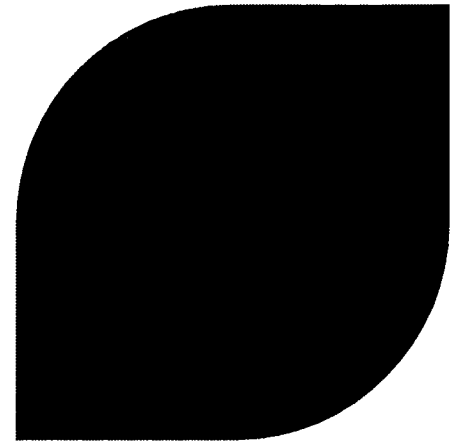


CHF Correlations for GAIA Fuel Assembly

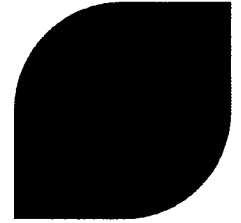
Pre-submittal Tactical Meeting

AREVA/NRC Meeting
Rockville, MD
May 28, 2015

Steven Lydzinski
Manager
US PWR Fuels, Thermal-Hydraulics
AREVA Inc.

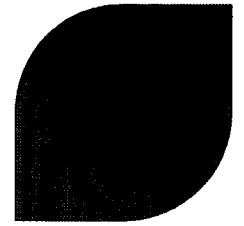


Acronyms



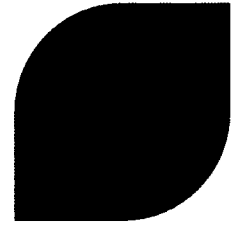
- ◆ **CFD – Computational Fluid Dynamics**
- ◆ **CHF – Critical Heat Flux**
- ◆ **DNB – Departure from Nucleate Boiling**
- ◆ **EOHL – End of Heated Length**
- ◆ **GAIA – AREVA's advanced fuel assembly design for PWR reactors**
- ◆ **GT – Guide Tube**
- ◆ **HMP – High Mechanical Performance**
- ◆ **HTP – High Thermal Performance**
- ◆ **IFM – Intermediate Flow Mixer**
- ◆ **IGM – Intermediate GAIA Mixer**
- ◆ **KATHY – KARlstein Thermal-HYdraulic test facility**
- ◆ **MDNBR – Minimum Departure from Nucleate Boiling Ratio**
- ◆ **ORFEO – Advanced CHF correlation form**

Agenda



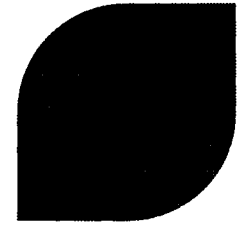
- ▶ **Objective and Schedule**
- ▶ **GAIA Fuel Assembly Design**
- ▶ **KATHY CHF Testing Facility**
- ▶ **CHF Testing Program for GAIA**
- ▶ **CHF Correlations for GAIA**
- ▶ **Topical Report Content**
- ▶ **Summary and Discussions**

Agenda



- ▶ **Objective and Schedule**
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- ▶ **Summary and Discussions**

Objective



- ▶ To discuss the [] Topical Report submittal for two CHF correlations applicable to GAIA fuel assembly design
 - ◆ CHF correlation based on the mixing (vaned) grid tests (GAIA structural grid and IGM grid)
 - ◆ CHF correlation based on the non-mixing (vaneless) grid tests (including HMP grid)
- ▶ As previously discussed with NRC, there will be one Topical Report submittal that will include both CHF correlations

Schedule

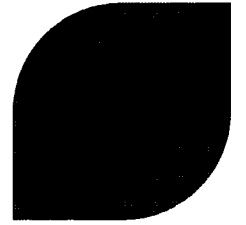


- ▶ **Pre-submittal tactical meeting (strategy and scope) – May 2015**
- ▶ **Pre-submittal meeting (content) – []**
- ▶ **Topical Report submittal to NRC – []**
- ▶ **Post-submittal meeting – []**
- ▶ **Additional meetings/technical audits as needed**



NRC approval is requested by []

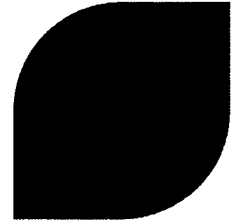
The Review Has Already Started ...



- **NRC staff members visited AREVA's KATHY test facility in Karlstein, Germany to observe a GAIA CHF test in March 2015**



Agenda



- ▶ **Objective and Schedule**
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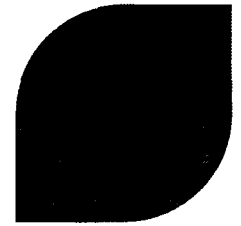
GAIA Fuel Assembly Design *Geometry*



