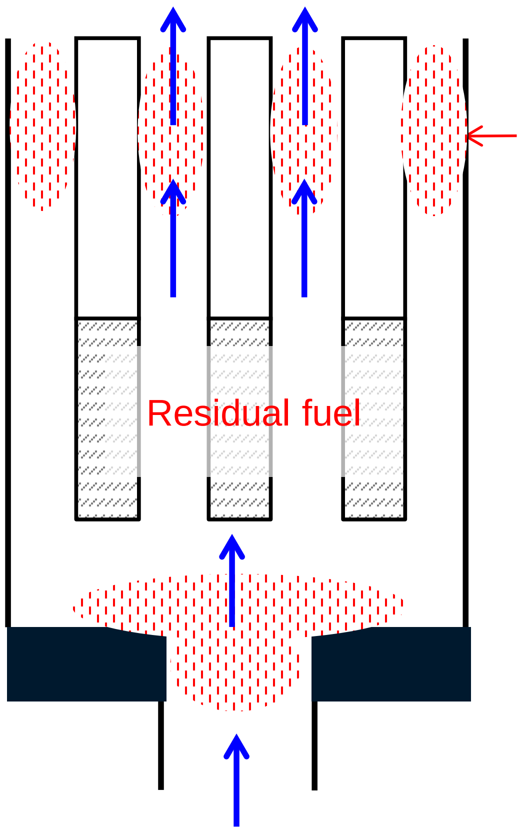
Event4

Molten fuel dispersion from core region

Neutronic shutdown by large negative reactivity

Event5

Event6

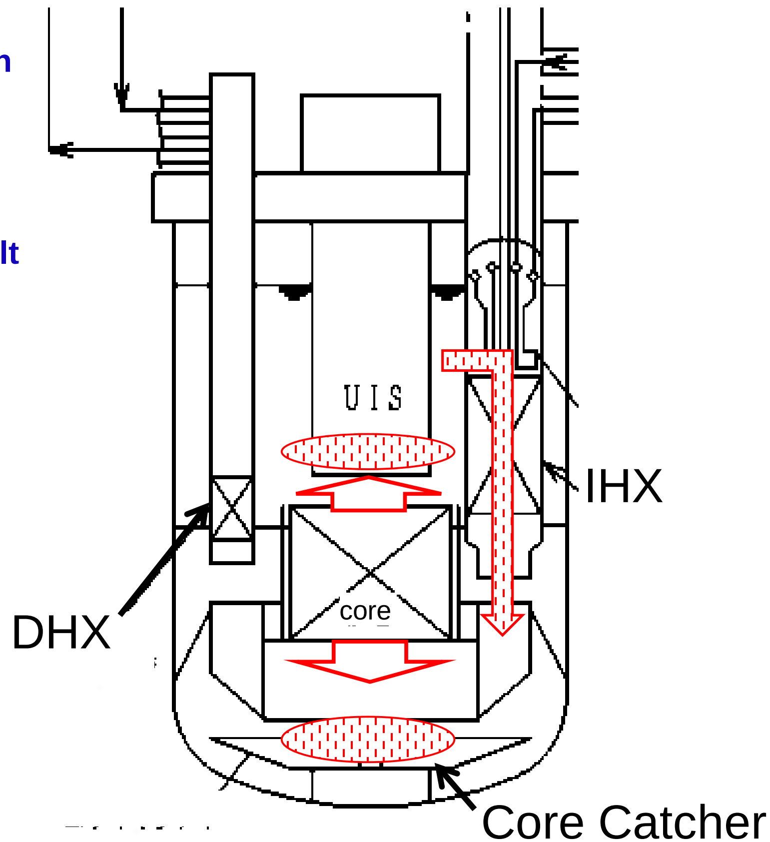


Coolant flow into assembly to cool the residual fuel

The coolability would be maintained if freezing fuel become porous debris with the large porosity.

If not,

The residual fuel would melt or the liquid eutectic compound of fuel and cladding would gradually move downward.



IVR ensured by cooling fuel relocated onto the core-catcher and the in-vessel structures

Event 7

2. SA scenarios Typical event sequences (4/4)

Uncertainty is large of the previous evaluation about event sequences especially after cladding failure.

Experimental information on the behavior of molten fuel motion after fuel release into the coolant flow path as plant scale with pin-bundle geometry is needed.

