PLUS7^{TM}

- PLUS7^{TM} Fuel TR Contents
- Design Features & Characteristics
- Fuel Assembly Design Criteria & Evaluation
- Components Design Criteria & Evaluation
- Irradiation Experience & Performance
- Conclusion

PLUS7 Fuel TR Contents (1/6)

PLUS7 Fuel TR Contents (2/6)

PLUS7 Fuel TR Contents (3/6)

2.3.2 Top Nozzle

- 2.3.2.1 Top Nozzle Description
- 2.3.2.2 Top Nozzle Design Bases and Criteria
- 2.3.2.3 Top Nozzle Evaluation

2.3.3 Holddown Spring

- 2.3.3.1 Holddown Spring Description
- 2.3.3.2 Holddown Spring Design Bases and Criteria
- 2.3.3.3 Holddown Spring Evaluation

2.3.4 Guide Thimble Tube/ Instrumentation Tube

- 2.3.4.1 Guide Thimble Tube/ Instrumentation Tube Description
- 2.3.4.2 Guide Thimble Tube/ Instrumentation Tube Design Bases and Criteria
- 2.3.4.3 Guide Thimble Tube/ Instrumentation Tube Evaluation

PLUS7 Fuel TR Contents (4/6)

PLUS7 Fuel TR Contents (5/6)

3.3 Design Evaluation

PLUS7 Fuel TR Contents (6/6)

PLUS7^{TM}

Design Features & Characteristics

Design Features & Characteristics (1/10)

Reconsitituable top nozzle

- Guide Post, holddown spring and adapter plate remains as an one piece after reconstitution

High burnup fuel rod

- Advanced Cladding Tube
  → ZIRLO Tube
- Optimized ROD OD
  → WH-17type STD Rod OD
- Axial Blanket
  → Improving Neutron Economy

Inconel top/bottom grid for high burnup

Mixing vaned mid grid

- Mixing vanes
  → Enhancing Thermal Margin
- Straight grid straps
  → Improving Seismic Resistance
- Reducing GTRF
  → conformal grid spring/dimple shape
  → large contact area

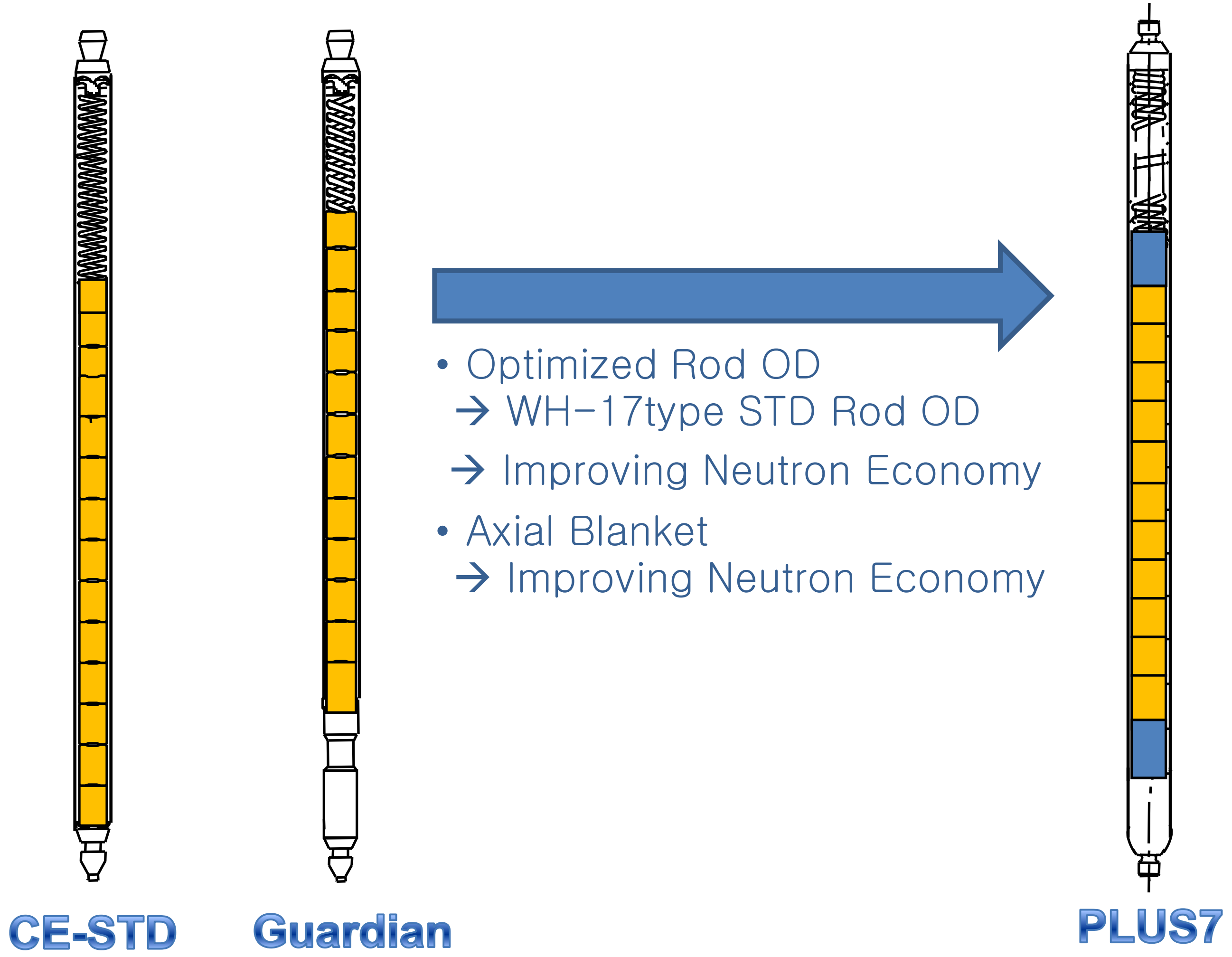
Protective grid for debris filtering

Debris filtering bottom nozzle

- Increasing Debris Filtering Efficiency
- Small hole/slot Bottom Nozzle
- Support fuel against GTRF

Design Features & Characteristics (2/10)

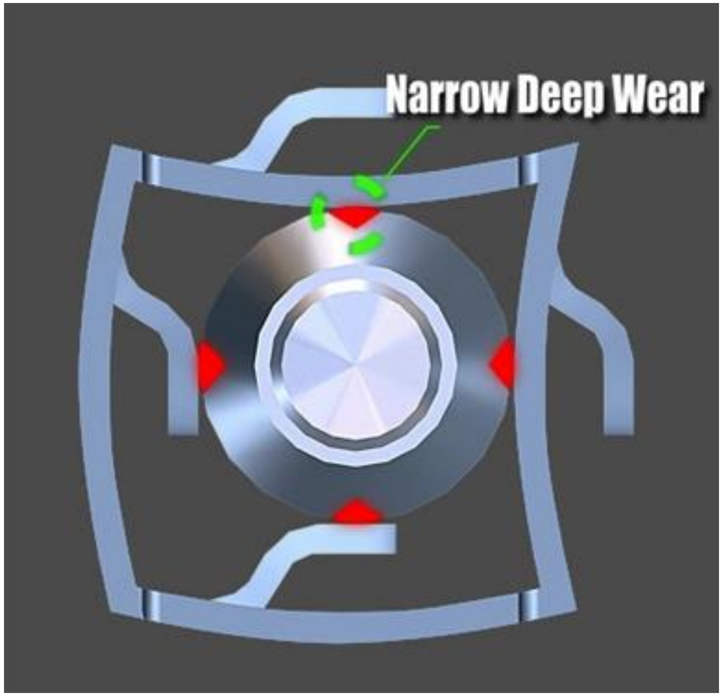
- Fuel Rod



- Optimized Rod OD
  → WH-17type STD Rod OD
  → Improving Neutron Economy
- Axial Blanket
  → Improving Neutron Economy

Design Features & Characteristics (3/10)

- Mid Grid

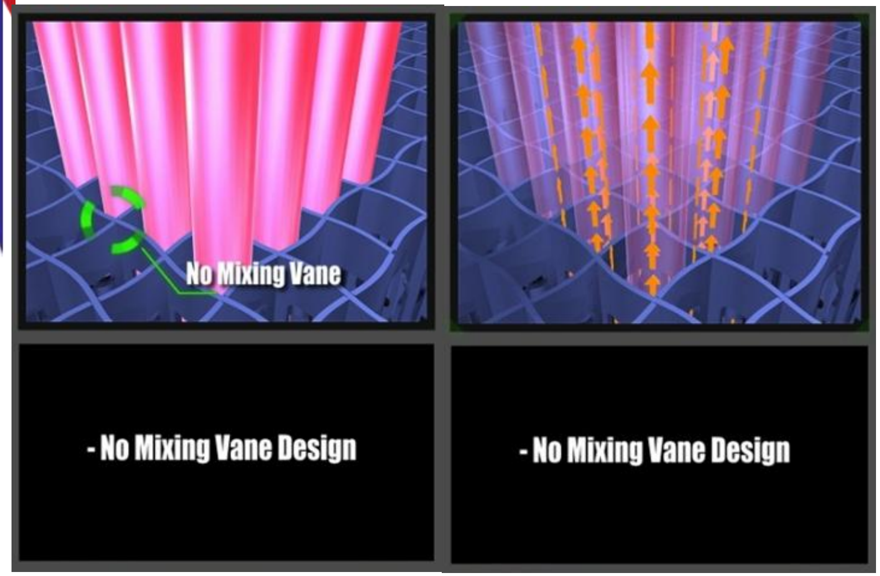


Guardian

PLUS7

Design Features & Characteristics (4/10)

- Mid Grid



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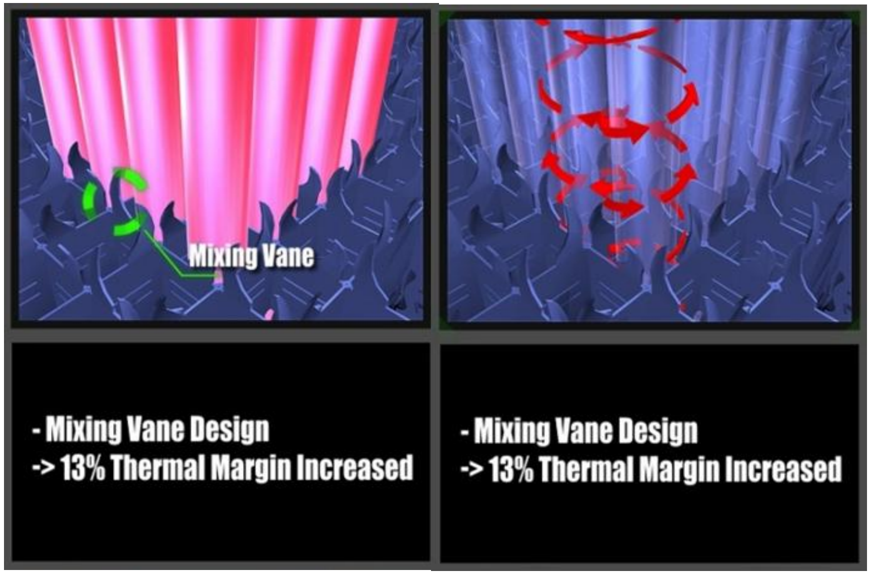
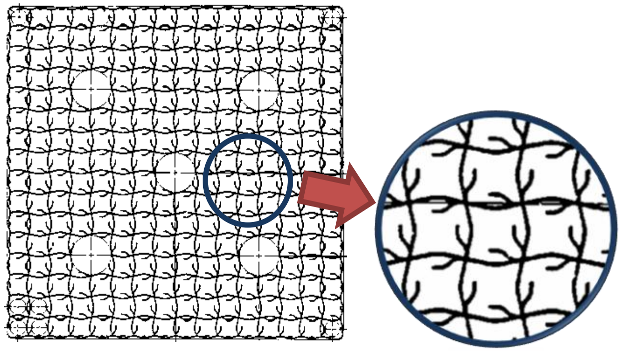


PLUS7

Design Features & Characteristics (5/10)

- Mid Grid



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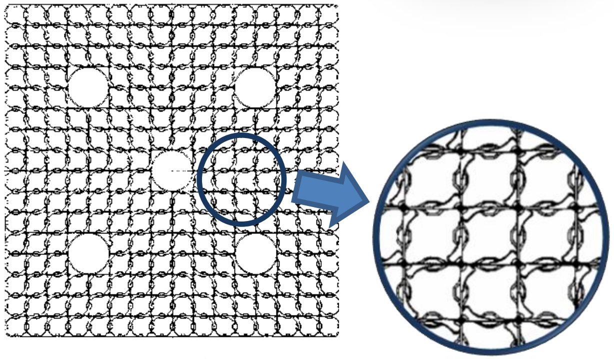
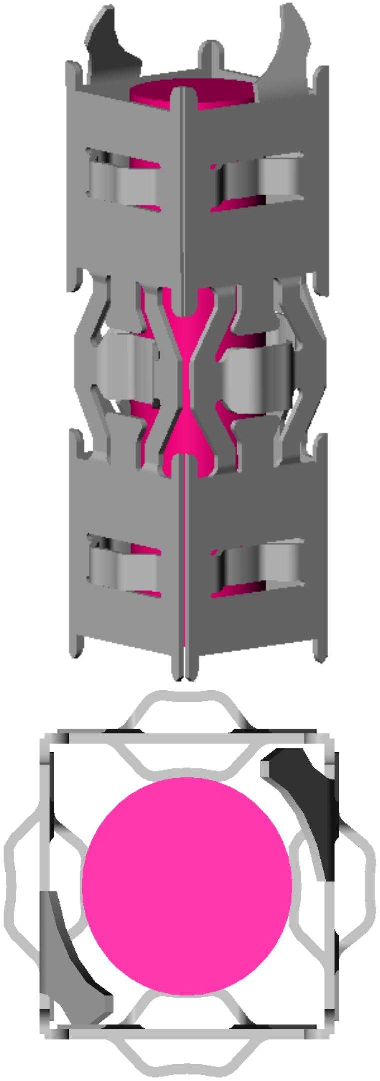
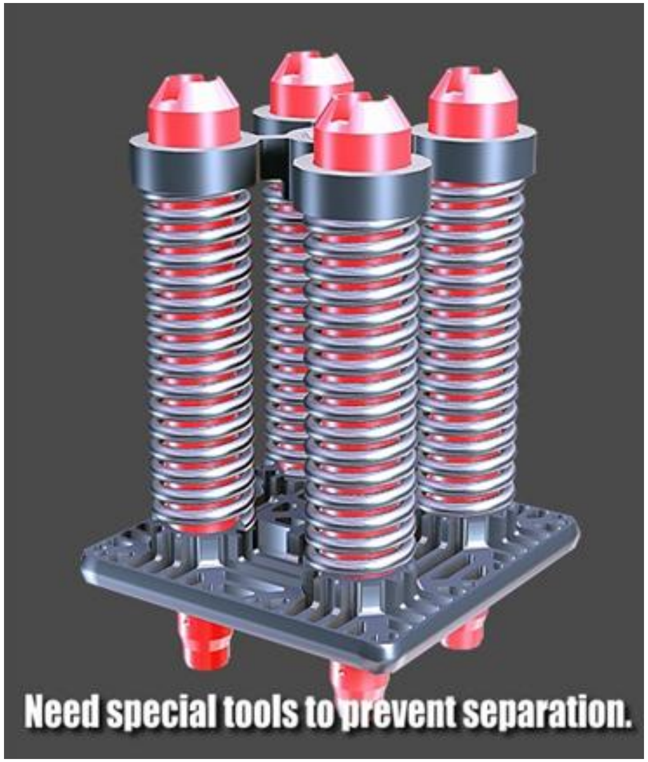


PLUS7



Design Features & Characteristics (6/10)

- Top Nozzle


Need special tools to prevent separation.

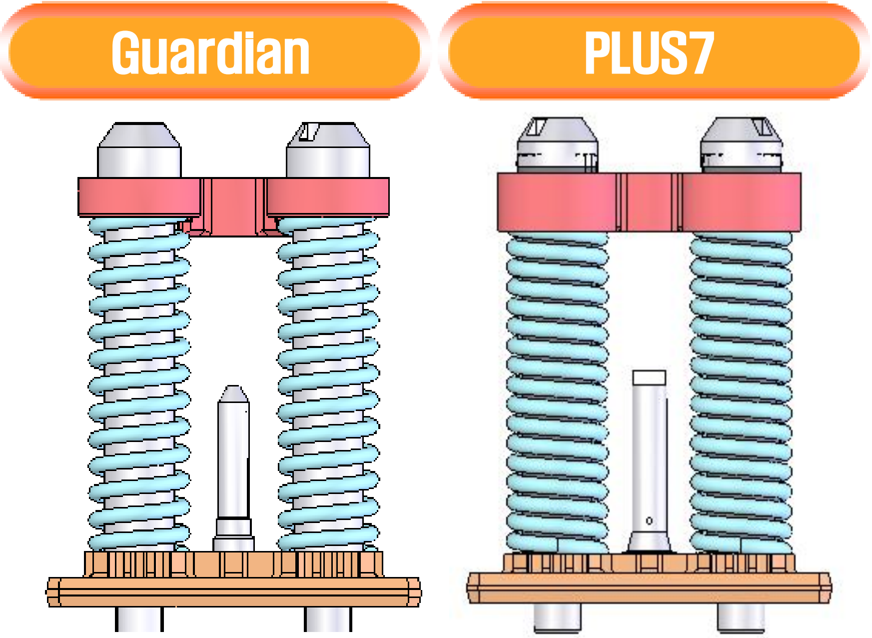
Guardian

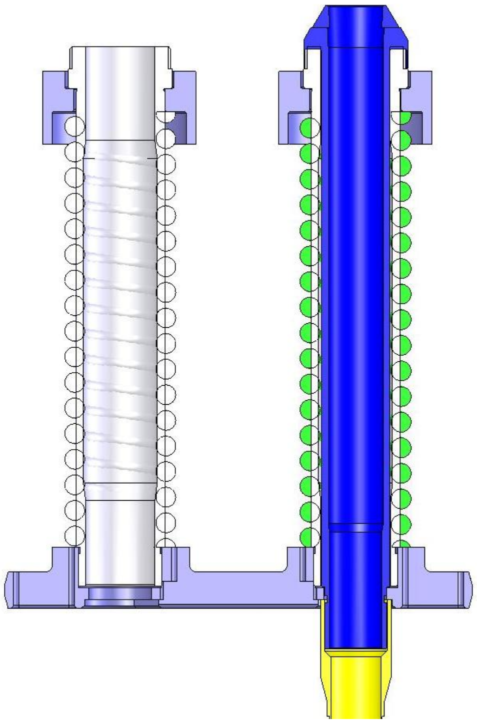

One piece separation. Fast & Safe.