1

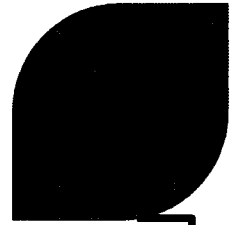
GAIA Fuel Assembly Design

Spacer Grids



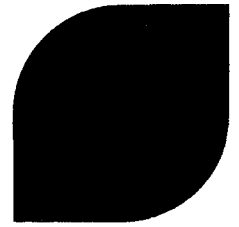
GAIA Fuel Assembly Design

Spacer Grids



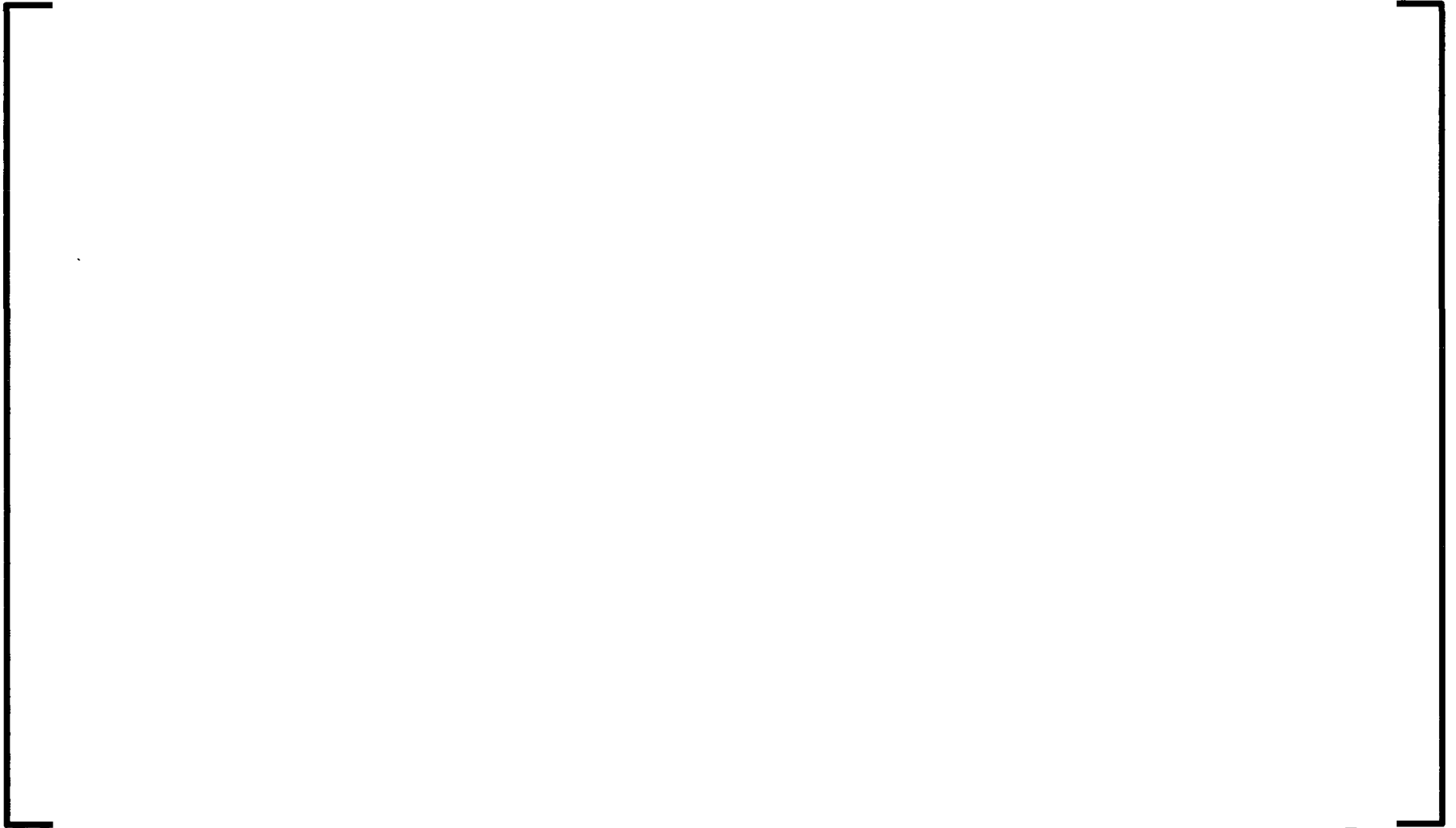
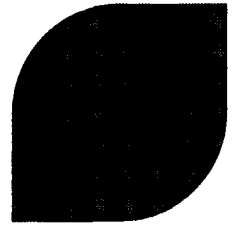
GAIA Fuel Assembly Design