- **Formation and coolability of frozen fuel in the upper gas plenum region**
- **Possibility of fuel dispersion into the upper plenum (UTOP and UTOP-ULOF)**
- **Fuel behavior (coolability) after release into the upper plenum**
- **Fuel coolability after moving to the lower fuel assembly region**
- **Transfer of fuel to the core catcher**

Possibility of re-criticality(large energy release) during typical event sequence process

- **Molten fuel freezes and stops in the pin-bundle at the upper core region in UTOP/UTOP-ULOF**

→ Positive reactivity insertion due to fuel motion toward the center of the core

Reactivity insertion rate is small as long as molten fuel movement toward center of core is incoherent

- **Gradual meltdown after settling at high temperature (long term cooling failure in ULOF or UTOP/UTOP-ULOF)**

Fuel melting or eutectic reaction continues in the core at low power level

→ Positive reactivity insertion by fuel liquefaction and meltdown

Reactivity insertion rate is small because of no pressure source that can drive molten fuel

Possibility of Prompt critical/large mechanical energy release is small

Post accident heat removal (in-vessel retention is necessary)

CDA analysis for metal-fueled core

To perform calculations with analysis tools is necessary to clarify the CDA sequences because the spectrum of CDA event sequences is very wide.

- Evaluation taking into account the incoherency of molten fuel movement in UTOP or UTOP-ULOF is essential.
  SAS4A by ANL or CANIS by CRIEPI are the candidates.

- **Gradual meltdown after settling at high temperature**
  Calculation model of eutectic reaction is necessary

Evaluation assuming the prompt criticality

Was it a request of NRC in PRISM licensing?

Thanks to smaller reactor power, prospects may be favorable.

3. Discussions

1. Application of the simplified evaluation method

Dr. Wade et al. proposed an evaluation method*1 based on the balance of reactivity feedbacks under the ATWS events. It is a convenient method for a plant of preliminary design stage. The result heavily depends on the negative reactivity effects to take into account.

*1 D.C.Wade and E.K.Fujita,"Trends vs. Size of Passive Reactivity Shut down and Control Performance," NSE,103,PP182-195(1989)

1.1 ULOF response

We would like to ask your comments on the trustworthiness of some reactivity effects.

Radial expansion reactivity coefficient: The bowing effect due to burnup or thermal effect is difficult to evaluate, especially in our country where requirement to core clamping is strict in order to cope with earthquakes. Do you have prospect of taking credit of it in a licensing by analysis?

GEM(Gas Expansion Module): We think GEM is a very good feature of the passive safety although it works only against ULOF type. Our question is whether you are aware of noted drawbacks of GEM or not.

1.2 UTOP response

The UTOP type events due to mal-function of control rod drive system tend to become crucial for a small metal-fueled core. The devices for limiting amount of control rod withdrawal are needed to attain the passive safety for such events. The same kind of device, rod stop, is adopted in PRISM and a sketch is shown in NUREG-1368.

Our concerns about the rod stop mechanism are:

- Resetting of the rod stop mechanism is inevitable during reactor operation. Isn't it troublesome?
- Is it dependable? Safety grade reliability can be assured or not including the human-reliability issues.

We are aware of several papers by Argonne staff that recommend power control by coolant temperature, not using the control rods. Are there any reactors which use such a system? What are the possible drawbacks of such a method?

3. Discussions

1.3 ULOHS response

Passive shutdown is easily attained on ULOHS mainly due to negative feedback effect of the radial expansion of the core support plate. We assume that the expansion of the core support plate is more dependable than the radial expansion because the bowing behavior of subassemblies is not involved. We would like to have your comments.

1.4 Question about the method by Dr. Wade et al.

There is a criteria related to the coast down time of primary coolant pump. According to the previously referred NSE paper in page 192,

$\tau\lambda(1+A/B)^2|B| \geqq 1\$$,

τ : time constant of primary coolant flow,

λ : inverse of time constant of power reduction due to the delayed neutron source.

If we use an average of delayed neutron time constant for λ, which is (inverse of) a few seconds, the acceptable τ value tends to become the order of seconds, which seems quite optimistic judging from the experiences of evaluation using plant dynamics codes.

In page 192 of the NSE paper above, there is a footnote that recommends 12 s^{-1} for λ. Could you please show us the background of the value?

2. TREAT M-Series Tests

It is obviously a very valuable source of the knowledge about the metallic fuel under accident condition. We have the following questions.

We are interested in the scenario related to the molten fuel ejected in the coolant channel due to cladding failure under over-power situation. If the test results show that ejected fuel is swept out of the coolant channel, coolability of remaining fuel is almost assured. We would like to hear your understanding about the issue. Possible discussions are:

(1) Final destination of ejected fuel in the M-Series tests. Does it swept out or stays at the gas plenum part of the pin?