PLUS7

Design Features & Characteristics (7/10)

- Top Nozzle





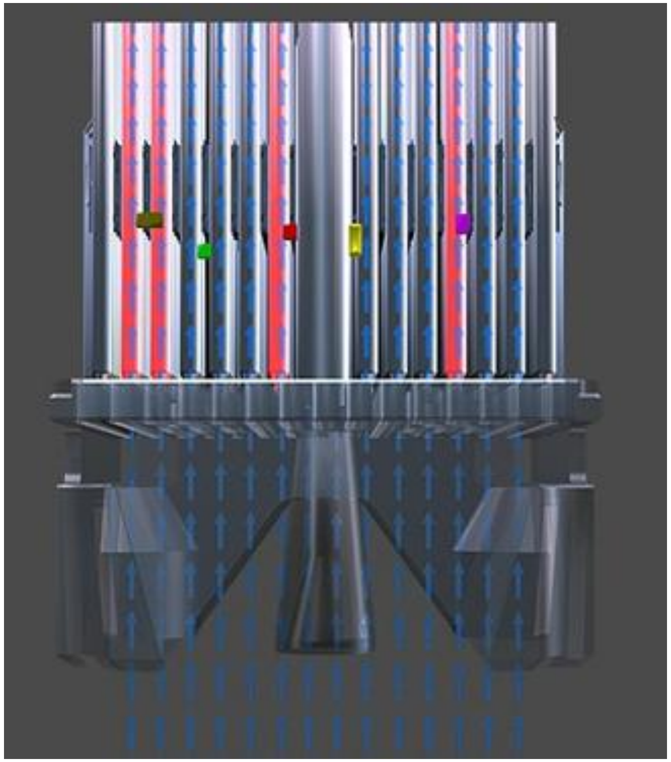
Spring Rate

Free Length

Wire Diameter

Design Features & Characteristics (8/10)

- Bottom Nozzle



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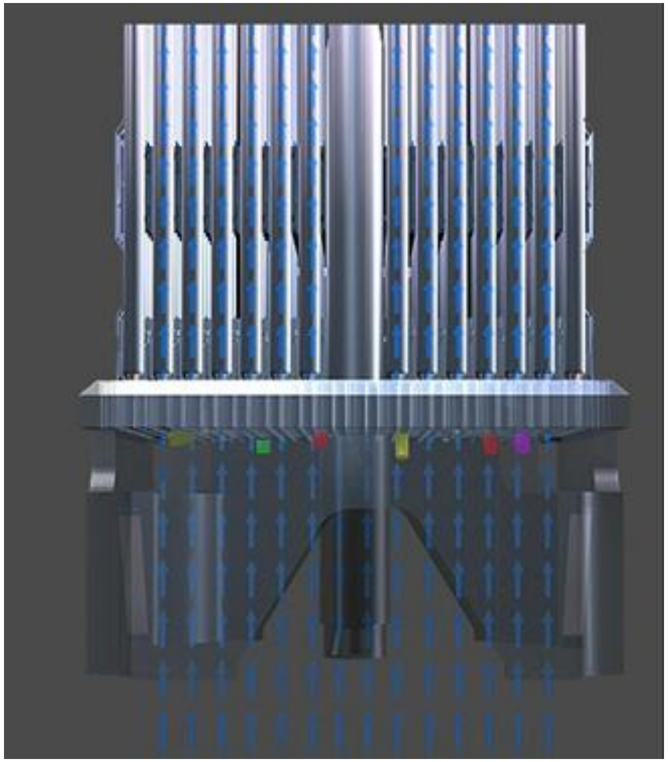
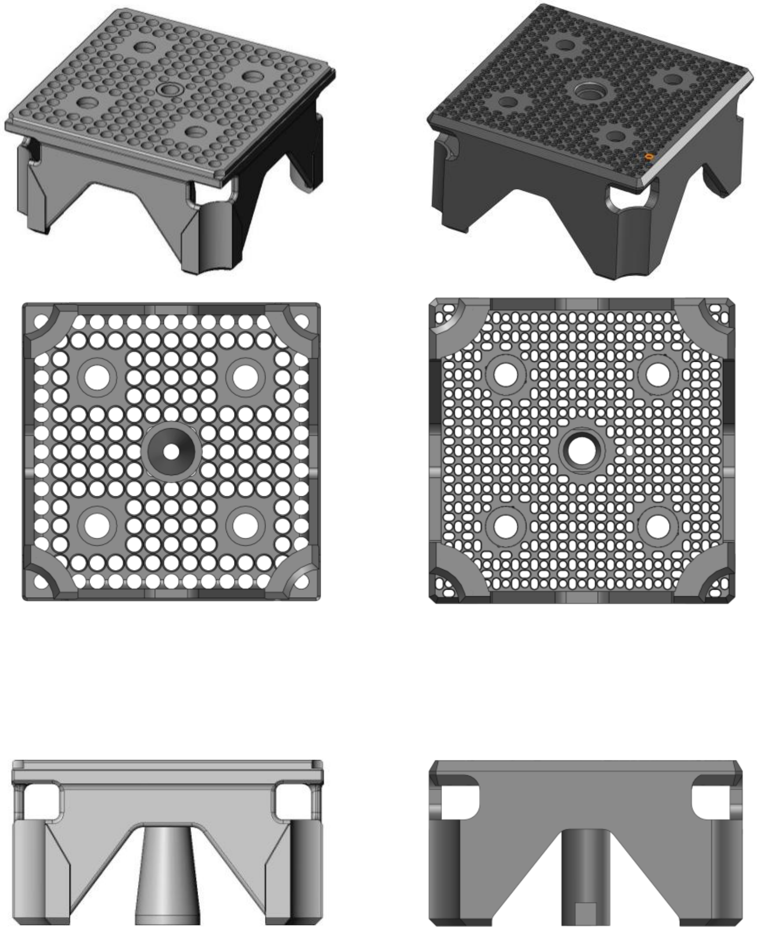


PLUS7

Pre Submittal Meeting

Design Features & Characteristics (9/10)

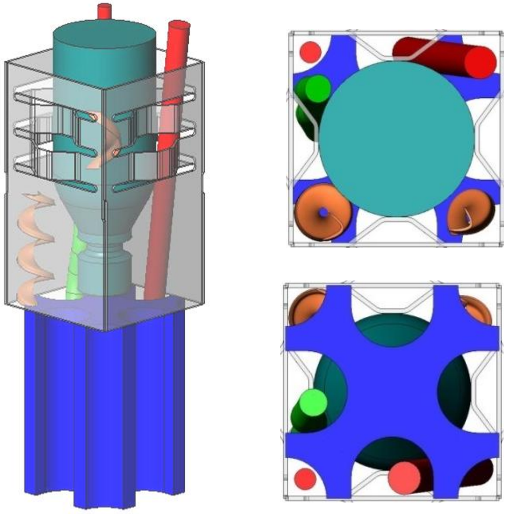
- Bottom Nozzle



Guardian

PLUS7

- Debris Filter Design



Design Features & Characteristics (10/10)

Design Summary

Item	Guardian	PLUS7	Remarks
Cladding	Zry-4	ZIRLO™	High Burnup
Rod diameter	0.382 ”	0.374”	Neutron Economy
Axial Blanket	-	O	
Spring	cantilever	conformal	GTRF Resistance
Dimple	arched	conformal	
Strap	wavy	straight	Seismic Resistance
Mid Grid Mixing Vane	-	O	Thermal Performance
Bottom nozzle	Large Hole	Small Hole & Slot	Debris Filtering

Pre Submittal Meeting

PLUS7^{TM}

Design Criteria & Evaluation

- Fuel Assembly

- Components

FA Design Criteria & Evaluation (1/6)

Code and Standards

- 10 CFR 50 Appendix A. GDC 10 Reactor design
- NUREG-0800, Standard Review Plan 4.2 Fuel system design
- ASME Code Section Ⅲ, Division 1, Subsection NB

FA Design Criteria & Evaluation (2/6)

- **Fuel Assembly**

Items	Design Criteria	Satisfy?	Remarks
Rod-to-Top Nozzle Axial Clearance	• Axial Gap > 0	yes	• PLUS7 LTA PSE & Gap Calculation
Hydraulic Stability	• No Vibration Resonance • No Fuel Rod Fretting Wear Failure	yes	• FACTS FA Vibration Test • VIPER Long-Term Endurance Test
Shipping and Handling Loads	• Stress Criteria - Axial Load : 4g, Lateral Load : 6g	yes	• FEM Analysis
Mechanical Compatibility	• Compatible with internal Structure and Core Component	yes	• Interface Dimensional Analysis

FA Design Criteria & Evaluation (3/6)

- **Fuel Assembly**

- Hydraulic Stability

Bases

- Cladding will not be weared by excessive vibration resulting from relative motion between the fuel rods and the grid springs or dimples

Criteria

- Vibration resonance of the FR and FA should not occur
- FR fretting wear failure should not occur until EOL

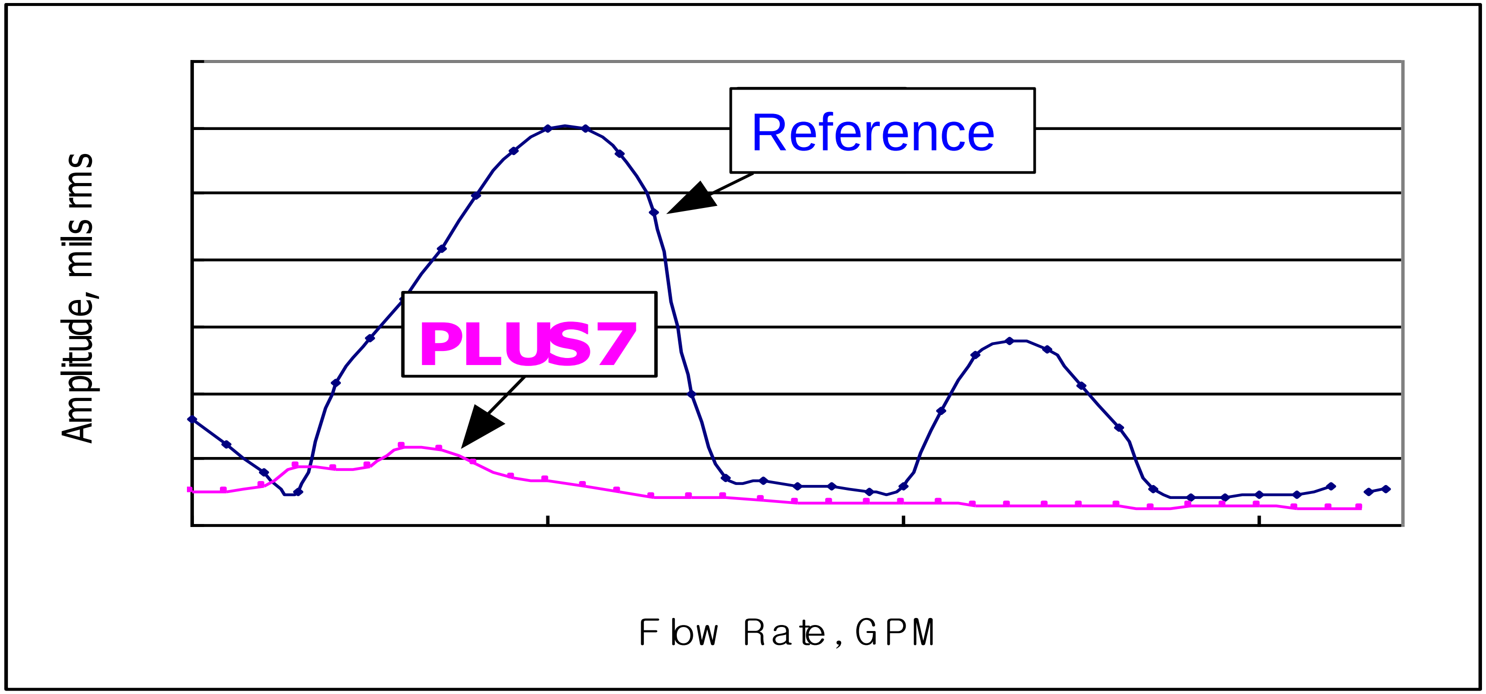
Evaluation Results

- PLUS7 had no resonance vibration peaks at reactor operating range. (FACTS FA vibration test)
- There was no measurable wear on all oxidized rods. (VIPER long-term endurance test)

FA Design Criteria & Evaluation (4/6)

- **Fuel Assembly**

- FACTS LOOP FA Vibration Test

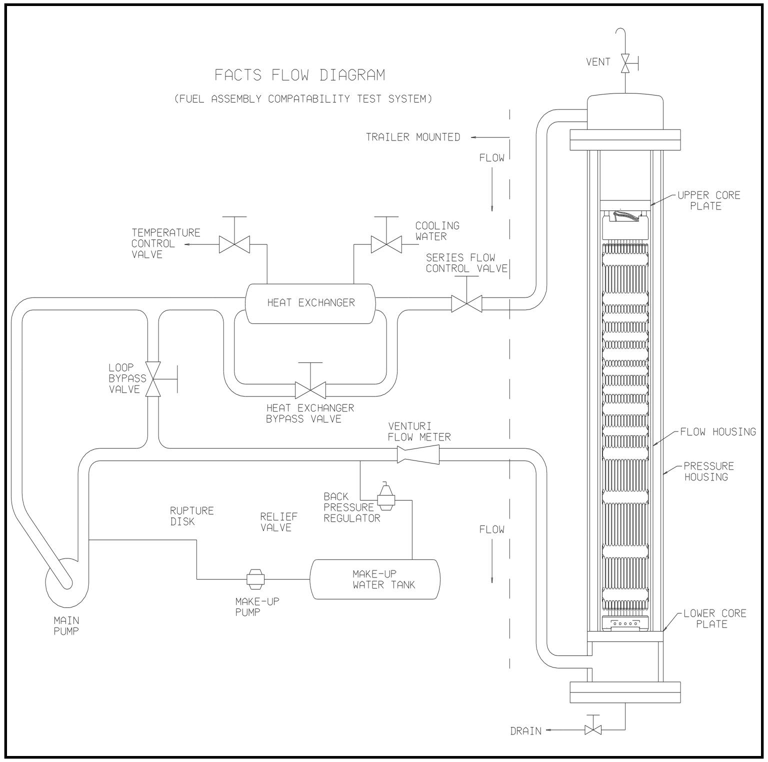


Result of Vibration Test on PLUS7 FA

FA Design Criteria & Evaluation (5/6)

- **Fuel Assembly**

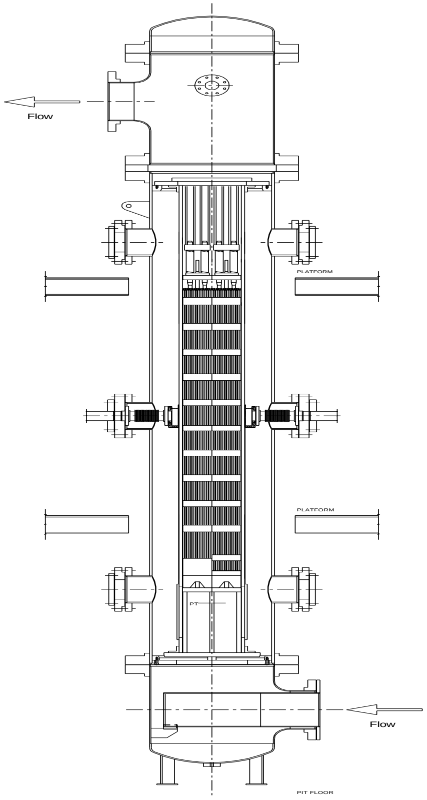
  - **FACTS Pressure Drop Test**



FA Design Criteria & Evaluation (6/6)

- **Fuel Assembly**

  - VIPER Long-term Endurance Test



Components Design Criteria & Evaluation (1/12)

1. Bottom Nozzle

Bases

- Bottom nozzle will maintain structural integrity

Criteria

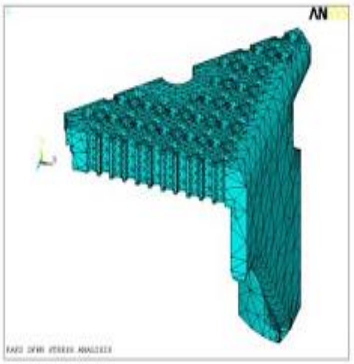
- Structural integrity should be maintained under shipping, handling and condition I,II,III and IV load

Components Design Criteria & Evaluation (2/12)

1. Bottom Nozzle

Evaluation

- **FEM Analysis confirmed that Bottom Nozzle maintained structural integrity**



Analysis Condition	Maximum Stress (S_I, ksi)	Allowable Stress (S_a, ksi)	S_I/S_a
Shipping and Handling Load			
Condition I & II			
Condition III & IV			

Components Design Criteria & Evaluation (3/12)

2. Top Nozzle

Bases

- Top nozzle will maintain structural integrity

Criteria

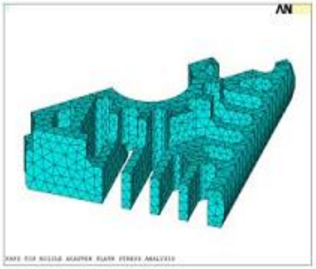
- Structural integrity should be maintained under shipping, handling and condition I,II,III and IV load

Components Design Criteria & Evaluation (4/12)

2. Top Nozzle

Evaluation

- FEM Analysis confirmed that top nozzle maintained structural integrity



Analysis Condition	Structure Parts	Maximum Stress ($S_{I,}$ ksi)	Allowable Stress ($S_{a,}$ ksi)	S_I/S_a
Shipping and Handling Load	Hold-down Plate			
	Adapter Plate			
Condition I & II	Hold-down Plate			
	Adapter Plate			
Condition III & IV	Hold-down Plate			
	Adapter Plate			

Components Design Criteria & Evaluation (5/12)

3. Holddown Spring

Bases

- Fuel assembly, reactor internals and core support structure will not be damaged by fuel assembly lift-off during normal operation

Criteria

- FA should not lift-off in the normal operation condition

Components Design Criteria & Evaluation (6/12)

3. Holddown Spring

Evaluation

- FACTS FA lift-off test confirmed that PLUS7 did not lift-off
- Minimum holddown margin was [ ] lbs at BOL hot condition

[

Results for Hold down Margin (lbs)		
	BOL	EOL
Lower 95%		
Best Estimate		
Upper 95%		

]

Pre Submittal Meeting

Components Design Criteria & Evaluation (7/12)

4. Guide Tube

Bases

- The structural integrity will be maintained according to ASME Code Section III, Division 1, Subsection NB
- CEAs will be inserted to guide tube to shut down the reactor reliably

Criteria

- Maximum stress should be less than allowable stress under condition I,II,III and IV
- The geometric shape of a guide tube should be maintained for the CEA drop time to be shorter than SCRAM time limit

Components Design Criteria & Evaluation (8/12)

4. Guide Tube

Evaluation

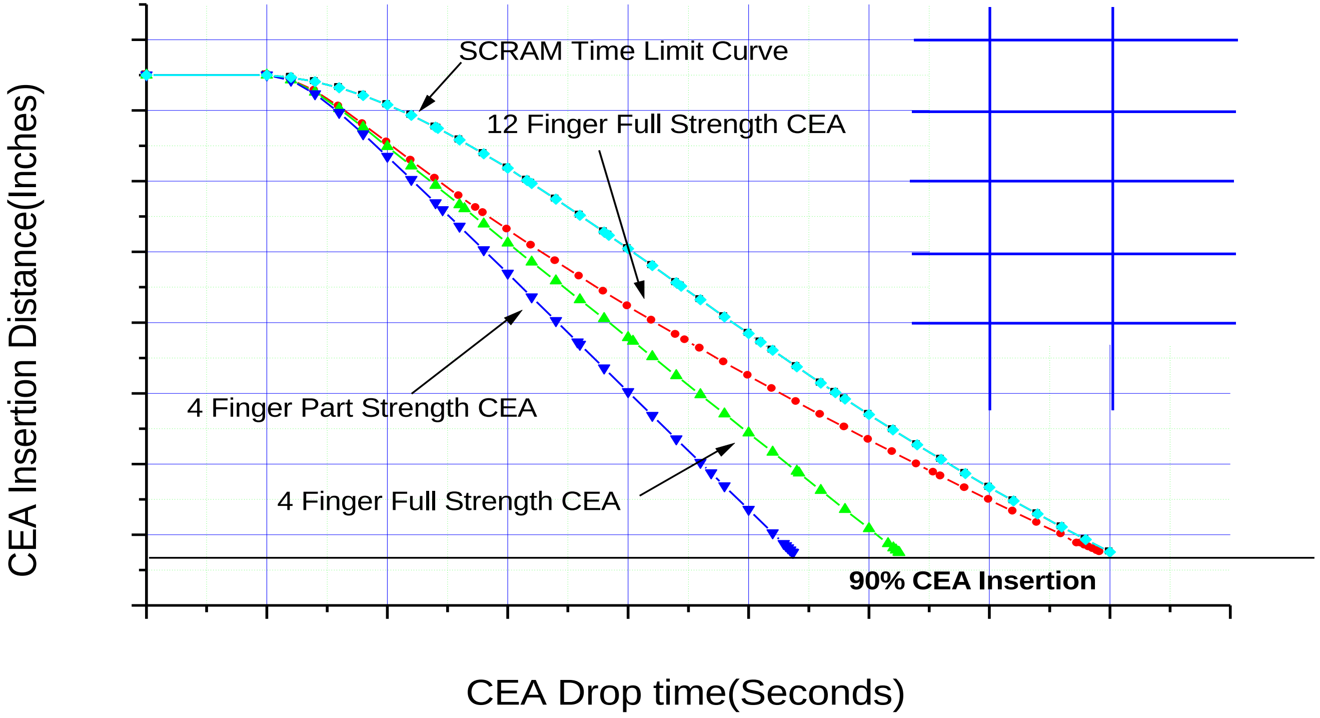
- Guide tube stress satisfied design limits
- SCRAM time satisfied the CEA drop time limit curve

Analysis Condition		Maximum Stress (S_I)	Allowable Stress (S_a)	S_I/S_a
Shipping and Handling Load				
Condition I & II	Cold			
	Hot			
Condition III & IV				

Components Design Criteria & Evaluation (9/12)

4. Guide Tube

CEA Drop time



Components Design Criteria & Evaluation (10/12)