Spacer Grids



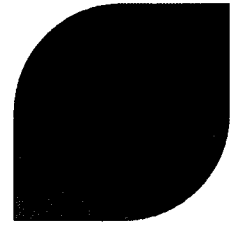
GAIA Fuel Assembly Design

Spacer Grids



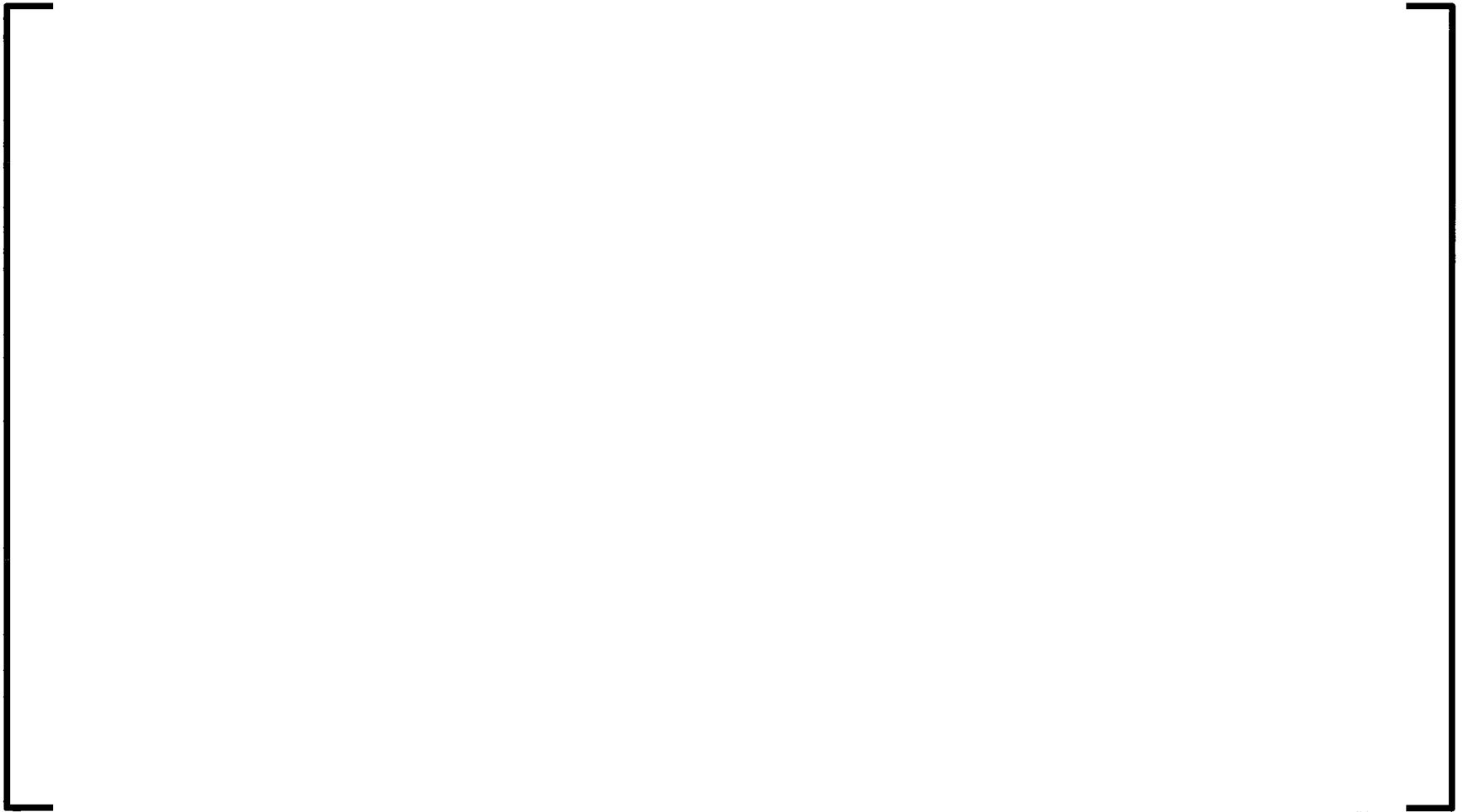
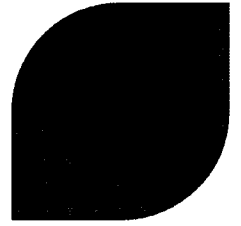
GAIA Fuel Assembly Design

Spacer Grids



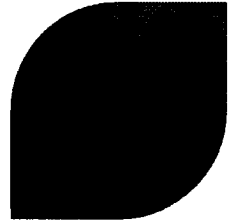
GAIA Fuel Assembly Design

Spacer Grids

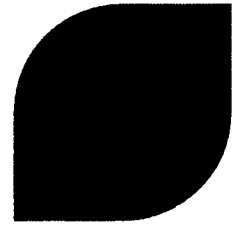


GAIA Fuel Assembly Design

Spacer Grids



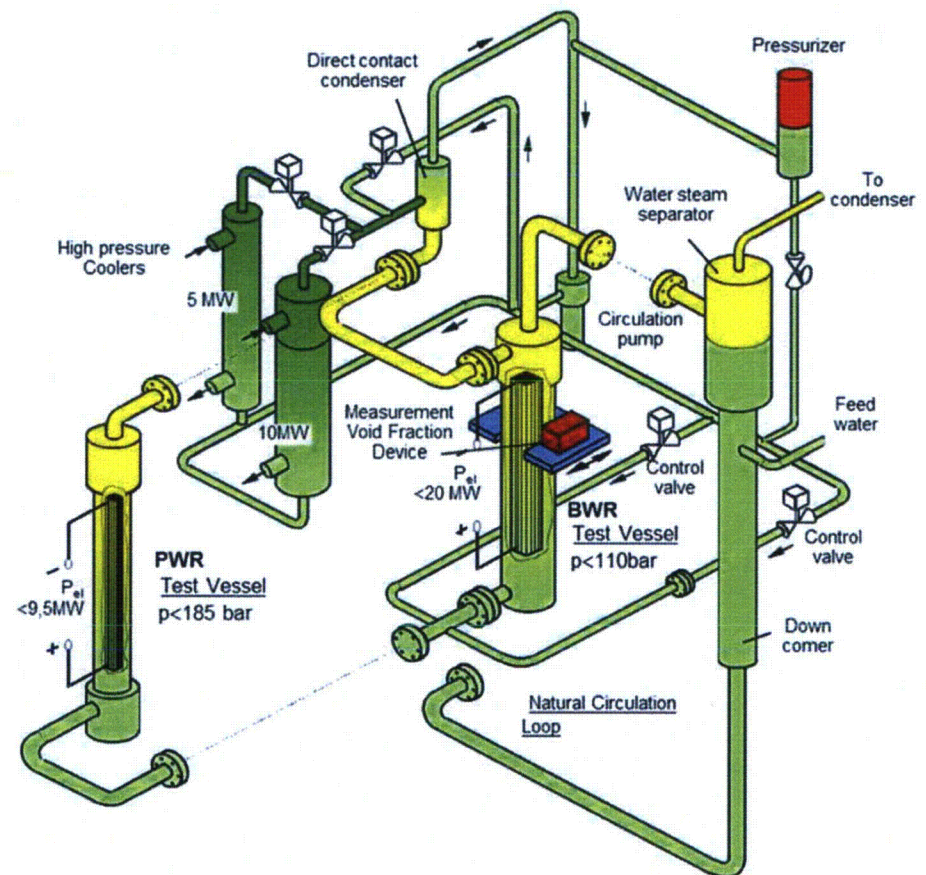
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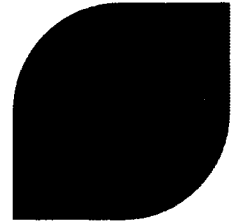
KATHY CHF Testing Facility Description