(2) Prototypically of the M-Series test channel: coolant channel around a pin, large structure wall to pin perimeter ratio, no spacer wire for the tests M5-M7 as shown in FIg.1[*2]. The length of the part above the core is rather short as shown in Fig.2.

[*2] T.H.Bauer, et al., “Behavior of Modern Metallic Fuel in TREAT Transient Overpower Tests” Nucl. Tech., #92,p325(1990)

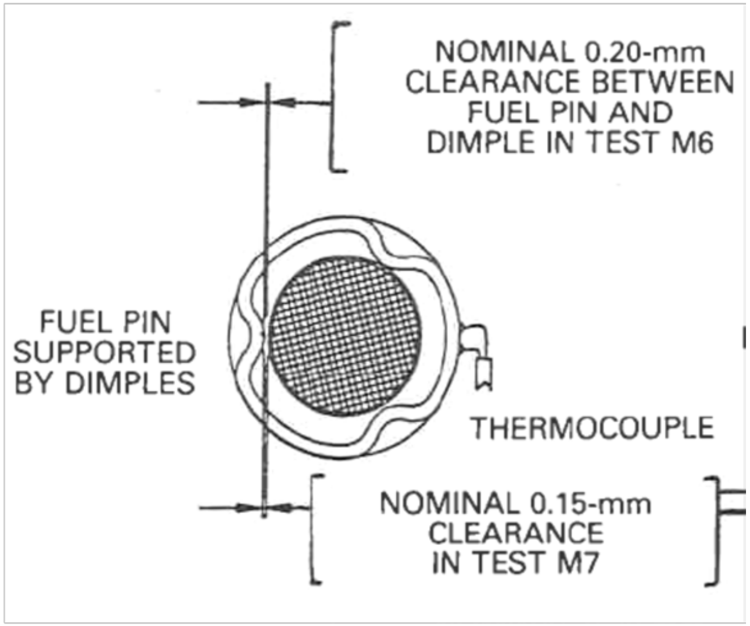


Fig.1[*2]

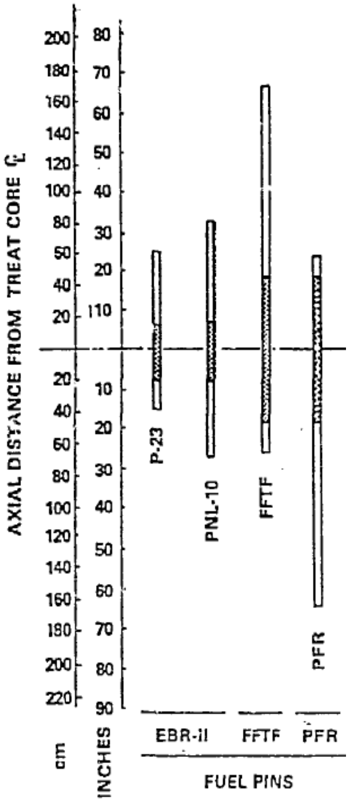


Fig.2[*2]

(3) What form is the debris solidified in the coolant channel? We do not aware of the destructive PTE result of the M-Series test section. It is reported, as the result of out-of-pile tests[*2], that the molten metal fuel forms very porous debris bed in a sodium pool. Is it similar or there is marked difference in the TREAT tests?

(4) Effect of TREAT transients in power and coolant flow (trip sequence).

[*3] J.D.Gabor, et al., “Breakup and Quench of Molten Metal Fuel in Sodium,”Proc. of International Topical Mtg. on Next Generation Power Reactors, Seattle, pp838-843 (1988).

3. Long term coolability issues

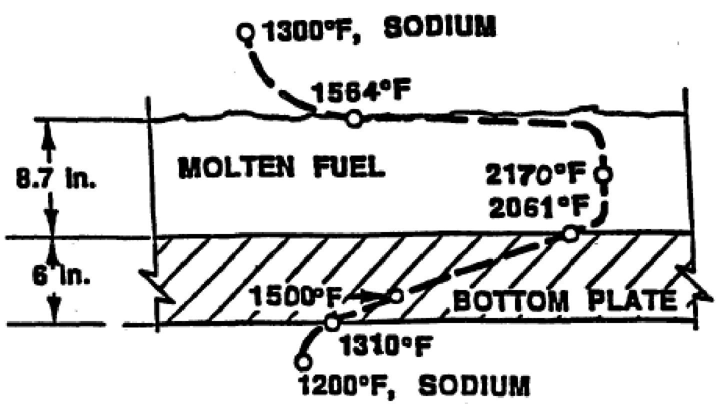
3.1 The behavior of fuel debris swept out to the upper plenum

Provided that the M-Series experiments support the sweep out of the fuel, how do you evaluate the long term coolability of the debris in the upper plenum?