5. Spacer Grid

Items	Design Criteria	Satisfy?	Remarks
Shipping and Handling	• No Plastic Deformation • No Shift & Slide	yes	• Static Grid Crush Test • Spring Force Analysis
Fuel rod fretting	• No FR Fretting Wear Failure	yes	• VIPER Long-Term Endurance Test
Grid spring and dimple fatigue	• $U_{CUM} \leq 0.8$	yes	• Grid Spring Fatigue Test
Fuel rod bowing	• < 0.5 Gap $_{Initial}$	yes	• PLUS7 LTA PSE
Mid grid dynamic buckling strength	• CEA Insertability • Coolable Geometry	yes	• SKN 3 & 4
Dimensional stability	• Adequate FA Gap	yes	• PLUS7 LTA PSE

Components Design Criteria & Evaluation (11/12)

5. Spacer Grid

Mid grid dynamic buckling strength

Bases

- Mid grid will not be damaged under Condition IV design basis earthquake events and LOCA

Criteria

- Grid deformation should not impair the CEA insertability and maintain Coolable Geometry

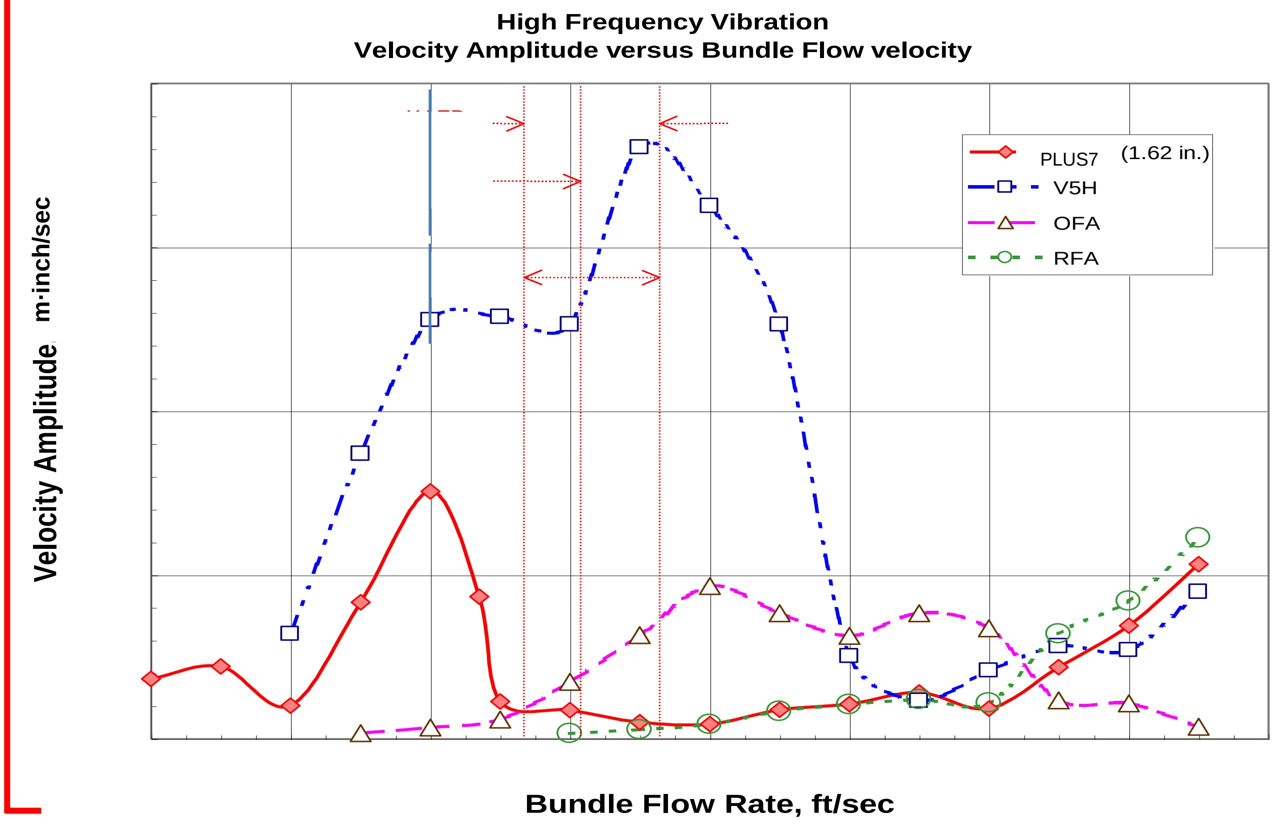
Evaluation

- Mid grid dynamic buckling strength was increased about 44% from Guardian grid

Components Design Criteria & Evaluation (12/12)

5. Spacer Grid

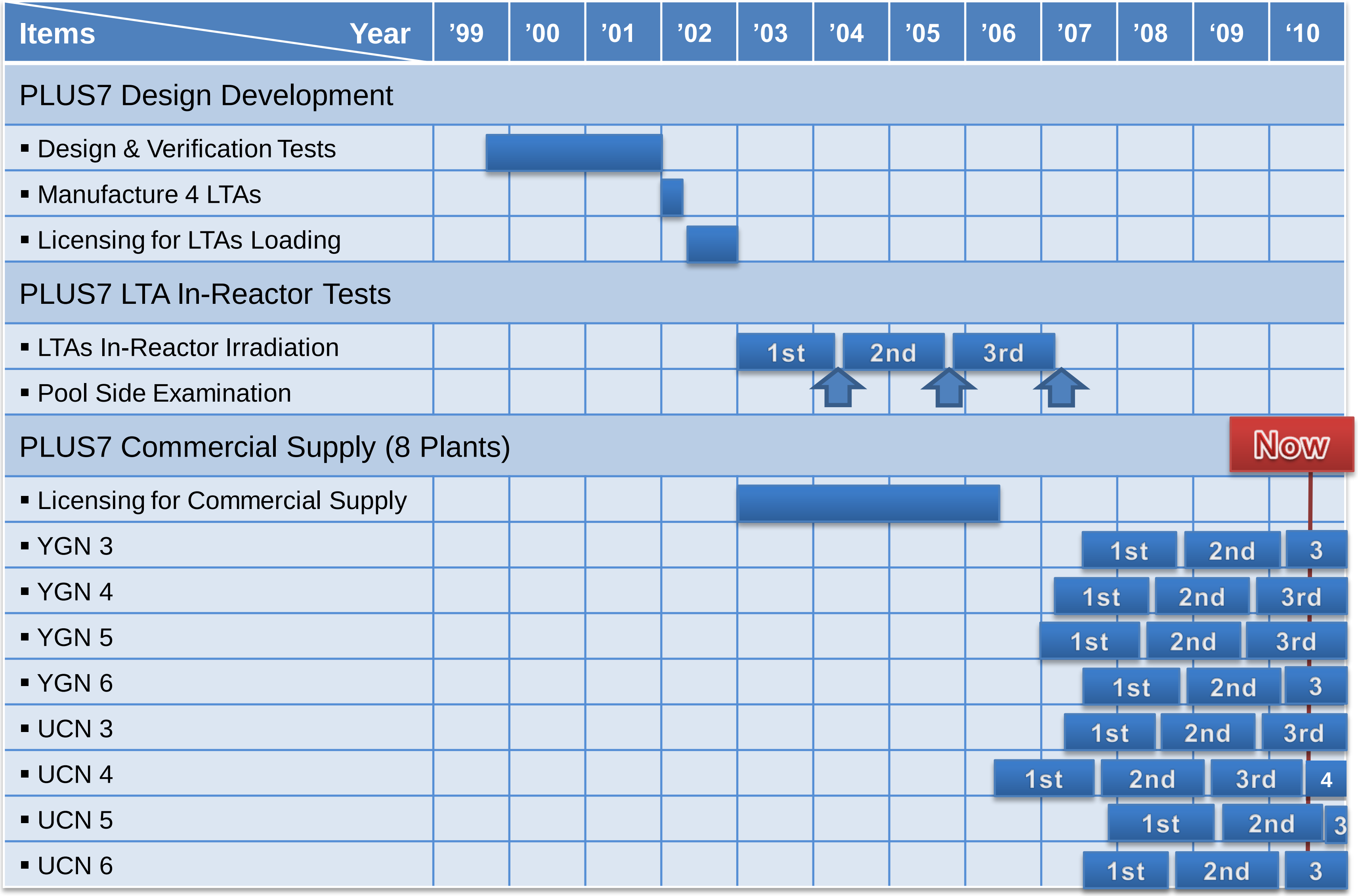
HFV Test



PLUS7^{TM}

Irradiation Experience & Performance

Irradiation Experience & Performance (1/10)



Items / Year

PLUS7 Design Development

- Design & Verification Tests
- Manufacture 4 LTAs
- Licensing for LTAs Loading

PLUS7 LTA In-Reactor Tests

- LTAs In-Reactor Irradiation
- Pool Side Examination

PLUS7 Commercial Supply (8 Plants)

- Licensing for Commercial Supply
- YGN 3
- YGN 4
- YGN 5
- YGN 6
- UCN 3
- UCN 4
- UCN 5
- UCN 6

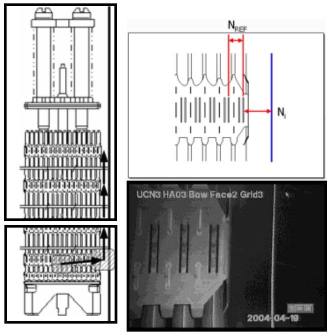
Irradiation Experience & Performance (2/10)

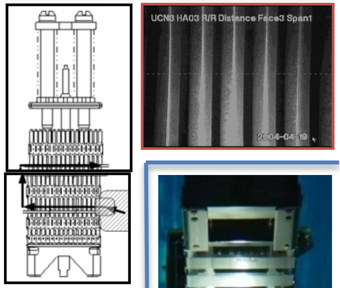
PLUS7 Commercial Loading Status

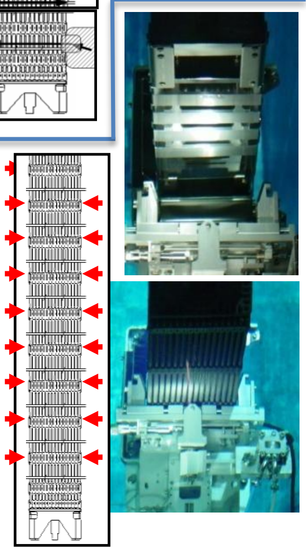
Plant	FA (EA)			
	1st Cycle	2nd Cycle	3rd Cycle	Total
YGN3	64	64	60	188
YGN4	64	64	64	192
YGN5	68	64	64	196
YGN6	64	64	60	188
UCN3	64	64	64	192
UCN4	64	64	64	192
UCN5	60	64	60	184
UCN6	64	64	64	192
Total	**512**	**512**	**500**	**1,524**

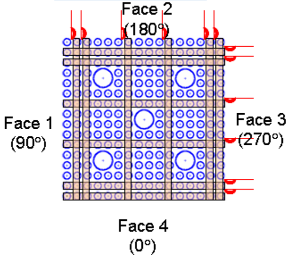
Irradiation Experience & Performance (3/10)

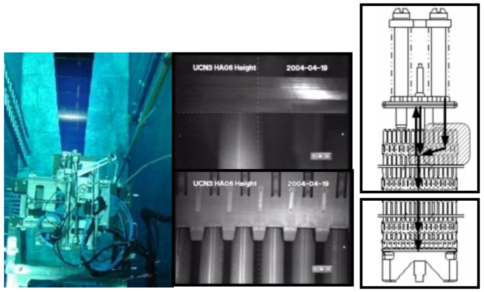
ITEM	Objective
Visual Examination	To inspect Surface Condition
FA Length Growth	Compatibility to Reactor Internals
FA Bow	Loading & Unloading
FA Twist	Loading & Unloading
FR-FR Gap	DNB Penalty
Grid Growth	Loading & Unloading GTRF
FR Creep	Integrity
Cladding Oxide	Integrity

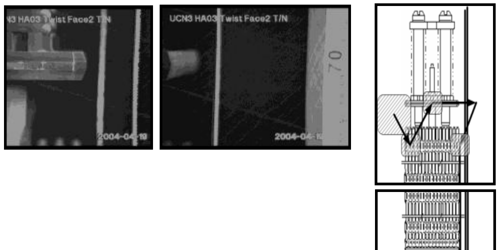


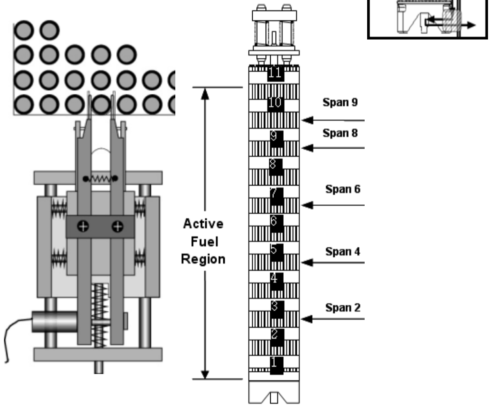






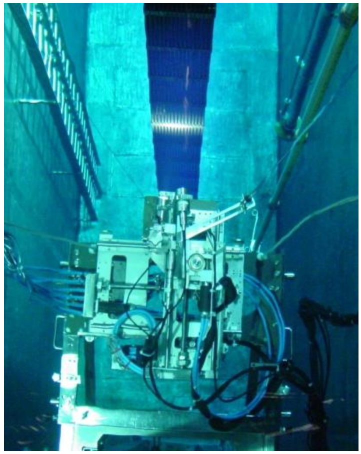




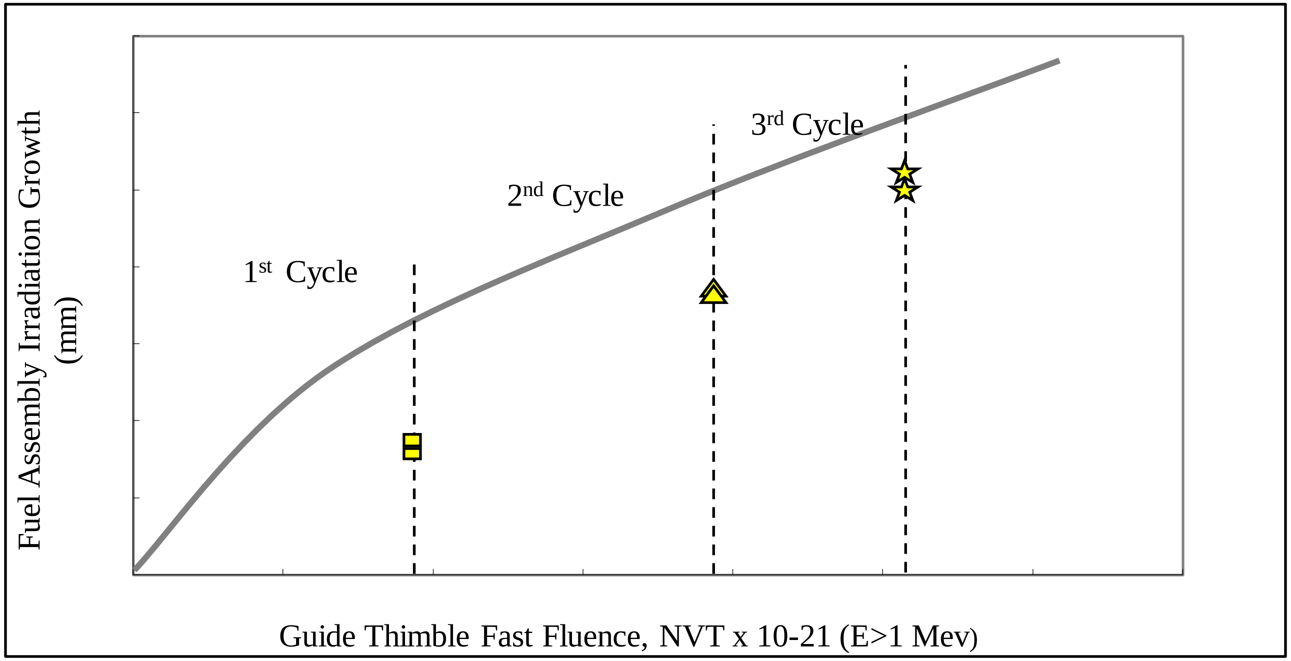


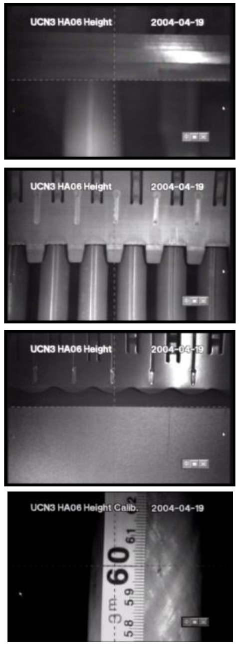
Irradiation Experience & Performance (4/10)

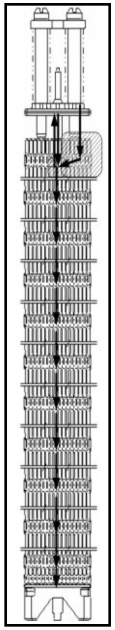
1. Fuel Assembly Irradiation Growth



- Purpose : To evaluate excessive growth due to irradiation, etc., and then to check the compatibility with the reactor internals.
- Method : After calibrating an encoder using a calibrated ruler, measure each elevation of FA



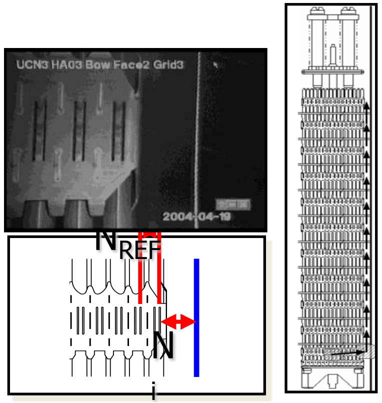




Irradiation Experience & Performance (5/10)

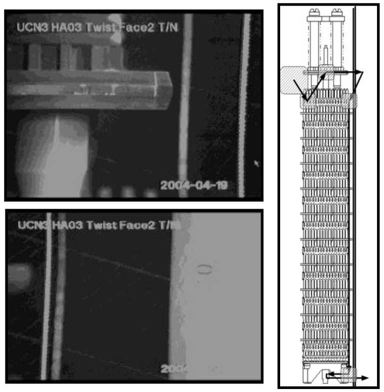
2. Fuel Assembly Bowing

- Purpose : To evaluate FA bow characteristics
- Method : To setup a plume line on the right side of FA, then measure grids to plumes line distance



3. Fuel Assembly Twist

- Purpose : To evaluate FA twist characteristics
- Method : To calibrate angle by distance and to setup two lines on the right side of FA, then to record nozzles and two lines, and finally to calculate two angles between nozzles' faces and an absolute plane by two line

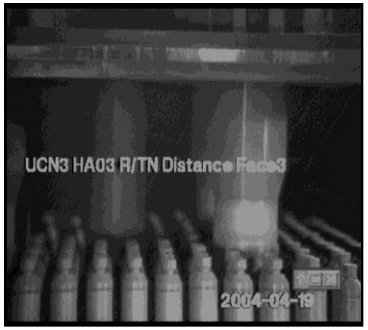


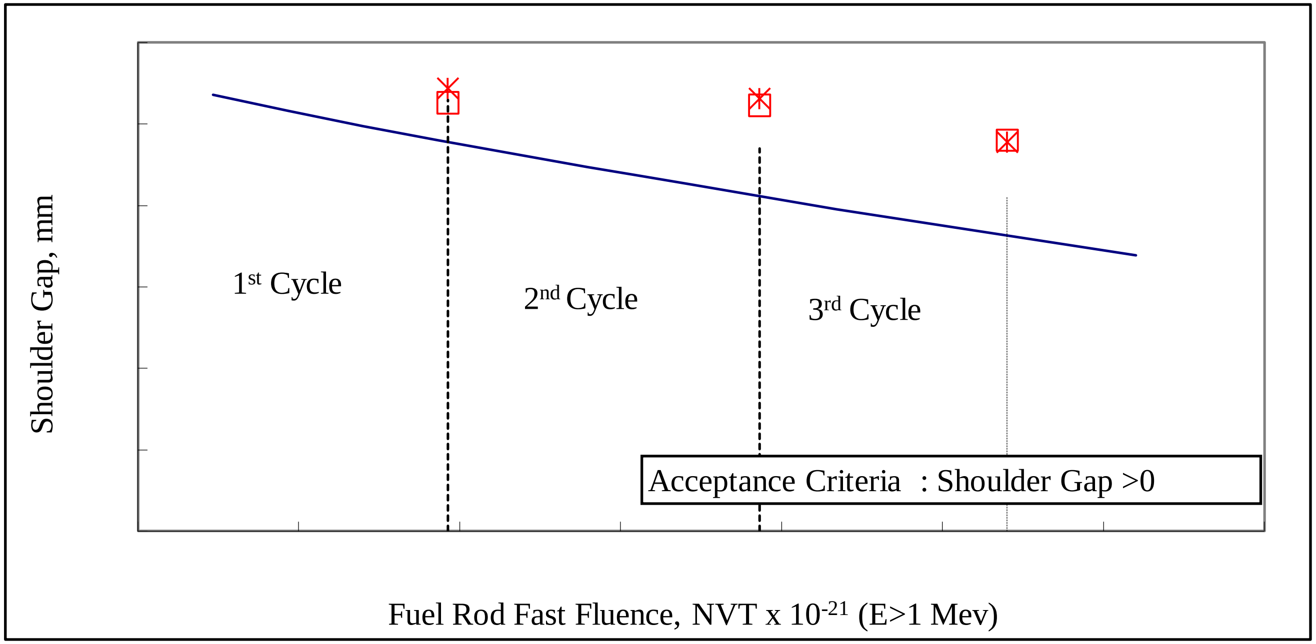
FA No.	1 Cycle	2 Cycle	3 Cycle
	Bowing/Twist	Bowing/Twist	Bowing/Twist
U3HA03			
U3HA06			