- ▶ **K**arlsruhe **T**hermal-**H**Ydraulic test facility operated by AREVA
- ▶ Used for research, development and licensing of PWR and BWR nuclear fuel assemblies
- ▶ Facility start-up: 1986
- ▶ Extended qualification in 2002 and 2003 for PWR measurements
- ▶ More than 80 PWR DNB tests
- ▶ More than 140 BWR dryout tests



KATHY CHF Testing Facility

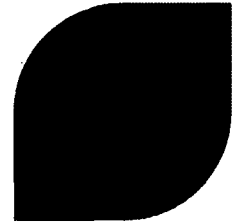
Qualification



► The GAIA measured CHF performance is obtained from a qualified test facility

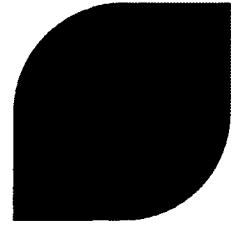
- ◆ **KATHY was qualified during the ACH-2 CHF correlation review process by performing a comparison against Columbia University's HTRF**
- ◆ **The ACH-2 CHF correlation (for the US EPR fuel design) approved by NRC in 2007 (ANP-10269P-A) was the first US PWR application based on CHF test data collected in KATHY**
- ◆ **Benchmarked to OMEGA loop (France)**
- ◆ **The AREVA's sole source of new CHF measurements for the past 10 years**

Compliance with Regulatory Requirements



- ▶ **The CHF testing performed in the KATHY loop complies with the regulatory requirements of 10 CFR 50 Appendix B (Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants)**
- ▶ **The CHF correlations applicable to GAIA fuel assembly comply with the requirements of NUREG-0800 (Standard Review Plan) Sections 4.2 and 4.4**

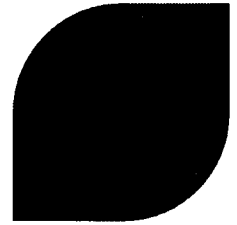
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CHF Testing Program for GAIA

Test Basis

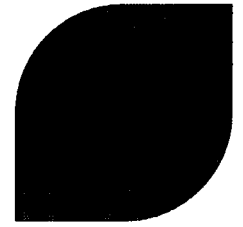


► Mixing grid (GAIA, IGM)

- ◆ Over [] CHF tests representative of a 17x17 geometry have been performed during the development and characterization of the GAIA grid
- ◆ The majority are associated with the interstitial grid design
- ◆ Multiple grid variants and sub-variants have been tested to isolate desired CHF results
- ◆ After the GAIA structural grid and the IGM grid designs were set, the licensing CHF tests were performed

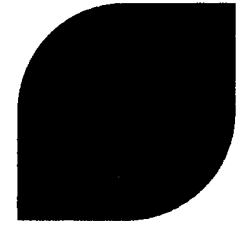
CHF Testing Program for GAIA

Test Assembly Configurations



CHF Testing Program for GAIA

Test Basis and Assy. Configuration



► Non-mixing grid

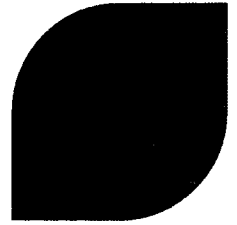
◆ Database includes CHF test data collected for

◆ Database includes CHF test data collected in the following test loops

- ARC (Alliance Research Center, USA)
- HTRF (Columbia University, USA)
- OMEGA (France)
- KATHY (Germany)
- EURATOM (Italy)

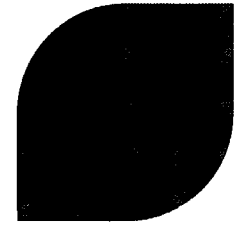
CHF Testing Program for GAIA

Data Collection Ranges

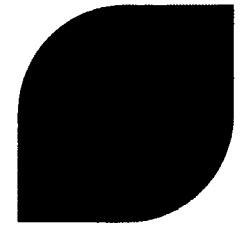


CHF Testing Program for GAIA

Data Collection Ranges



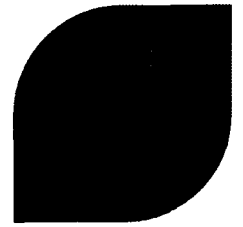
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CHF Correlations for GAIA