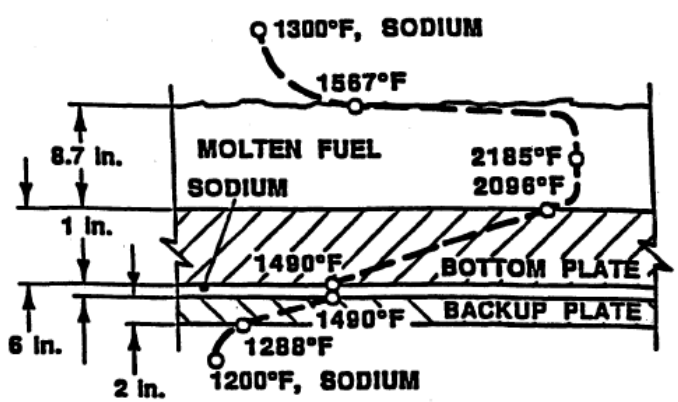
3.2 Debris retention at the space below the core support structure

In NUREG-1368 for PRISM, a scenario of debris retention at the core support structure is described with the figures shown in Fig.3. It seems the fuel forms a layer of liquid eutectic.

We have a current plan to install a core-catcher to retain the debris in the region between the core structures and RV. Our question is that the fuel debris accumulating on the core catcher is very porous or not. According to the experimental results by Dr. Gabor et al., very porous debris bed of around 90% porosity was formed.



A - Without Backup Plate



B - With Backup Plate

Fig. 3
(NUREG-1368)

4. Analysis tools

4.1 SAS4A/SASSYS code

We have read the code description published in the home page of ANL. Some of the questions are:

(1) Does it have capability of fuel characterization reflecting the irradiation history during normal operation?

(2) In a paper[*2] of TREAT M-Series, it is reported that they can reproduce the extrusion behavior in M2-M4 U-Fs type fuel pins as shown in Fig.4. It is a remarkable result.

Does the same model apply to M5-M7 ternary fuel pins? Or, was a different model developed.

Finally, are such extrusion models introduced and validated in SAS4A?

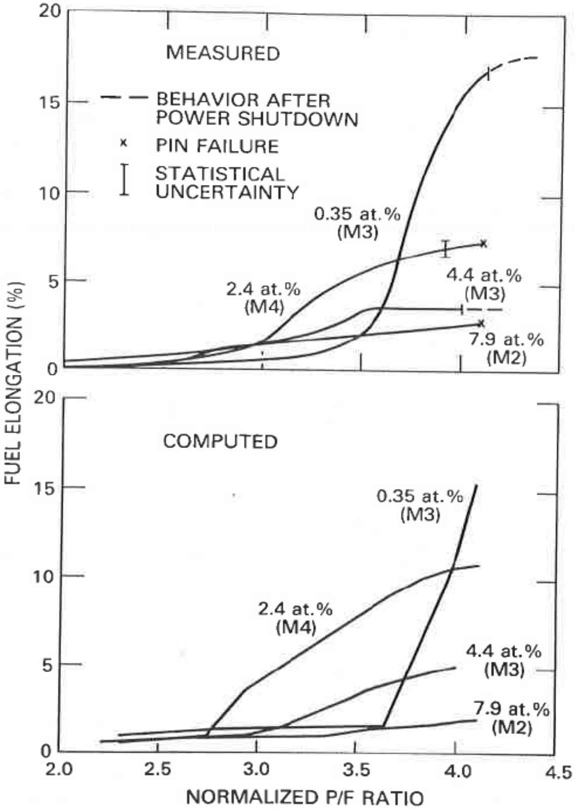


Fig. 15. Measured and computed time dependence of prefailure axial expansions: U-Fs fuel covering the range of tested burnup.

Fig. 4 [*2]

(3) It seems that the modules for metallic fuel such as FPIN2,DEFORM5 covers only until the fuel pin failure. The LEVITATE (and PINACLE) modules which cover the fuel behavior beyond pin failure does not have capability of metallic fuel. Are there any changes or improvement plan for the near future?

4.2 Analysis tools of movement of eutectic material after pin failure

Are there any computer codes or models to simulate the progression of eutectic formation and movement of eutectic in the core? We assume such a model is needed for assessment of the severe accident scenarios in the metallic fuel cores. The SIMMER code is a candidate, however, no model of eutectic formation is available in SIMMER.

Another question is the availability of physical properties of the eutectic species.

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