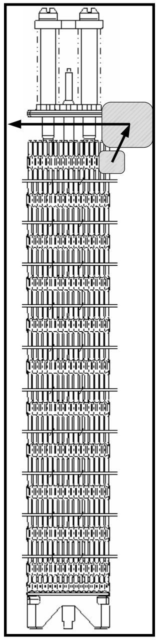
Irradiation Experience & Performance (6/10)

4. Rod-to-Top Nozzle Axial Clearance

- Purpose : To evaluate gap due to fuel rod irradiation growth
- Method : To get all outside gaps by using measured reference gap of rod at the center position after recording the gaps



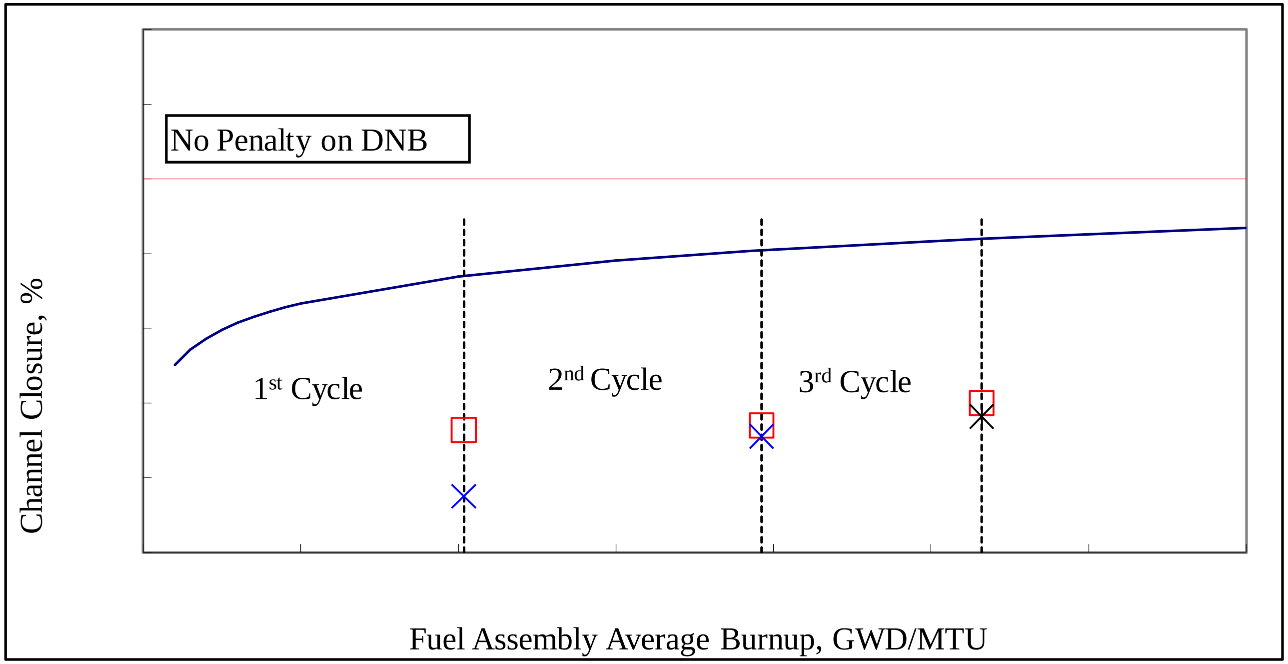


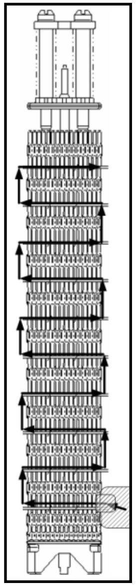


Irradiation Experience & Performance (7/10)

5. Fuel Rod Bowing

- Purpose : To evaluate Fuel Rod bow
- Method : To get rod-to-rod gaps by using reference rod diameter at the both side after recording the gaps on the span center

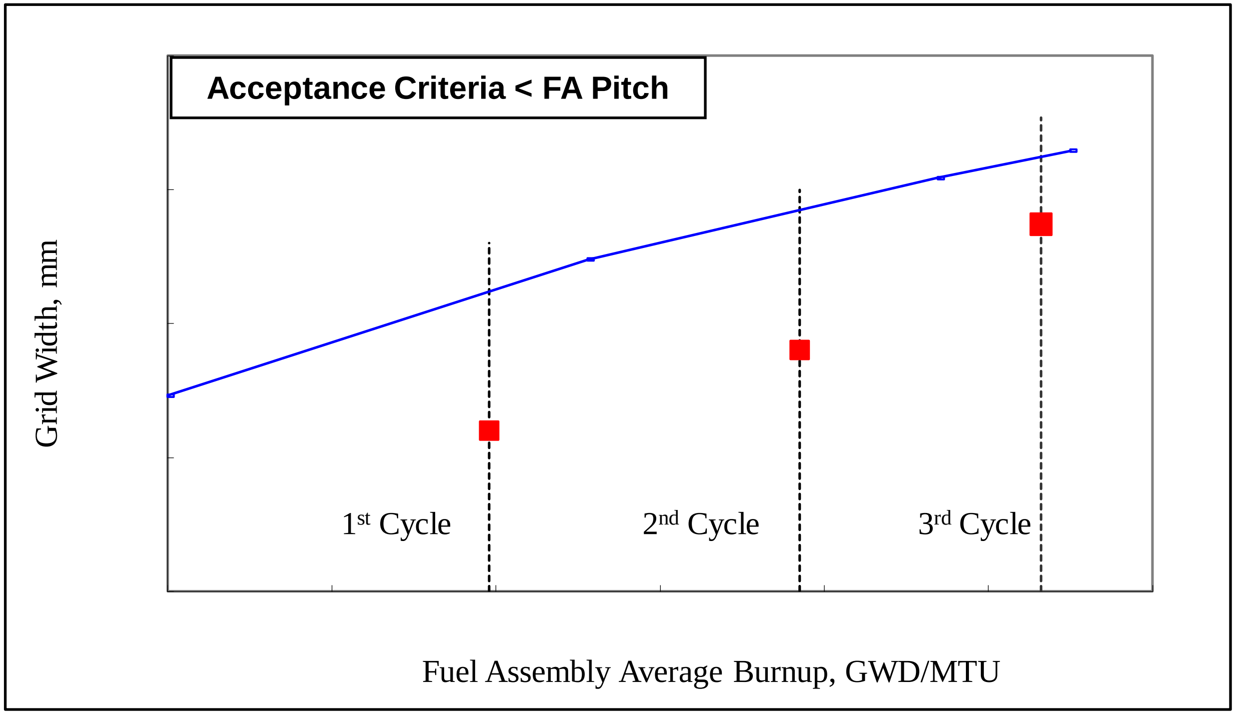


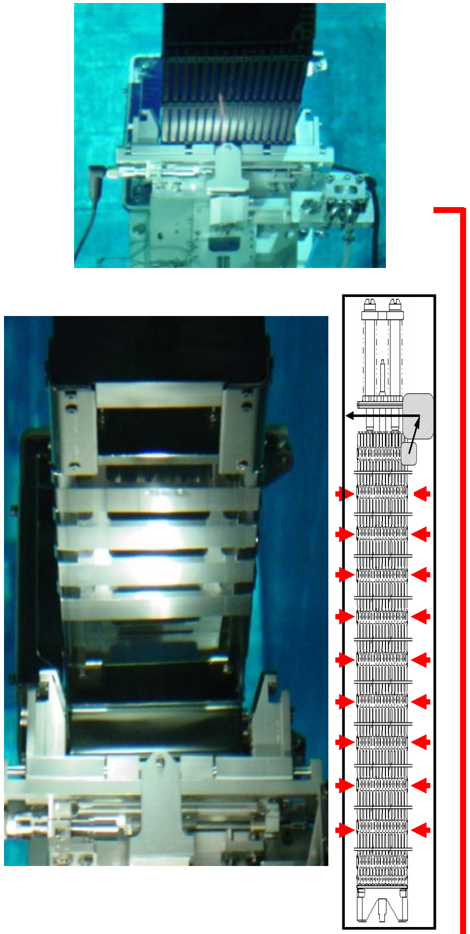


Irradiation Experience & Performance (8/10)

6. Spacer Grid Width

- Purpose : To evaluate grid irradiation growth
- Measurement device : LVDT

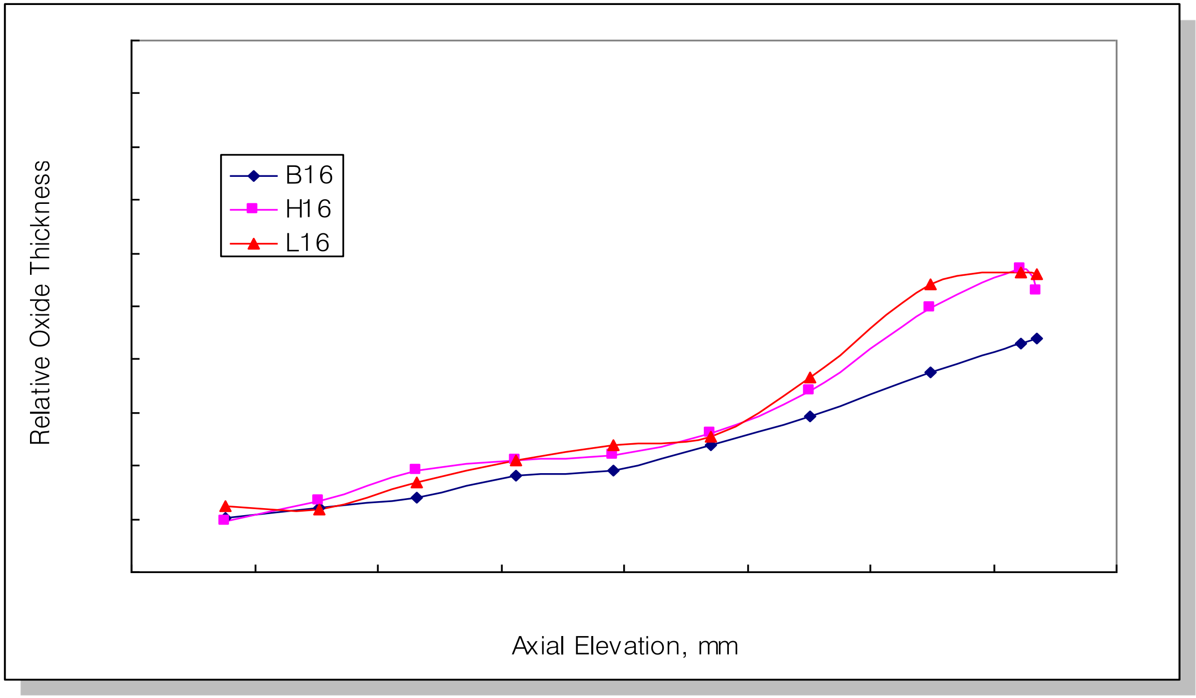


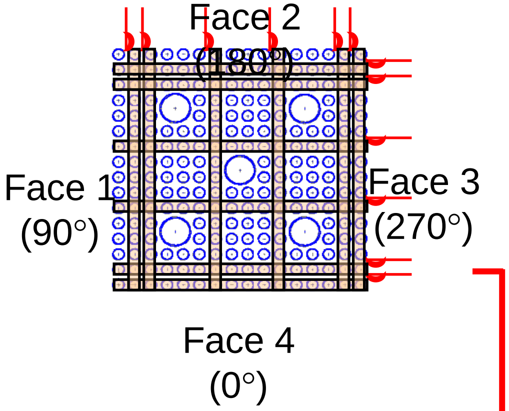


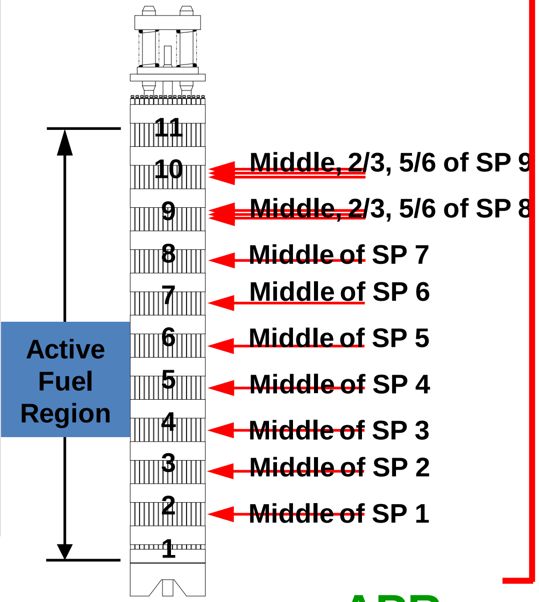
Irradiation Experience & Performance (9/10)

7. Cladding Oxide Thickness

- Purpose : To evaluate cladding oxide performance
- Measurement Device : ECT



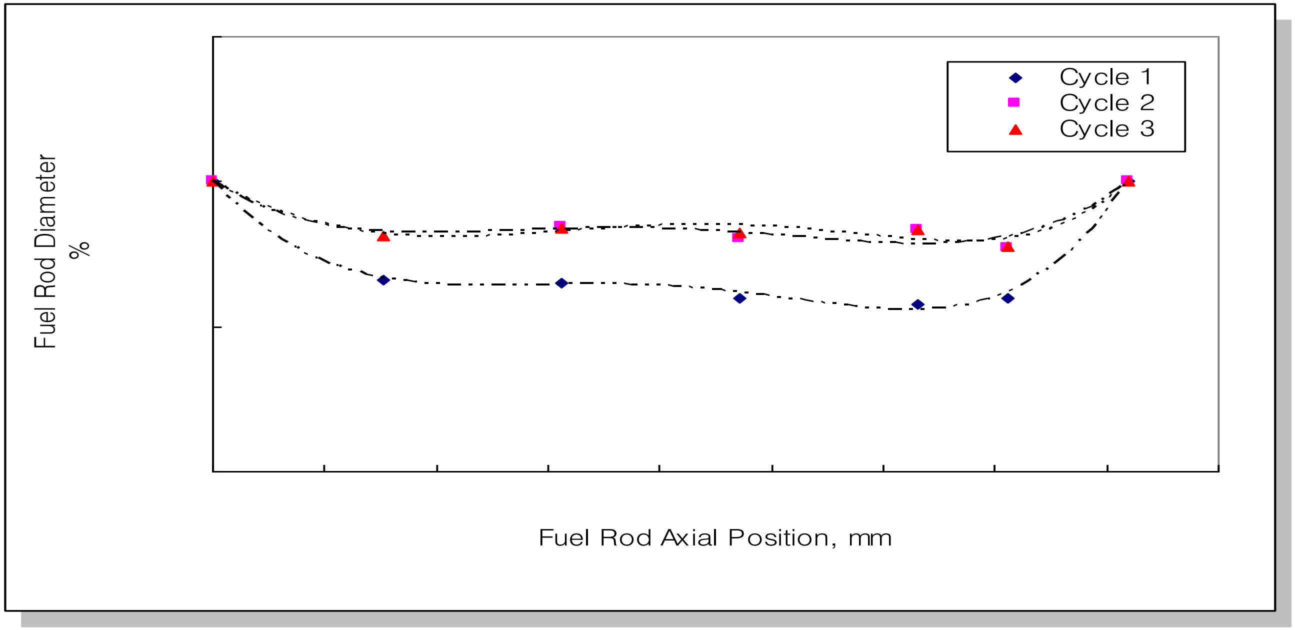


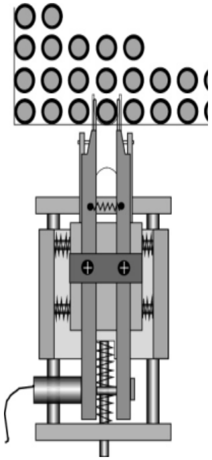


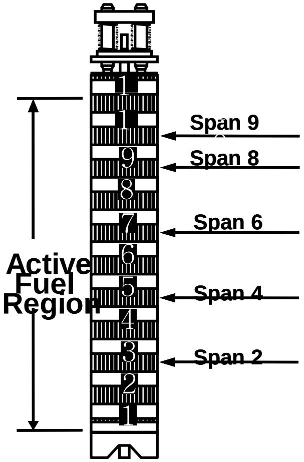
Irradiation Experience & Performance (10/10)

8. Cladding Outer Diameter (Creepdown)

- Purpose : To Evaluate Fuel Rod Creepdown
- Measurement Device : LVDT







PLUS7^{TM}

Conclusion

Conclusions

- **All of the design criteria of Fuel Assembly and Components of PLUS7^{TM} were verified through evaluations and tests**
- **Wide Range of Verification Tests were conducted**
  - Assembly and Components were tested at development stage (1999 ~2002)
  - Lead Test Assemblies were tested to confirm Irradiation Performance
- **Operating Experiences and Performance**
  - PLUS7 Fuel is operating at all of the eight OPR 1000 NPPs in Korea
  - PLUS7 Fuel will be loaded at APR 1400 NPPs as Initial Core

PLUS7- Fuel Rod Design

PLUS7 Fuel Rod Features

Overview of PLUS7 Fuel Rod Design

Fuel Rod Design Criteria and Evaluation

Conclusions

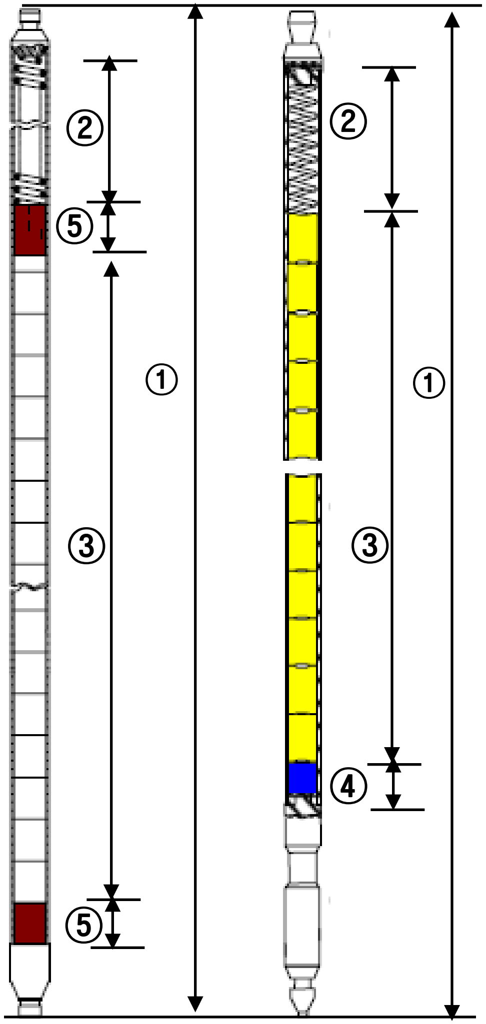
PLUS7 Fuel Rod Features

☐ Design Features and Characteristics of PLUS7 Fuel Rod

- Optimized Fuel Rod Outer Diameter
- Low Volume Variable Pitch Plenum Spring
- Optimized Helium Initial Pressure
- Advanced Cladding : ZIRLO
- Poison Rod : Gd_2O_3-UO_2 Rod
- Axial Blanket

❑ Fuel Rod Dimensions of PLUS7

Components	Guardian (Inch)	PLUS7 (Inch)	17x17 Type (Inch)
① Fuel Rod Leng.	[ ]	[ ]	[ ]
② Plenum Length	[ ]	[ ]	[ ]
③ Fuel Stack Len.	150.0	150.0	144
④ Spacer Disk	0.250	-	
⑤ Axial Blanket	N/A	6.0	
Clad Outer Dia.	0.382	0.374	
Clad Inner Dia.	0.332	0.329	
Dia. Gap	0.007	0.0065	
Backfill Pre. (psi)	[ ]	[ ]	



Overview of PLUS7 Fuel Rod Design

❑ Design Methodology and Evaluation

- Same design criteria and methodologies as the CE fuel design were used.
- Fuel rod evaluation was performed to maximum fuel rod average burnup of 60,000 MWd/MTU.