Functional form

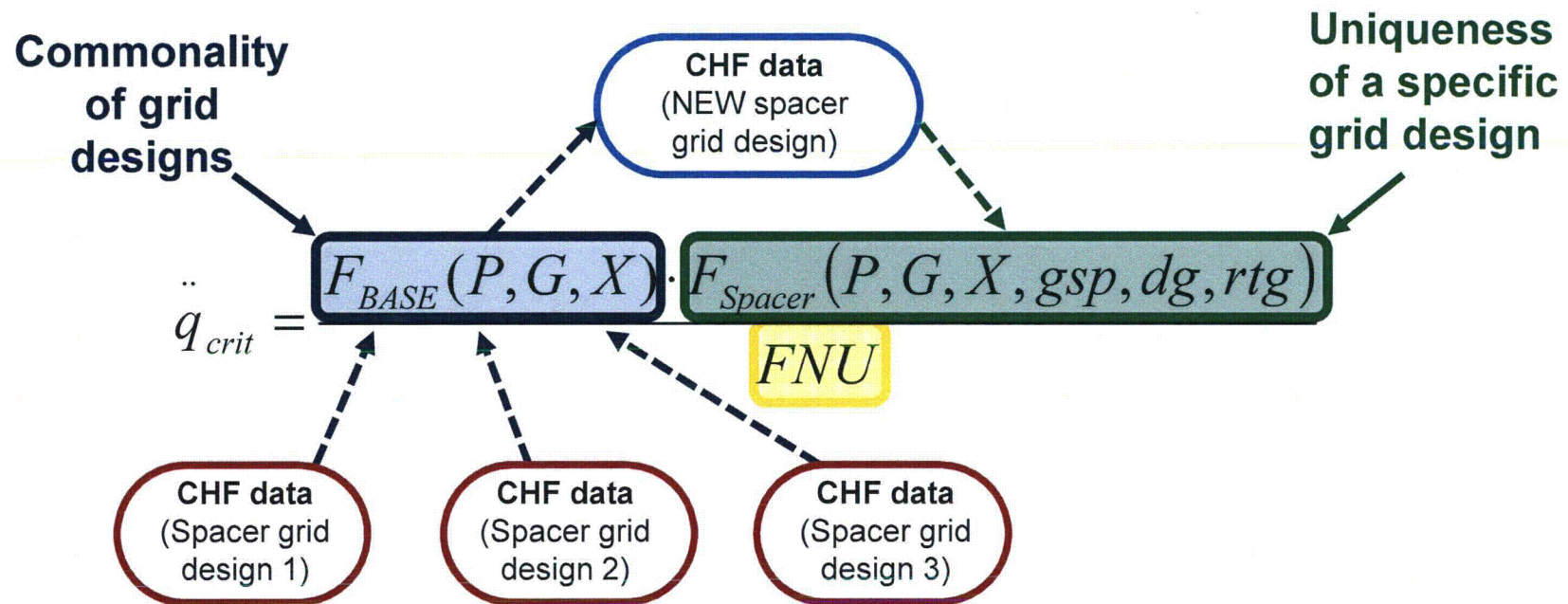


- ▶ **Development of an advanced correlation form (ORFEO) started in 2006**
- ▶ **ORFEO utilizes a modular approach, consisting of**
 - ◇ **A general representation term (PGX) based on multiple grid designs,**
 - ◇ **A specific adjustment term based on a specific grid design, and**
 - ◇ **A correction factor to account for non-uniform axial power profiles**
- ▶ **ORFEO form is used for both CHF correlations applicable to GAIA fuel assembly**
 - ◇ **CHF correlation based on the mixing grid tests**
 - ◇ **CHF correlation based on the non-mixing grid tests**

CHF Correlations for GAIA

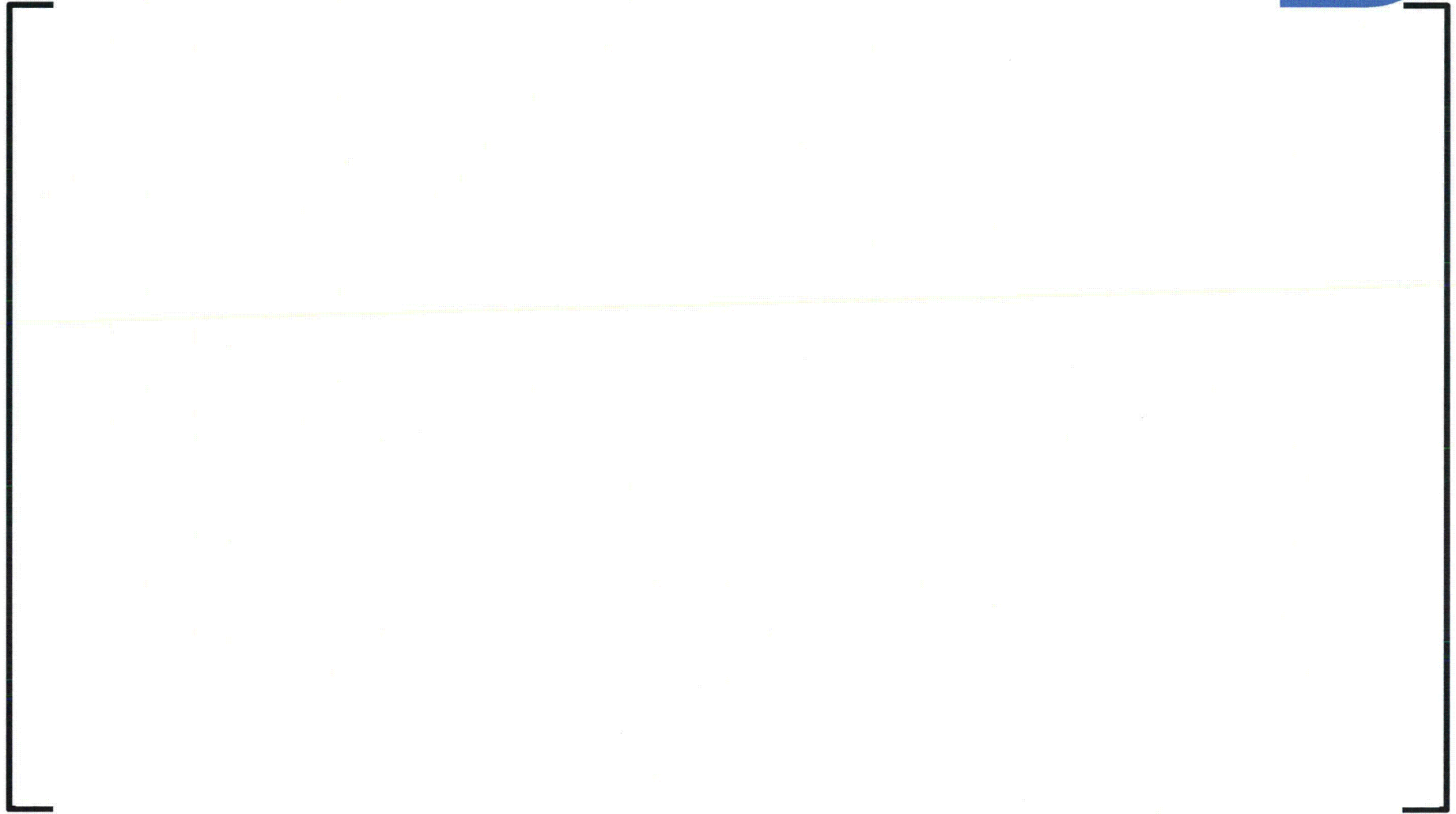
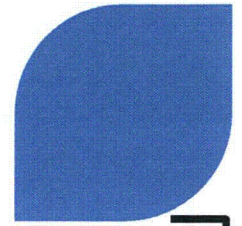
Functional form