❑ Design Condition for Fuel Rod Evaluation

10 CFR 50	ANS 51.1
Normal	Condition I
AOO	Condition II
Accidents	Condition III
	Condition IV

❑ Fuel Rod Design Codes

Design Parameters	Codes(*)
Clad Stress under Condition II / III	FRODO_694
Cladding Strain under Condition I	TREMET_392
Cladding Strain under Condition II / III	FRODO_694
Cladding Fatigue	TREMET_392
Cladding Oxidation	COROSN 7.0.3 (**)
Rod Internal Pressure	FATES3B_5Mod0
DNB Propagation	INTEG_1Mod4
Cladding Collapse	CEPANFL_996
Overheating of Fuel Pellet (Melting)	FATES3B_5Mod0
Cladding Strain for PCMI	FRODO_694

(*) Modified with Material Properties and Models of ZIRLO Cladding
(**) Adopted from W type methodology

Fuel Rod Design Criteria and Evaluation

❑ Cladding Stress

Criterion

Stress	Condition	Criteria
Tensile Stress	Condition I and II	2/3 $\sigma_{Y.S}$
	Condition III	$\sigma_{Y.S}$
Compressive Stress	Condition I, II,III	$\sigma_{Y.S}$

Evaluation

- Stress analyses for condition I are performed using general shell theory.
- Stress analyses for condition II/III are performed using FRODO.
- Conservative approach
  - Deterministically combined input data

Result

- Design criteria for stress are satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Cladding Strain

Criterion

- Plastic Circumferential Tensile Strain < 1.0 %
  for During Condition I or Following Any Single Condition II or III event
- Total(elastic+plastic) Circumferential Strain < 1.0 % for Any Single Condition II or III event (greater than 52,000 MWd/MTU).

Evaluation

- Strain analyses for condition I are performed using TREMET.
- Strain analyses for condition II/III are performed using FRODO.
- Conservative approach
  - Deterministically combined input data

Result

- Design criteria for strain are satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Cladding Fatigue

Criterion

- Cumulative Fatigue Damage Factor at EOL < 0.8

$$Fatigue\ damage\ Factor = \sum\left(\frac{n}{N_f}\right)$$

where, n : Number of cycles at a specific strain N_f : Allowable number of cycles at a specific strain

Evaluation

- The fatigue analyses are performed using TREMET.
  - Daily Load Following Operation(10% - 100%), Reactor Trips and Startup/Shutdown
  - O'Donnel & Langer Design Curve

Result

- The design criterion for fatigue is satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Cladding Oxidation

Criterion

- Best Estimated Cladding Oxide Layer Thickness < 100 μm

Evaluation

- The oxidation analyses are performed using COROSN.
- Cycle-average rod power histories generated from bounding power history

Result

- The criterion for oxide layer thickness is satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Rod Internal Pressure (1/2)

Criterion

- Fuel Rod Internal Gas Pressure < Pressure to cause Clad Lift-off
  and Extensive DNB Propagation

Evaluation

- The rod internal pressures analyses are performed using FATES3B.
- Composite rod power history [Figure 1]
- Deterministically combined input data by 2σ variation

Result

- The criterion for rod internal pressure is satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Rod Internal Pressure (2/2)

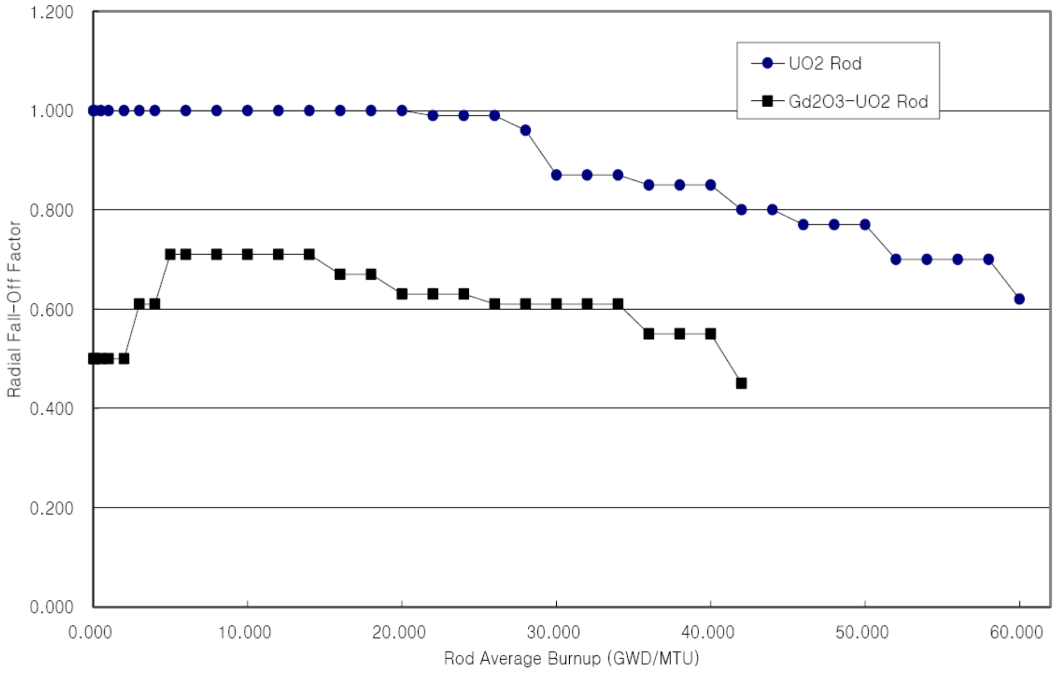


Figure 1 : Bounding Rod Power History

Fuel Rod Design Criteria and Evaluation

☐ Cladding Collapse

Criterion

- Time Required for Clad Collapse > Reactor Operating Time

Evaluation

- The cladding collapse analyses are performed using CEPANFL.
- Assumptions for analyses
  - Inter-pellet gap
  - Upper bound initial ovality and lower bound clad wall thickness
  - No fission gas release
  - Oxide layer thickness as a function of operation time

Result

- Design criterion of cladding collapse is satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Overheating of Fuel Pellet (Melting)

Criterion

- Maximum Centerline Temperature of Fuel Pellet < Melting Temperature
  - Power-to-Melt > SAFDL (Specified Acceptable Fuel Design Limit) of 21 kw/ft

Evaluation

- The fuel temperature analyses are performed using FATES3B.
- Melting temperature of UO_2 and UO_2 -Gd_2O_3 rods

$$T_{melt} = 5{,}080 - 5.8\ BU - [\qquad]\ X$$

where, T_{melt} = melting temperature in °F, X = Gd_2O_3 content in weight %, BU = burnup in GWd/MTU

Result

- The design criterion of fuel melting is satisfied.

Fuel Rod Design Criteria and Evaluation

☐ Pellet-to-Cladding Interaction

Criterion

- Total Cladding Strain (elastic+plastic) Change During Transient < 1%
- No Fuel Melting

Evaluation

- The same codes and methods are used as plastic strain and the overheating of fuel pellet.

Result

- The design criteria of PCI are satisfied.

Fuel Rod Design Criteria and Evaluation

❑ Summary of Fuel Rod Evaluation Results

Conclusions

- **The Same Design Criteria and Methodologies as the CE Fuel Design were used.**
- **All of the Fuel Rod Design Criteria were Verified Up to**

  60,000 MWd/MTU .

KCE-1 CHF Correlation for PLUS7^{TM} Thermal Analysis

Overview (1/3)

- **PLUS7^{TM} Developed for APR1400 & OPR1000***
  - Joint Program with Westinghouse Electric Co. (WEC)
  - April 1999 ~ March 2002
- **CHF Test for PLUS7^{TM}**
  - To check the improvement of thermal performance (w.r.t. CE-STD and/or Guardian^{TM})
  - To get the data for CHF correlation development (KCE-1)
  - Planned/performed with WEC-Columbia, SC
- **CHF Correlation**
  - Developed with WEC-Windsor, CT
  - Differences in method/assumption/minimum required test configuration (w.r.t. those of WEC-Columbia, SC)

* OPR1000 : Optimized PWR with 1000MWe

Overview (2/3)

Table of Contents : KCE-1 TR

Overview (3/3)

4.0 CHF Correlation Development

4.1 CHF Test Data
4.2 Local Fluid Condition Calculation
4.3 Correlation Formula and Assumptions
4.4 Correlation Coefficients and Applicable Ranges of Parameters

5.0 Correlation DNBR Limit

5.1 Statistical Analysis for Data Base
5.2 Establishment of Correlation DNBR Limit
5.3 Validation and Verification

6.0 Conclusions

7.0 References

Appendix A Tests and Analyzed Data for KCE-1 CHF Correlation Development
Appendix B Statistical Analysis

PLUS7^{TM} Design Features (1/3)

Reconsitituable top nozzle

- Guide Post, holddown spring and adapter plate remains as an one piece after reconstitution

High burnup fuel rod

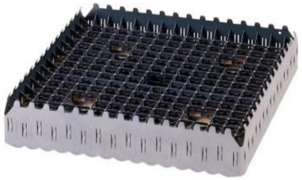
- Advanced Cladding Tube
  → ZIRLO Tube
- **Optimized ROD OD**
  → WH-17type STD Rod OD
- Axial Blanket
  → Improving Neutron Economy

Inconel top/bottom grid for high burnup

Mixing vaned mid grid

- **Mixing Vanes (MV)**
  → Enhancing Thermal Margin
- Straight grid straps
  → Improving Seismic Resistance
- Reducing GTRF
  → conformal grid spring/dimple shape
  → large contact area

Protective grid for debris filtering



Debris filtering bottom nozzle

- Increasing Debris Filtering Efficiency
- Small hole/slot Bottom Nozzle
- Support fuel against GTRF

PLUS7^{TM} Design Features (2/3)

Fuel Assembly	**Guardian**	**PLUS7**
Fuel rods Array in FA	16x16	16x16
Number of Fuel Rods per FA	236	236
Number of Guide Thimble Tubes per FA	4	4
Number of Instrumentation Tubes per FA	1	1
Number of Spacer Grid	Top (1) Mid w/o MV(9) Guardian (1)	Top (1) Mid w/ MV (9) Bottom (1) Protective (1)
	Total (11)	Total (12)
Fuel Rods		
Outer Diameter	0.382 in.	0.374 in.
Pitch	0.506 in.	0.506 in.
Active Fuel Length	150.0 in.	150.0 in.
Guide / Instrumentation Tubes		
Outer Diameter	0.980 in.	0.980 in.

PLUS7^{TM} Design Features (3/3)

- Mid Grid

Test Facility and Test Section (1/6)

- **Heat Transfer Research Facility (HTRF)**
  - Columbia University, New York, NY
  - Qualified Testing Services for PWR, BWR and PHWR Fuels since 1970s
  - Closed on 2003

- **HTRF Components**
  - Heat Transfer Loop
  - Control System
  - Electrical System
  - Instrumentation
  - etc.

Test Facility and Test Section (2/6)

- **Schematics of HTRF**

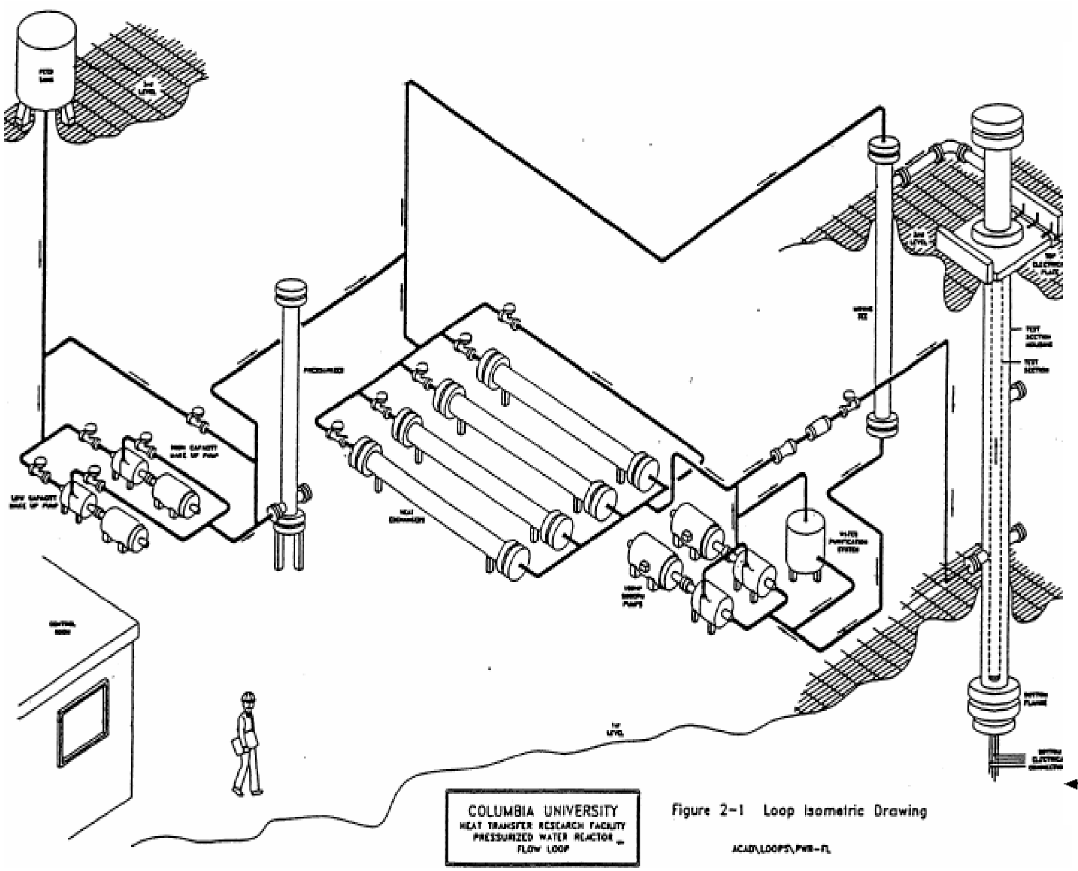
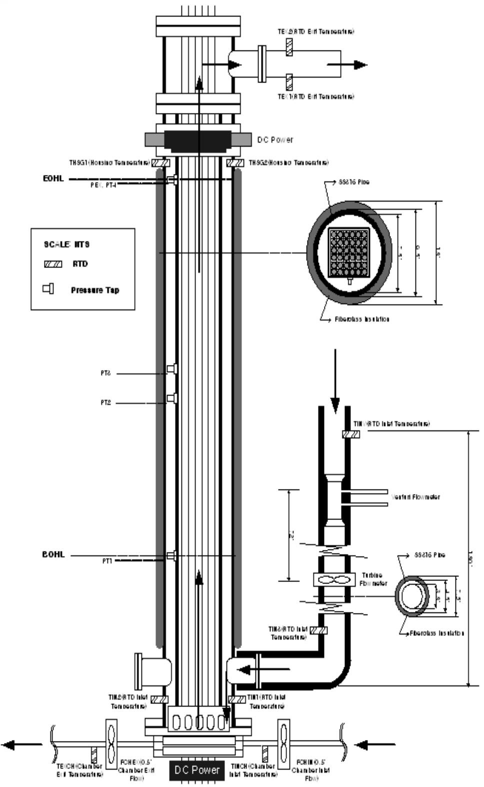


Figure 2-1 Loop Isometric Drawing



Test Facility and Test Section (3/6)

- **HTRF Capacity**
  - Power : ~ 10 MW
  - Inlet Temperature : ~ 650 deg. F
  - Exit Pressure : ~ 2,500 psia
  - Inlet Mass Velocity : ~ 3.7 Mlbm/hr-ft^2

Test Facility and Test Section (4/6)

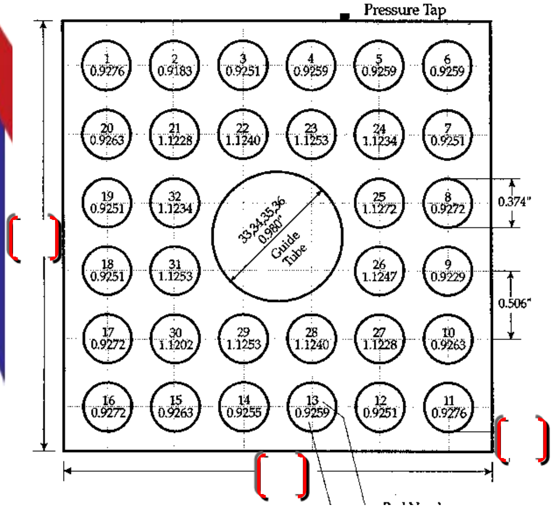
- **Test Section Configuration**

Unit : inch

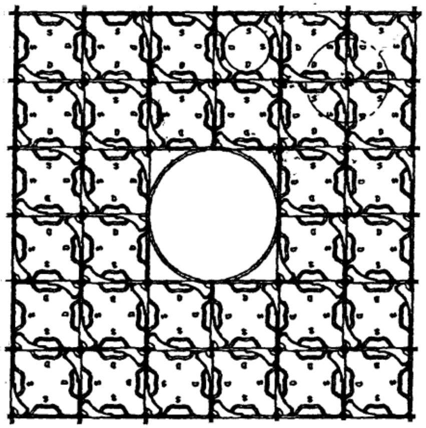
Test Section	Array	Heater Rod			Grid Spacing	Guide Tube Simulator OD	Axial Power Distribution
		OD	Pitch	Length			
101	6x6	0.374	0.506	150.0	15.7	0.980	1.475 Cosine
102						N/A	
PLUS7^{TM}	16x16	Same	Same	Same	Same	0.980	-

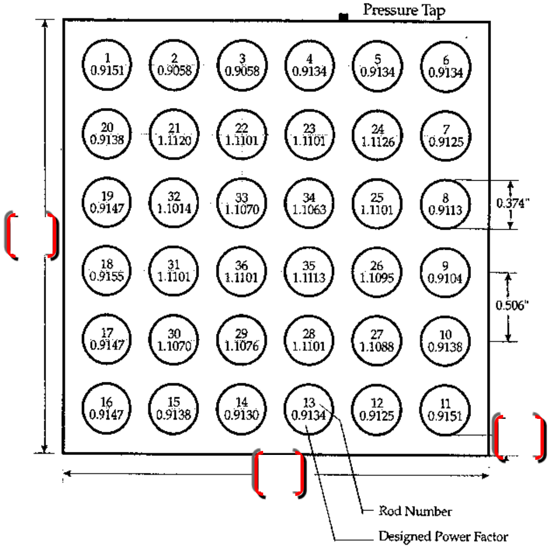
Test Facility and Test Section (5/6)

- **Radial Configuration & Spacer Grids**

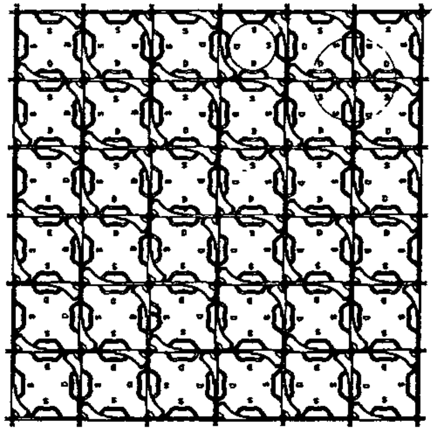


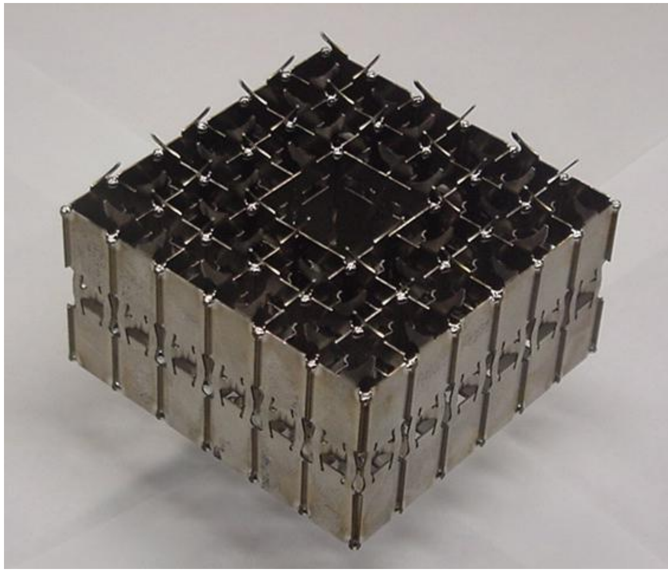
TS101 w/ GT





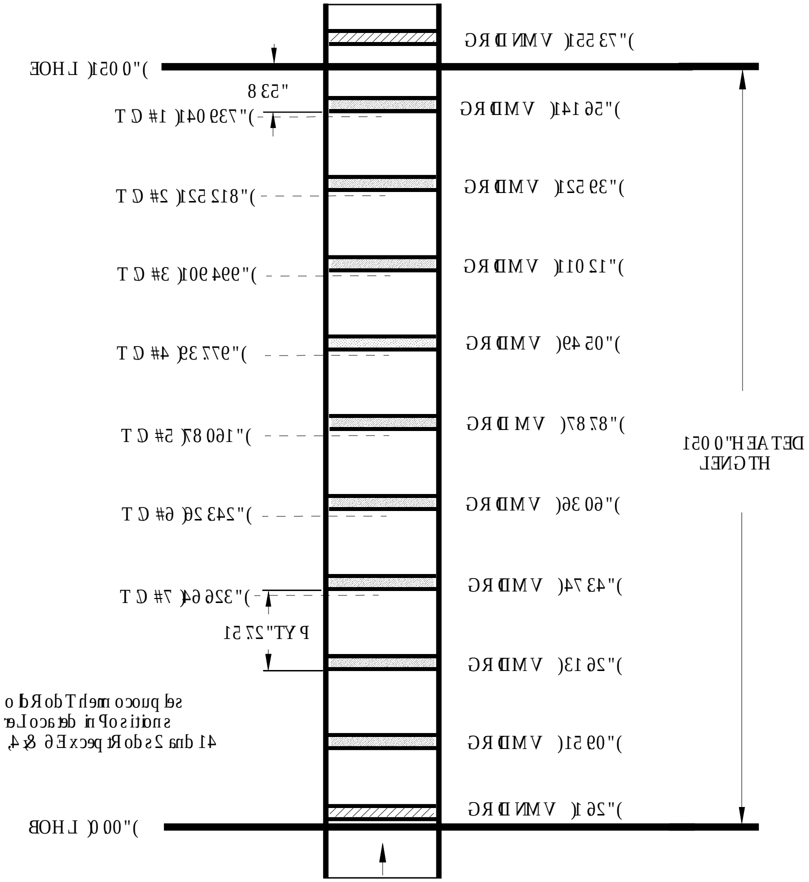
TS102 wo GT

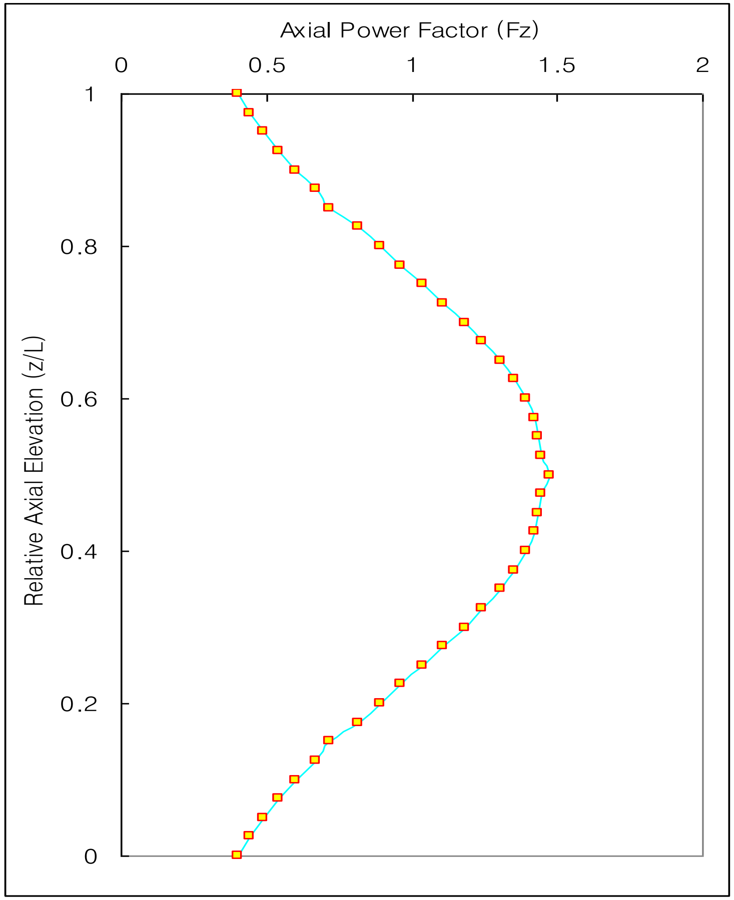




Test Facility and Test Section (6/6)

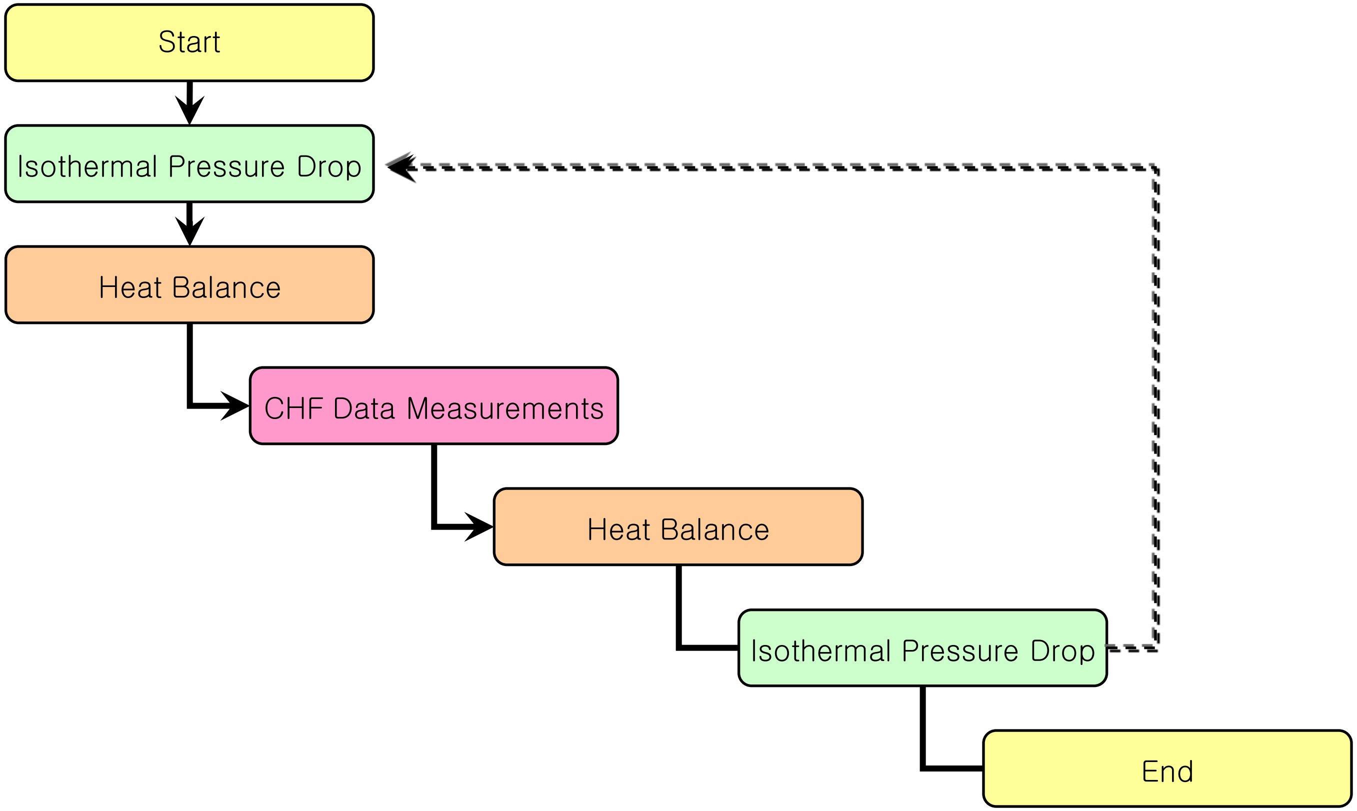
- **Axial Configuration & Power Distribution**





Test Procedure and CHF Measurement (1/6)

- **Flow Chart**


Start

Isothermal Pressure Drop

Heat Balance

CHF Data Measurements

Heat Balance

Isothermal Pressure Drop

End

Test Procedure and CHF Measurement (2/6)

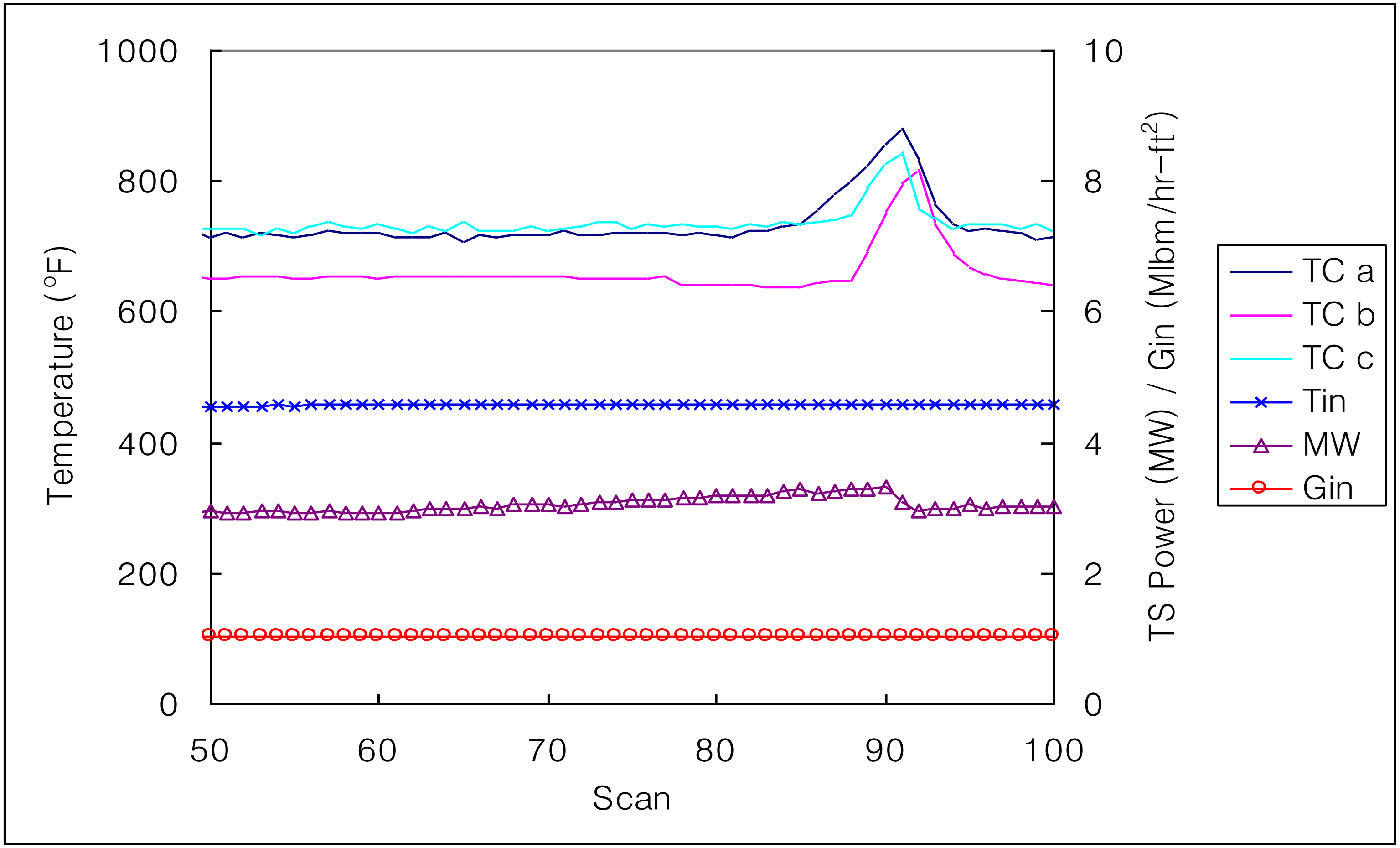
- **Isothermal Pressure Drop**
  - To check the Integrity of System (Test Section)
  - at the Condition of
    - Zero Power (Isothermal)
    - Low Pressure & Low Temperature
    - Various Flow Ranges
- **Heat Balance**
  - To check Heat Loss & Instrumentation Operability
  - at the Condition of
    - Low Power
    - Low Pressure
    - Single-Phase Fluid Condition

Test Procedure and CHF Measurement (3/6)

- **CHF Measurement**
  - Power Escalation
  - Maintaining Other Loop Parameters (Tin, Gin, Pexit) as Stable
  - Rate of Power Increase : Infinitesimal
  - Records
    - System Pressure
    - Inlet Mass Velocity
    - Inlet Temperature
    - Bundle Power
    - CHF Locations (Heater Rods & T/Cs)

Test Procedure and CHF Measurement (4/6)

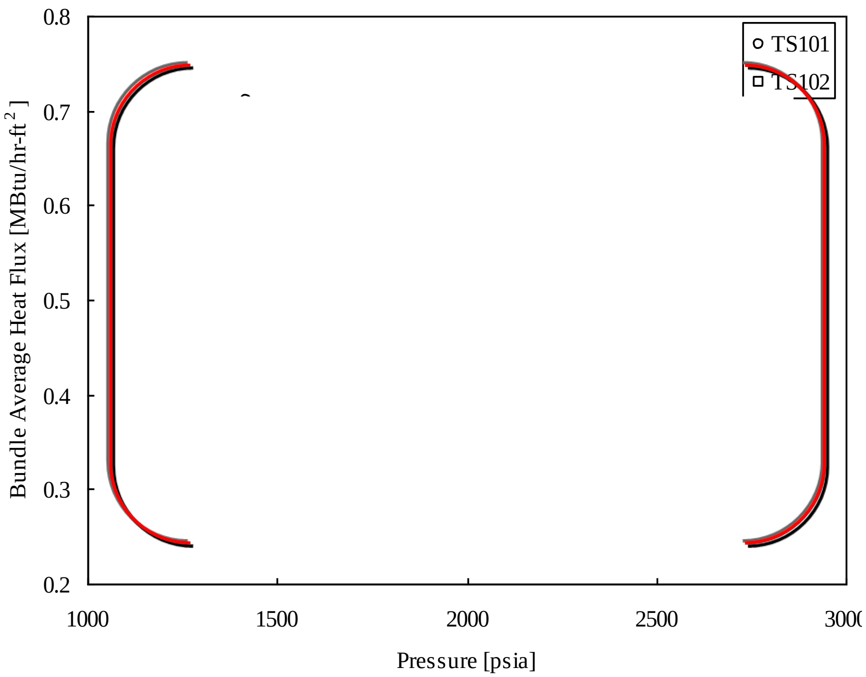
- Typical CHF Trace

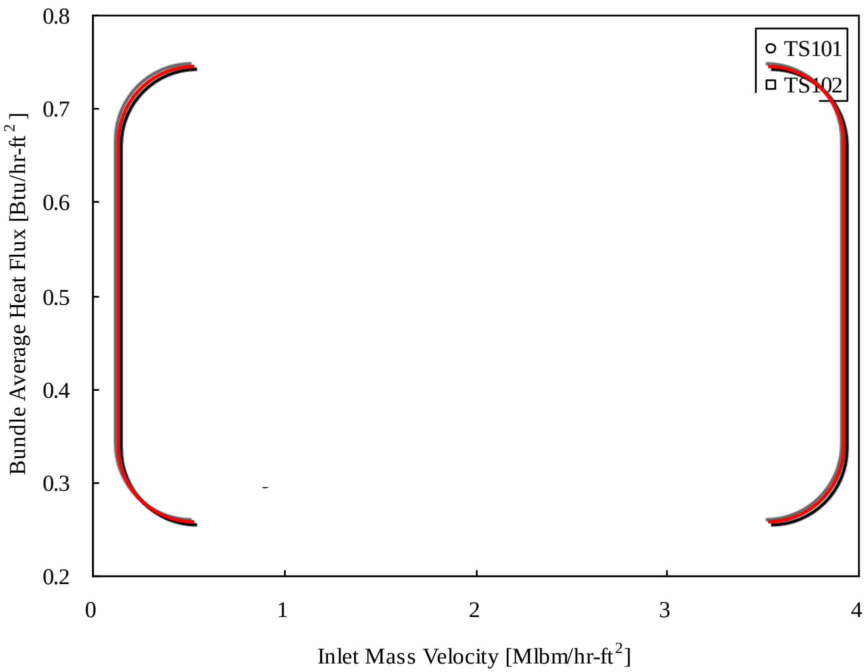


Test Procedure and CHF Measurement (5/6)

(CHF Test Data)

- **Total 219 CHF Data for PLUS7™**
  - 112 from TS101 (TS with GT)
  - 107 from TS102 (TS without GT)





Test Procedure and CHF Measurement (6/6)

- **Summary of Test Progress**
  - **CHF Test Requirements** : February 2001
  - **Test Prospectus** : April 2001
  - **QA Audit** : April 2001
  - **Testing** : May 2001 ~ July 2001
  - **Reporting** : August 2001 ~ May 2002

CHF Correlation Development (1/16)

- **Design Method/Assumption**
  - Subchannel Code : TORC
  - Design Constitutive Relations
  - No Conversion to Equivalent-Uniform Heat Flux (Assumed : Non-Uniform Heat Flux → Uniform Heat Flux)

- **Functional Formula**
  - CE-1 CHF Correlation (CENPD-162-P-A, 1976)

- **Specific Consideration**
  - Local Fluid Conditions per Channel Types
  - Tong F Factor (F_{Tong}) = 1.0 on Development,

    F_{Tong} = as Calculated (≥ 1.0) on Design Application
  - Resulting in some Conservatism

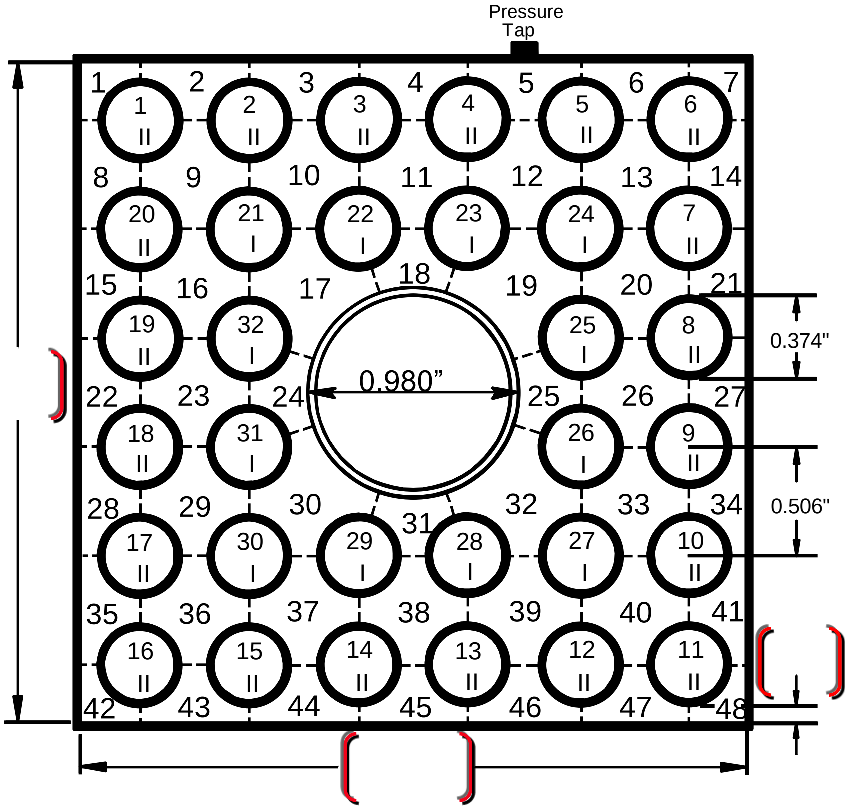
CHF Correlation Development (2/16)

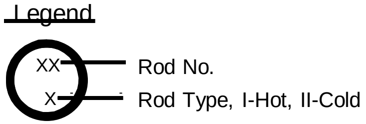
- **Subchannel Code TORC**
  - COBRA IIIC
  - Multi/Open Channel (steady-state)
  - Approved for Reactor Thermal Analysis (CENPD-161-P-A, 1986)
- **Design Constitutive Relations (w/ TORC)**
  - Single/Two Phase Friction Factor
  - Crossflow Model
  - Two Phase Void-Quality Model
  - Thermal Mixing Model
  - etc.