- ORFEO – an advanced CHF correlation form that separates the general representation parameters from the specific grid design parameters



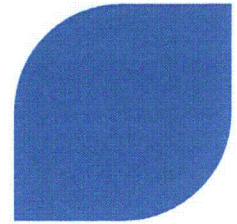
P: pressure, G: mass flux, X: quality, gsp: grid spacing, dg: dist. from upstream grid, rtg: guide tube factor, FNU: non-uniform factor

CHF Correlations for GAIA *Databases*



CHF Correlations for GAIA

Characteristics

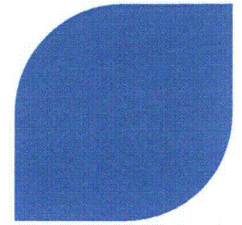


► ORFEO CHF correlation

- ◆ Utilizes physical elements within empirical correlation
- ◆ Adequately describes the influence of axial power shapes
- ◆ Is based on a CHF test suite that characterizes the effect of physical parameters used in the correlation form
- ◆ Incorporates basic dependencies adapted from mechanistic approach to DNB
- ◆ Incorporates a “**burnout length**” term (comparable to boiling length used in some BWR dryout correlations) – reduces the Measured over Predicted CHF variability at high qualities
- ◆ Minimizes the risk of overpredicting untested conditions (by acquiring high quality/high pressure data)

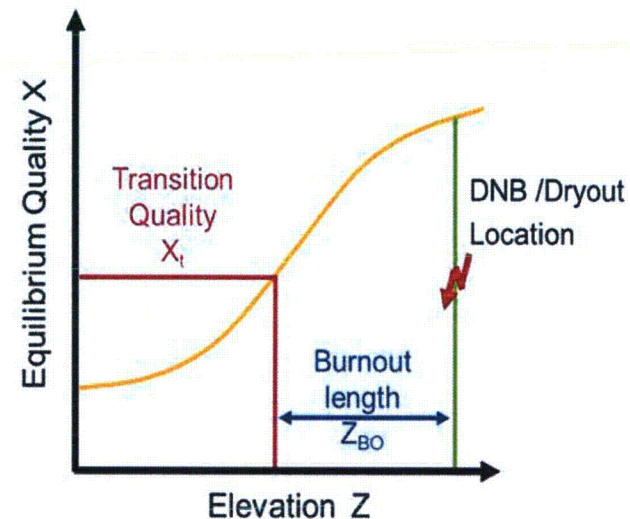
CHF Correlations for GAIA

Burnout length



- Models the transition between DNB (linear form) and dryout (exponential form) via a smooth function for a large range of qualities

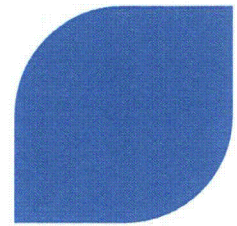
- ◆ takes into account the axial heat flux impact on the local quality
- ◆ is similar to the “boiling length” used in some BWR dryout correlations