CHF Correlation Development (3/16)

- **Specific Consideration-1 :**
  Extraction of Local Fluid Conditions per Types of Subchannel

- 3 Types of Channels (Inner)
- Channel with Maximum Quality for same Type of Channels
- 1 to 3 Local Fluid Conditions per Datum





CHF Correlation Development (4/16)

- **Specific Consideration-2 : Application of F_{Tong}**
  - Development Stage (CHF Data)
    - DNBR = $q''_{CHF,\ Pred} / q''_{CHF,\ Meas}$ (= $1/ [q''_{CHF,\ Meas} / q''_{CHF,\ Pred}]$)
    - $F_{Tong} = 1.0$: No Conversion to Equivalent-Uniform Heat Flux
    - $q''_{CHF,\ Pred\ (development)} = q''_{CHF,\ KCE\text{-}1U} \sim q''_{CHF,\ Meas}$
  - Application Stage (Reactor Thermal Design)
    - DNBR = $q''_{CHF,\ Pred} / q''_{local,\ Actual}$
    - F_{Tong} = as calculated (≥ 1.0) : Correct the effects of Non-Uniform Axial Power Distribution (NU APD) on CHF
    - $q''_{CHF,\ Pred\ (application)} = q''_{CHF,\ KCE\text{-}1U} / F_{Tong} \leq q''_{CHF,\ Meas}$
  - $q''_{CHF,\ NU} \leq q''_{CHF,\ U}$

CHF Correlation Development (5/16)

- **F_{Tong} : Correction Factor for the effects of NU APD on CHF**
  - $F_{Tong} = q''_{CHF,\,U} / q''_{CHF,\,NU}$
  - Relevant References
    - Tong, L.S., Journal of Nuclear Energy 21 (1967)
    - Rosal, E.R., et. al., Nuclear Engineering and Design 31 (1974)
    - CENPD-207-P-A (1984)

$$F_{Tong} = \frac{C}{q''_l \cdot [1.0 - \exp(-C \cdot l)]} \cdot \int_{ZS}^{l} q''(z) \cdot \exp[-C \cdot (l - z)]\, dz$$

$$C = d_1 \cdot \frac{(1 - X_{loc})^{d_2}}{(G_{loc}/10^6)^{d_3}} \qquad [1/inch]$$

where

d_1 = 1.5000000E-01
d_2 = 4.3100000E+00
d_3 = 4.7800000E-01

CHF Correlation Development (6/16)

- **Correlation Detail**

$$q''_{CHF,KCE-1U} =$$

Coefficient	CE-1	KCE-1
B_1		
B_2		
B_3		
B_4		
B_5		
B_6		
B_7		
B_8		

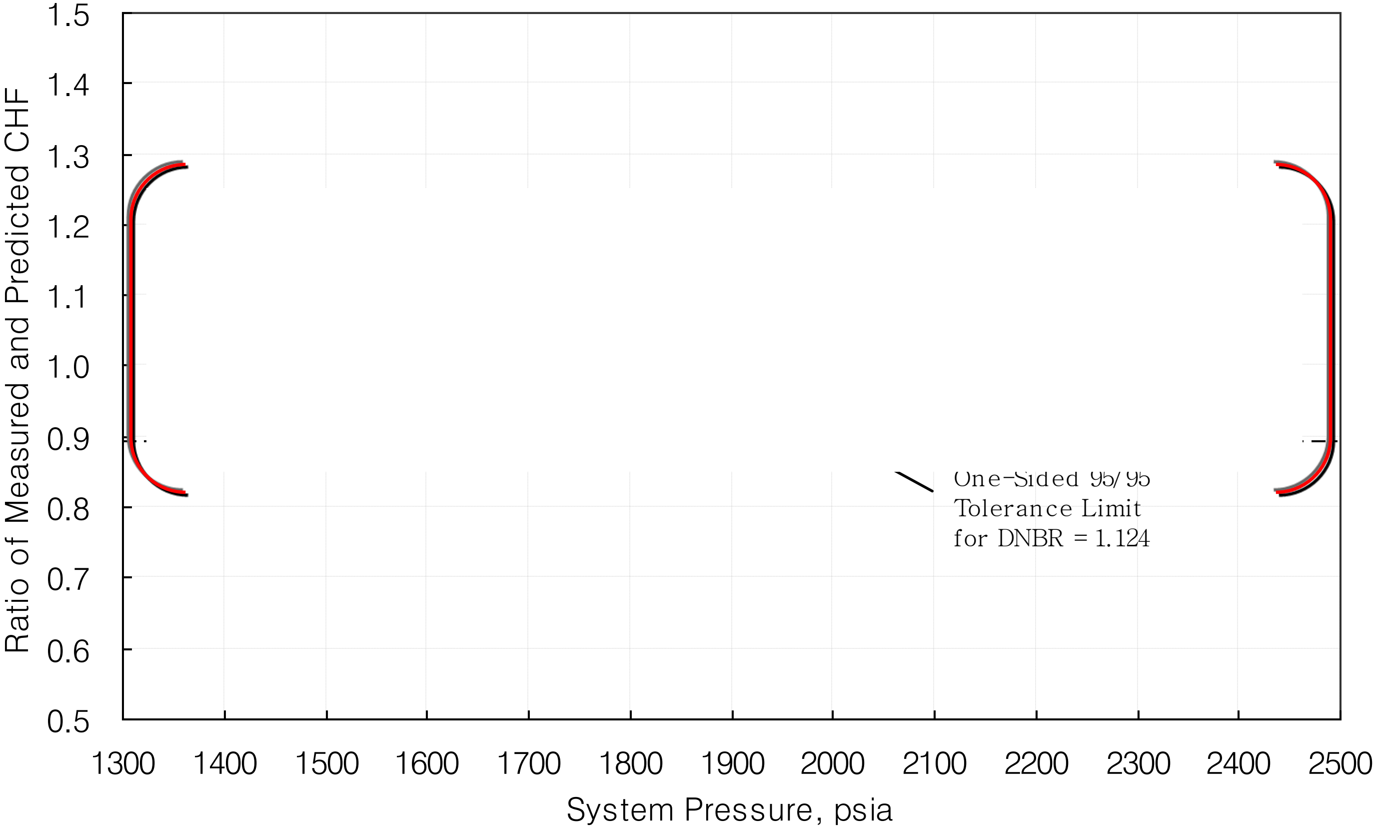
TS	*n*	Average $\bar{x}_{(M/P)}$	STD $s_{(M/P)}$
101	225		
102	96		
ALL	321		

Parameter Range	CE-1	KCE-1
Pressure, psia	1785 ~ 2415	1395 ~ 2415
Mass Velocity, Mlbm/hr-ft^2	0.87 ~ 3.21	0.85 ~ 3.15
Local Quality	-0.16 ~ 0.20	-0.15 ~ 0.28

CHF Correlation Development (7/16)

(Validation & Verification)

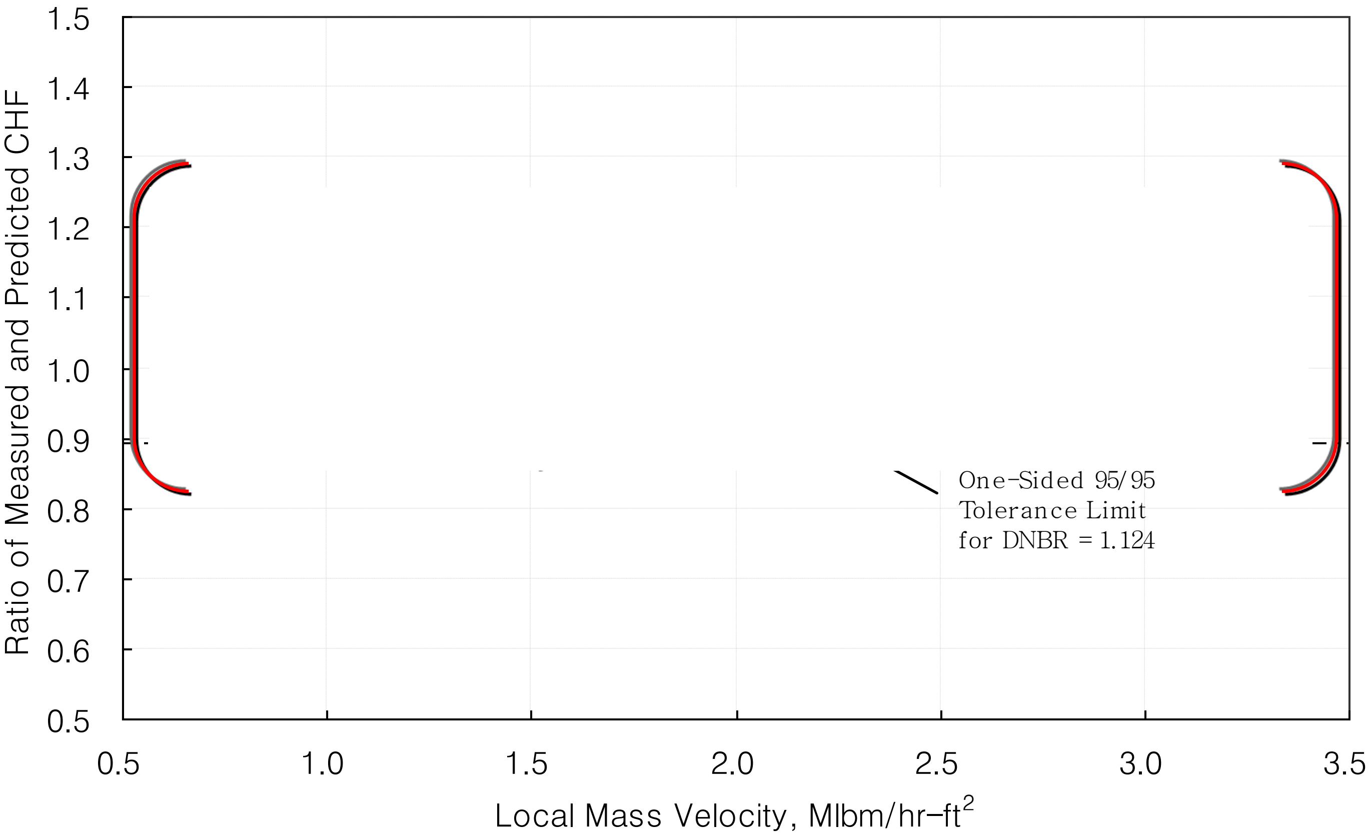
- **M/P Parametric Trends w.r.t. Pressure**



CHF Correlation Development (8/16)

(Validation & Verification)

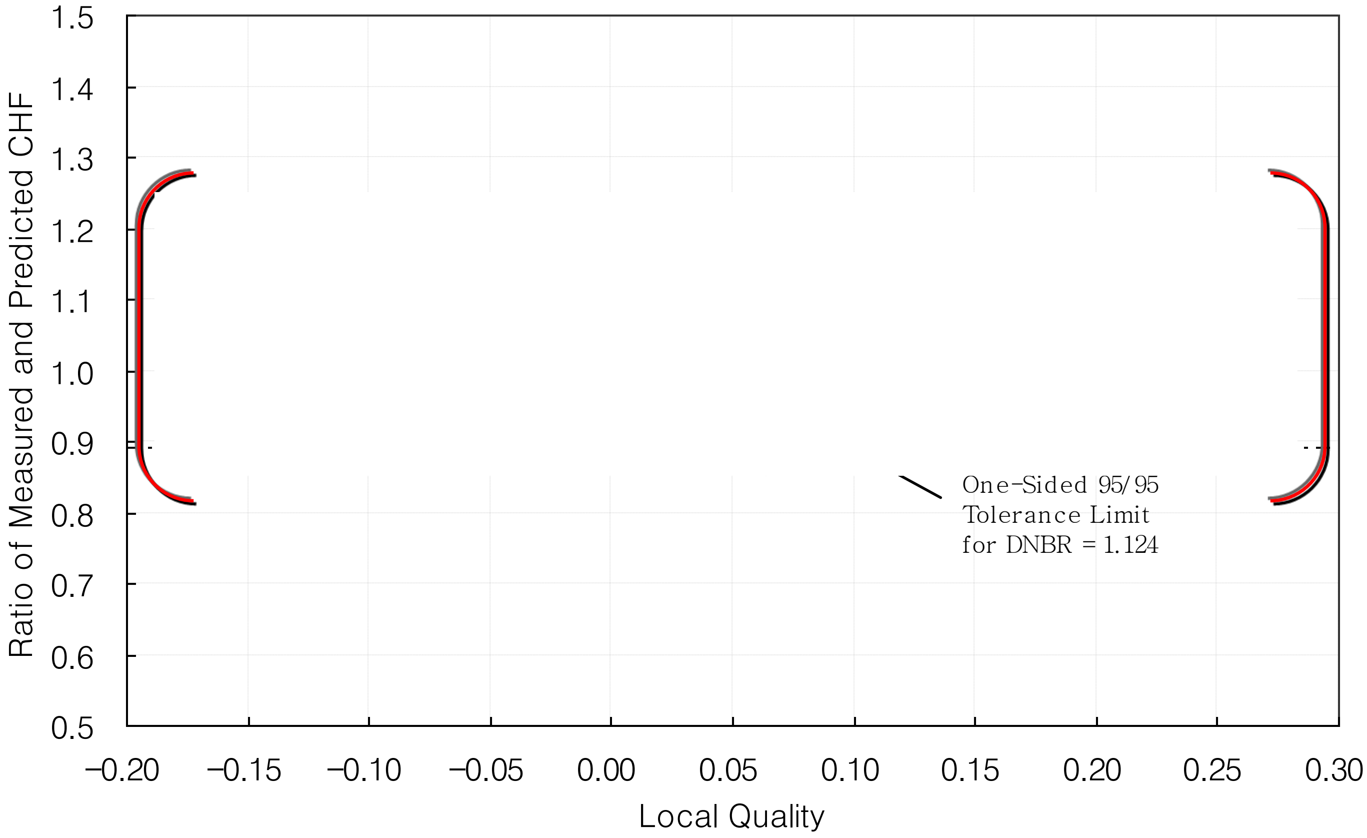
- **M/P Parametric Trends w.r.t. Local Mass Velocity**



CHF Correlation Development (9/16)

(Validation & Verification)

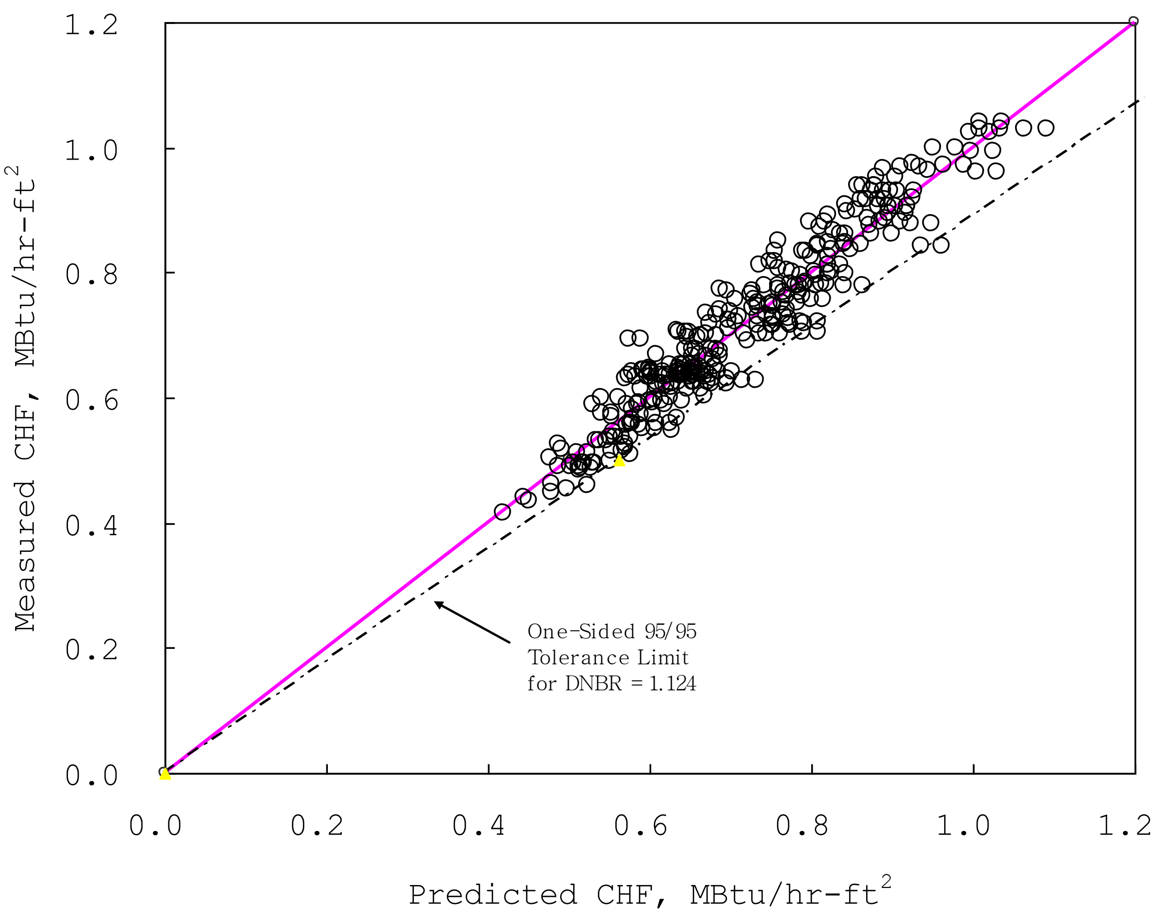
- **M/P Parametric Trends w.r.t. Local Quality**



CHF Correlation Development (10/16)

(Validation & Verification)

- **Measured CHF vs. Predicted CHF Trends**



CHF Correlation Development (11/16)

(Validation & Verification)

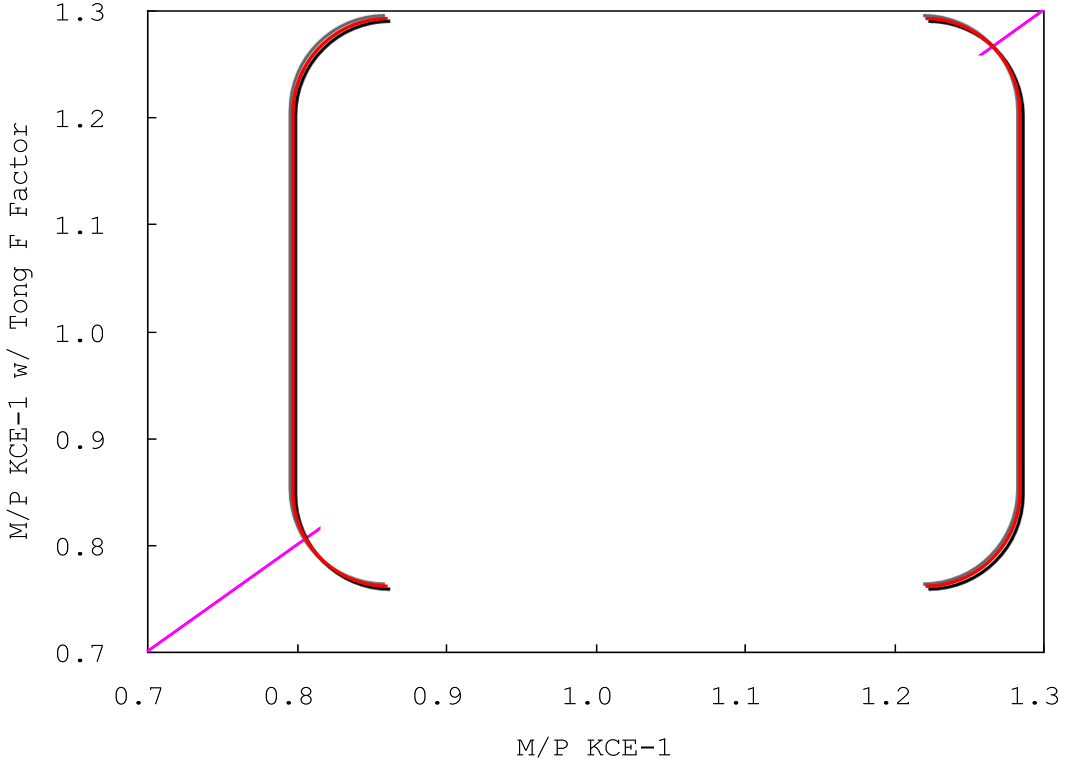
- **Validity of Specific Consideration-1**
  - Confirmed by Comparison of the 95x95 DNBR Limits
    - w/ Specific Considerarion-1 : 1.124 (see page 38)
    - w/o Specific Considerarion-1 : 1.112 (see Table below)
  - Conservative & Valid
  - Statistics of KCE-1 CHF Correlation w/o Specific Cosideration-1