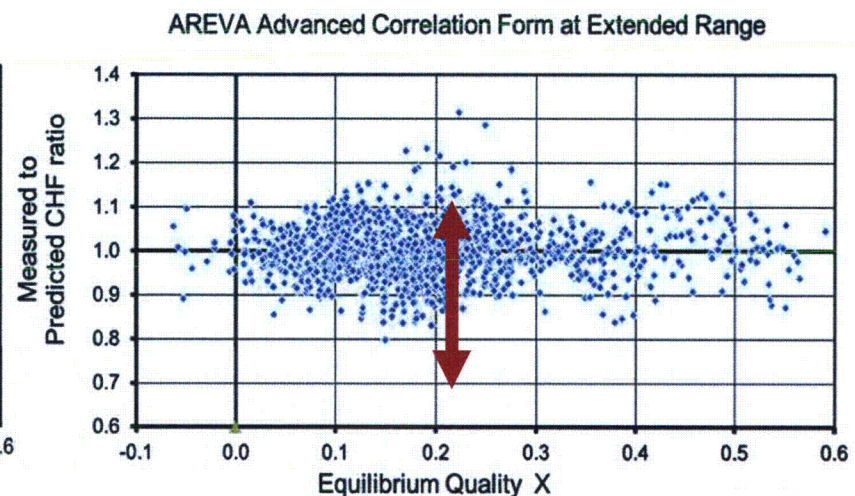
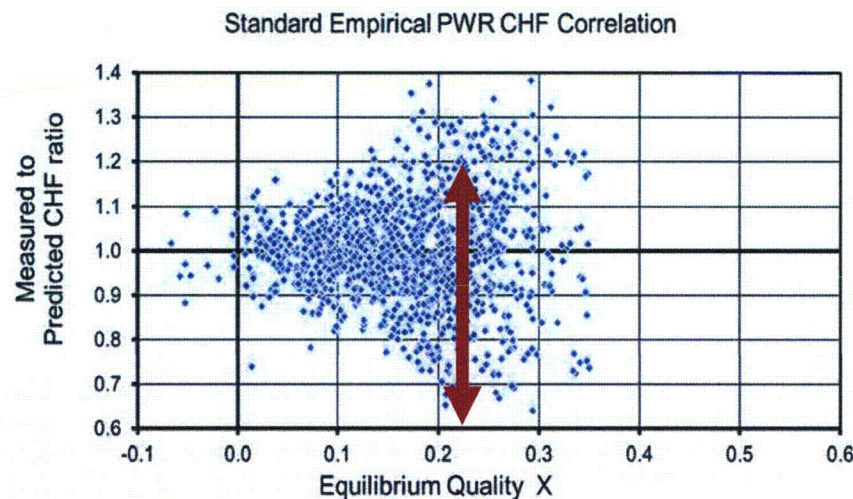
» Similarity in terms of modeling the boiling phenomenon between the PWR and BWR correlations

CHF Correlations for GAIA

Burnout length



- Application of the “burnout length” parameter leads to significantly reduced Measured to Predicted (M/P) variability



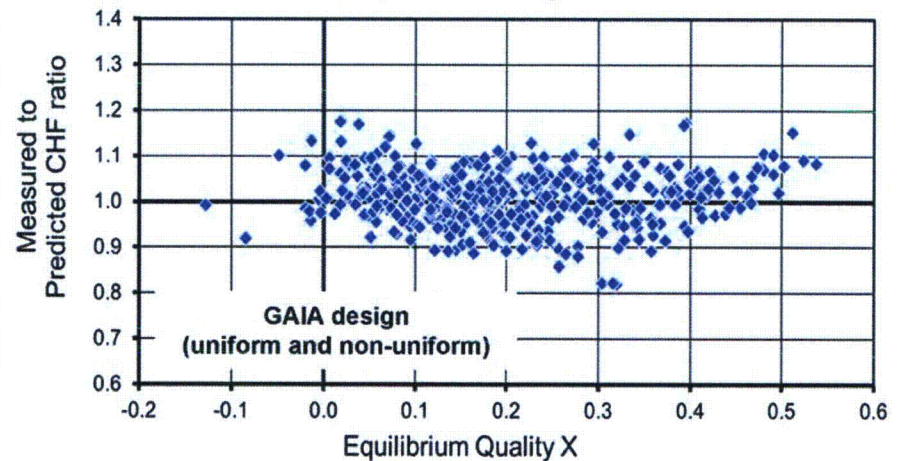
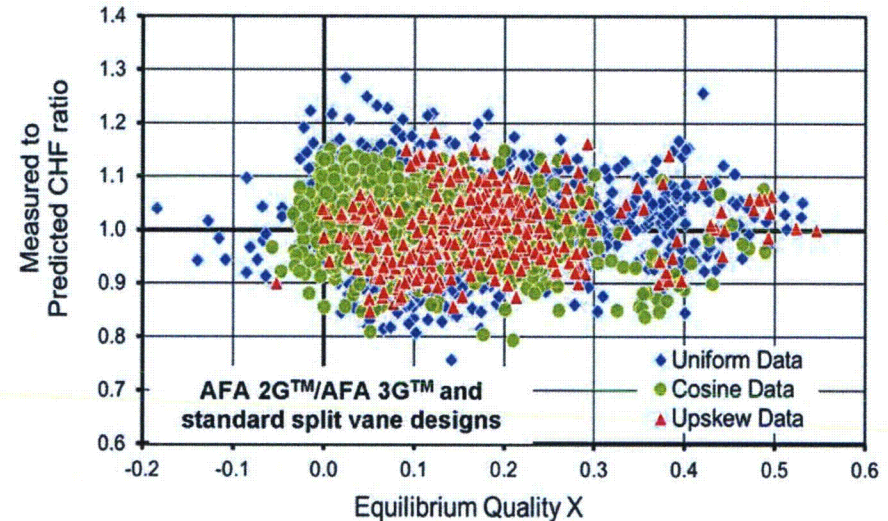
» The benefit of the reduced M/P variability even continues into the higher quality region

CHF Correlations for GAIA *Effectiveness*

► The effectiveness of the ORFEO CHF correlation form is shown for three types of grid designs

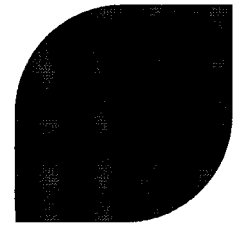
◆ Excellent fit for different axial power shapes and grid types