TS	n	$\bar{x}_{(M/P)}$	$s_{(M/P)}$	95x95 DNBR Limit
101	108			
102	96			1.087
ALL	204			

CHF Correlation Development (12/16)

(Validation & Verification)

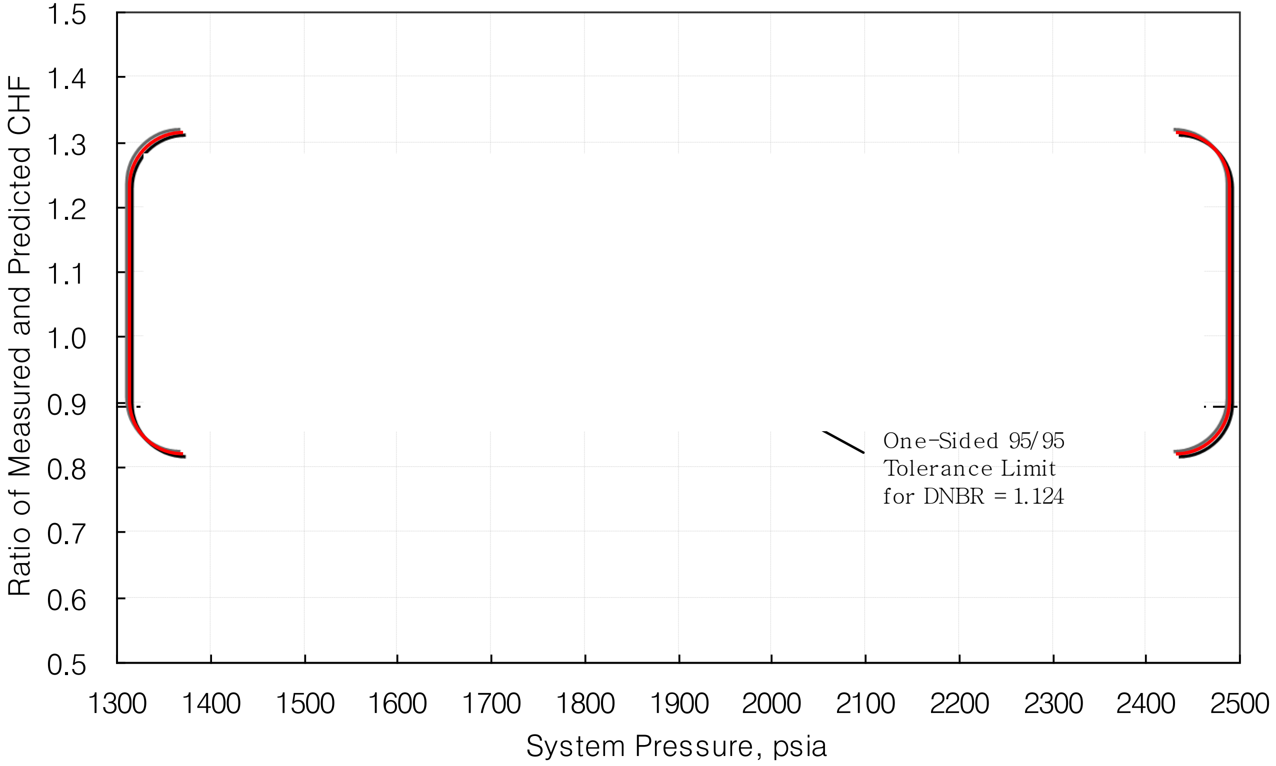
- **Validity of Specific Consideration-2**
  - Comparison of M/P for CHF Data (w/ Tong F Factor vs. w/o Tong F Factor)



CHF Correlation Development (13/16)

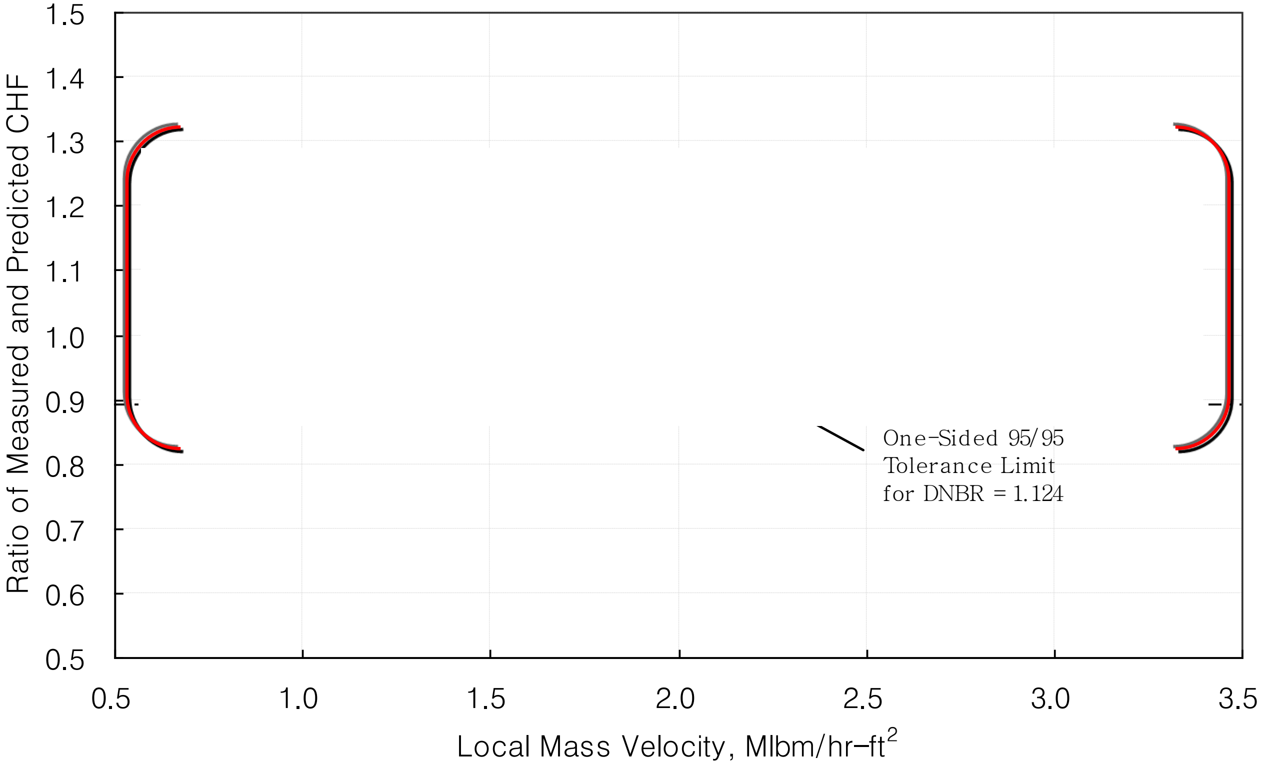
(Validation & Verification)

- Validity of Specific Consideration-2
  - M/P Trends w/ F_{Tong} Application to CHF Data (w.r.t. Pressure)



CHF Correlation Development (14/16)
(Validation & Verification)

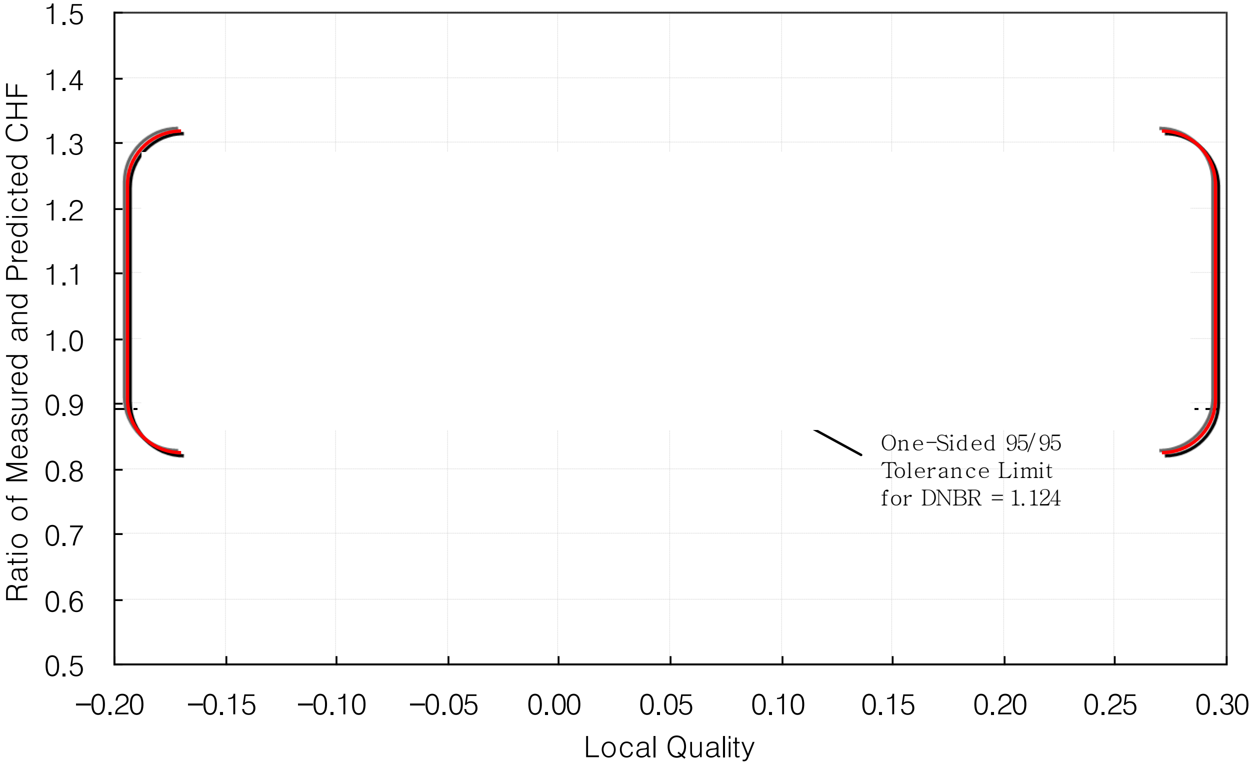
- **Validity of Specific Consideration-2**
  - M/P Trends w/ F_{Tong} Application to CHF Data (w.r.t. Local Mass Velocity)



CHF Correlation Development (15/16)

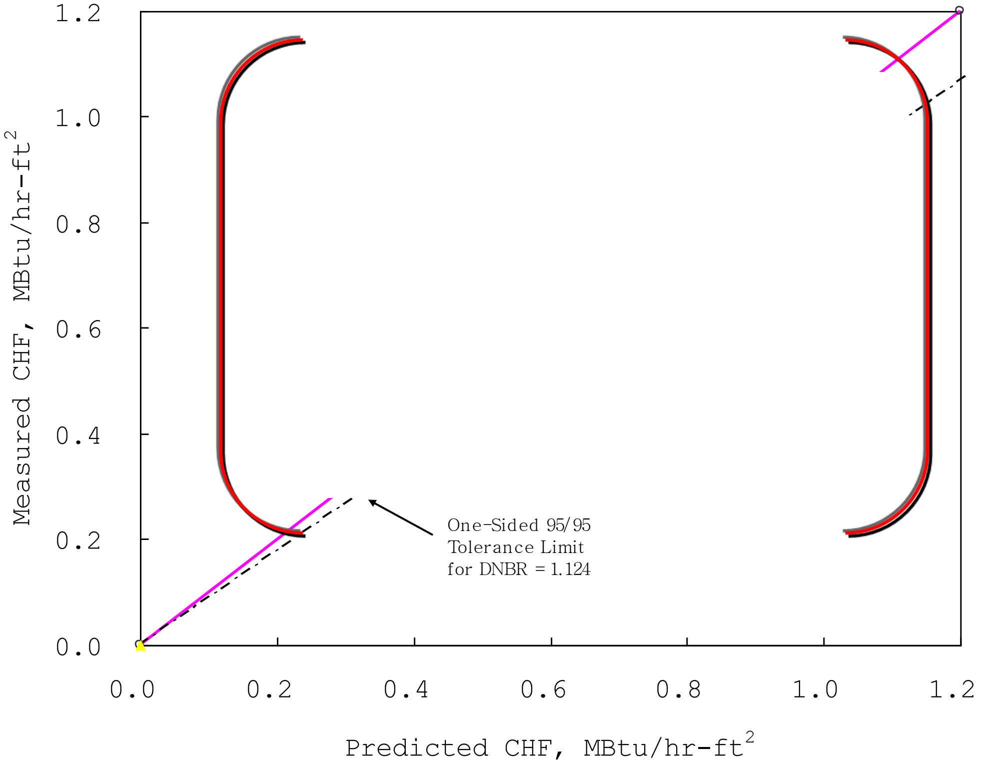
(Validation & Verification)

- Validity of Specific Consideration-2
  - M/P Trends w/ F_{Tong} Application to CHF Data (w.r.t. Local Quality)



CHF Correlation Development (16/16)
(Validation & Verification)

- **Validity of Specific Consideration-2**
  - M/P Trends w/ F_{Tong} Application to CHF Data (Measured CHF vs. Predicted CHF)



Correlation DNBR Limit (1/4)

- **Statistical Analysis**
  - Distribution Characteristics
    - D′-test/ W-test (ANSI N15.15-1974)
    - Parametric or Non-Parametric
  - Poolability
    - Parametric : F (Bartlett) test / T test
    - Non-Parametric : Wilcoxon-Mann-Whitney test
  - Outlier

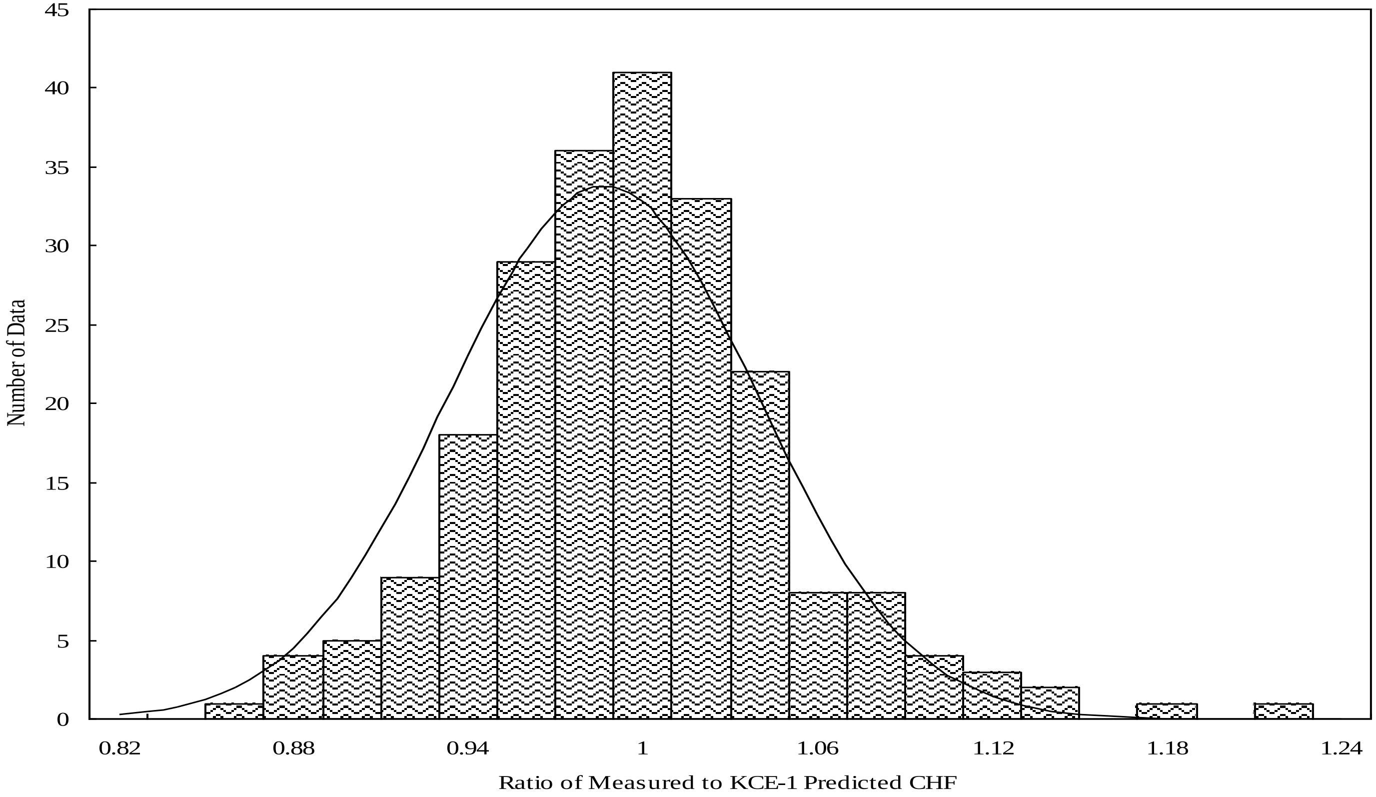
- **95x95 Limit**
  - Parametric : Inverse of M/P Lower Bound with Owen's 1-side Tolerance Factor (SCR-607, 1963)
  - Non-Parametric : Inverse of M/P at m-th rank (Experimental Statistics, Handbook 91, National Bureau of Standards, 1966)

Correlation DNBR Limit (2/4)

- **Distribution Characteristics**
  - D'-test
    - Pass : TS102, ALL (Combined)
    - Fail : TS101
  - Parametric and/or Non-Parametric
- **Poolability (TS101 & TS102)**
  - Parametric
    - F (Bartlett) Test : Pass
    - T Test : Fail
  - Non-Parametric
    - Wilcoxon-Mann-Whitney Test : Fail
- **Outlier**
  - 1 data from TS102

Correlation DNBR Limit (3/4)

- **M/P Frequency Distribution (TS101)**



Correlation DNBR Limit (4/4)

- **95x95 DNBR Limit**
  - Parametric

TS	n	$\bar{x}_{(M/P)}$	$s_{(M/P)}$	K_{95x95}	95x95 DNBR Limit
101	225			1.824	1.124
102	96			1.929	1.087
ALL	321			1.795	1.116

  - Non-Parametric

TS	γ	P	n	m	RunID	M/P	95x95 DNBR Limit
101	0.95	0.95	225	6			

Conclusion

- **CHF Test**
  - HTRF
  - 6x6 Rod Bundle (Best Representative of PLUS7^{TM})
  - NU APD (1.5 Cosine)
- **KCE-1 CHF Correlation**
  - Same Functional Formula with CE-1
  - Design Subchannel Code/Constitutive Relations
  - 95x95 Limit : 1.124
  - Specific Consideration resulting in Conservatism
- **Applied to APR1400 & OPR1000 Design Analysis**

Experiences of Design Application

- **Lead Test Assembly : 3 Cycles in an OPR1000**
- **Final Safety Analysis Report**
  - Reload Core Design : All OPR1000s on Operation
  - Initial Core Design : APR1400s in Republic of Korea under Construction

Acronyms

APD : Axial Power Distribution
CHF or q''_{CHF} : Critical Heat Flux
DH, DHM : Heated Diameter of Subchannel and DH of Matrix Subchannel, respectively
DNBR : Departure from Nucleated Boiling Ratio
F_{Tong} : Tong F Factor, Correction factor for the effects of NU APD on CHF
G or G_{loc} : Local Mass Velocity
Gin : Inlet Mass Velocity
h_{fg} : Latent Heat
K_{95x95} : Owen’s 1-side tolerance factor (per 95% probability with 95% confidence)
M/P : Ratio of Measured and Predicted CHF
n : Number of Data
NU, U : Non-Uniform and Uniform, respectively
OD : Outside Diameter
P or Pexit : System Pressure
$q''_{CHF,\ KCE-1}$: Predicted Critical Heat Flux by KCE-1 CHF Correlation
q''_{l} or $q''_{local,\ Actual}$: Actual Local Heat Flux
$q''_{CHF,\ Meas}$: Measured Critical Heat Flux
$q''_{CHF,\ Pred}$: Predicted Critical Heat Flux
STD : Standard Deviation
T/C : Thermocouple
Tin : Inlet Temperature
TS : Test Section
x or X_{loc} : Local Quality
z : Axial elevation
zs : Starting axial elevation for integration (per definition of F_{Tong})