Spacer grid	# of tests	# of data points	Average M/P	Std. dev.
Std. split vane	18	1452	1.000	0.063
AFA 2G and AFA 3G	24	2158	1.008	0.060
GAIA	4	430	1.009	0.059
All	46	4040	1.005	0.061



CHF Correlations for GAIA

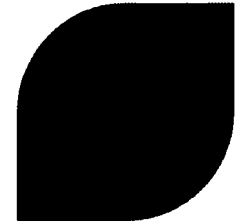
Regions of application



]

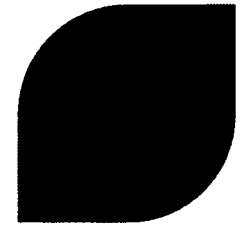
CHF Correlations for GAIA

Subchannel Code



- ▶ **COBRA-FLX is the AREVA's advanced methods subchannel thermal-hydraulic analysis code**
 - ◆ Approved by NRC for stand-alone application to nuclear core thermal-hydraulic analysis for steady-state and transient conditions in ANP-10311 P-A
- ▶ **GAIA CHF correlation will be developed using COBRA-FLX and the empirical correlations, numerical solution methods, etc. approved by NRC in the SER issued for the COBRA-FLX Topical Report**

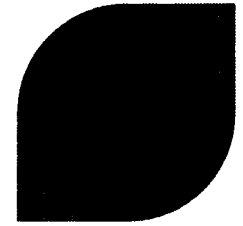
Agenda



- ▶ **Objective and Schedule**
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CHF Correlations for GAIA

Topical Report Content (1)



► Introduction

- ◆ Purpose of the report
- ◆ Intended application of the CHF correlations
- ◆ Need for new CHF correlations

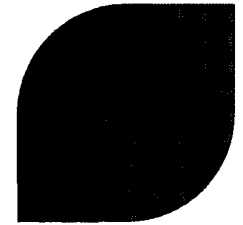
► Compliance with regulatory requirements – SRP Sections 4.2 and 4.4

► CHF testing facility

- ◆ Description and qualification
- ◆ Test procedures and data collection methods
- ◆ Test reproducibility

CHF Correlations for GAIA

Topical Report Content (2)



► CHF testing program

- ◇ Test assembly configurations
- ◇ Data collection ranges

► Generic ORFEO CHF correlation form

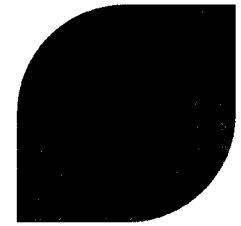
- ◇ Correlation functional form
- ◇ Data evaluation and optimization of coefficients

► Development of ORFEO CHF correlation based on the mixing grid tests (GAIA, IGM)

- ◇ Specific adjustments to the correlation form
- ◇ Subchannel code model
- ◇ Data evaluation and optimization of coefficients

CHF Correlations for GAIA

Topical Report Content (3)



► Development of ORFEO CHF correlation based on the non-mixing grid tests

- ◇ Specific adjustments to the correlation form
- ◇ Subchannel code model
- ◇ Data evaluation and optimization of coefficients

► Statistical analysis of CHF correlation

- ◇ Statistical evaluation of Measured over Predicted (M/P) data points for mixing grid tests
 - Development data set and validation data set
- ◇ Statistical evaluation of M/P data points for non-mixing grid tests
 - Development data set and validation data set

CHF Correlations for GAIA

Topical Report Content (4)



► Correlation application

- ◆ **Application range and design limit**
 - **Mixing grid correlation**
 - **Non-mixing grid correlation**

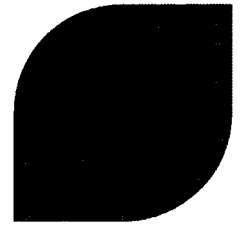
► Correlation behavior with respect to independent variables of pressure, mass flux and quality

► Conclusions and summary

- ◆ **Capability of the CHF correlations**
- ◆ **Ranges of applicability**
- ◆ **Overall statistics**
- ◆ **Comparison to experimental test data**

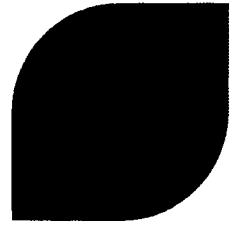
CHF Correlations for GAIA

Topical Report Content (5)



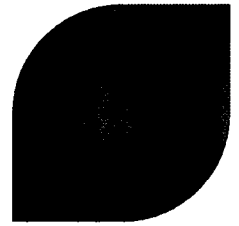
CHF Correlations for GAIA

Topical Report Content (6)

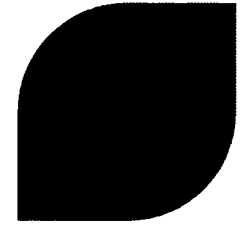


CHF Correlations for GAIA

Topical Report Content (7)



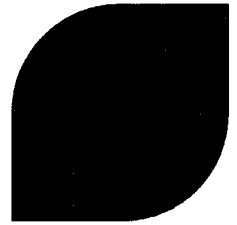
Agenda



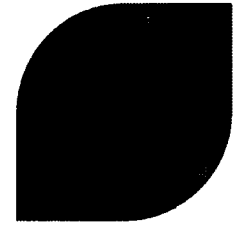
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CHF Correlations for GAIA

Summary and Discussions



CHF Correlations for GAIA



Questions / comments / feedback