Advanced Gas Reactor Fuels Program Review

AGR-3/4 Irradiation Summary

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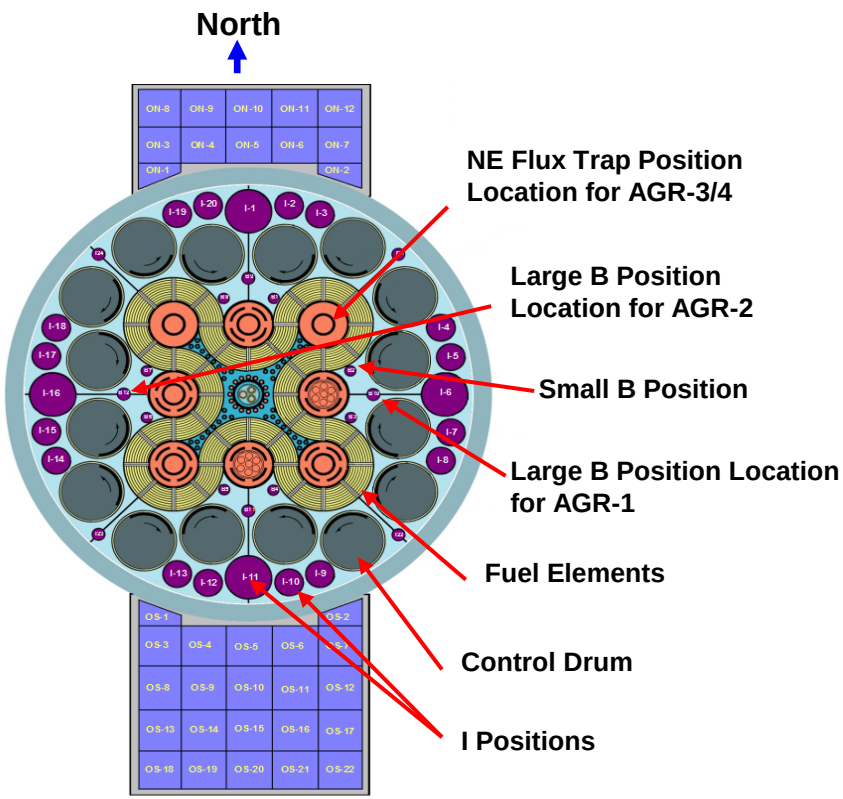
Idaho National Laboratory

Objectives

- Irradiate fuel containing uranium oxycarbide (UCO) designed-to-fail (DTF) fuel particles that will provide a known source of fission products for subsequent transport through compact matrix and structural graphite materials.
- Assess the effects of sweep gas impurities, such as CO, H_2O, and H_2 typically found in the primary coolant circuit of high temperature gas-cooled reactors.
- Conduct PIE including safety tests to study the irradiation effects related to fission product transport and sweep gas impurities.
- Use obtained data from irradiation testing and PIE to upgrade fission transport models.

ATR Irradiation Positions

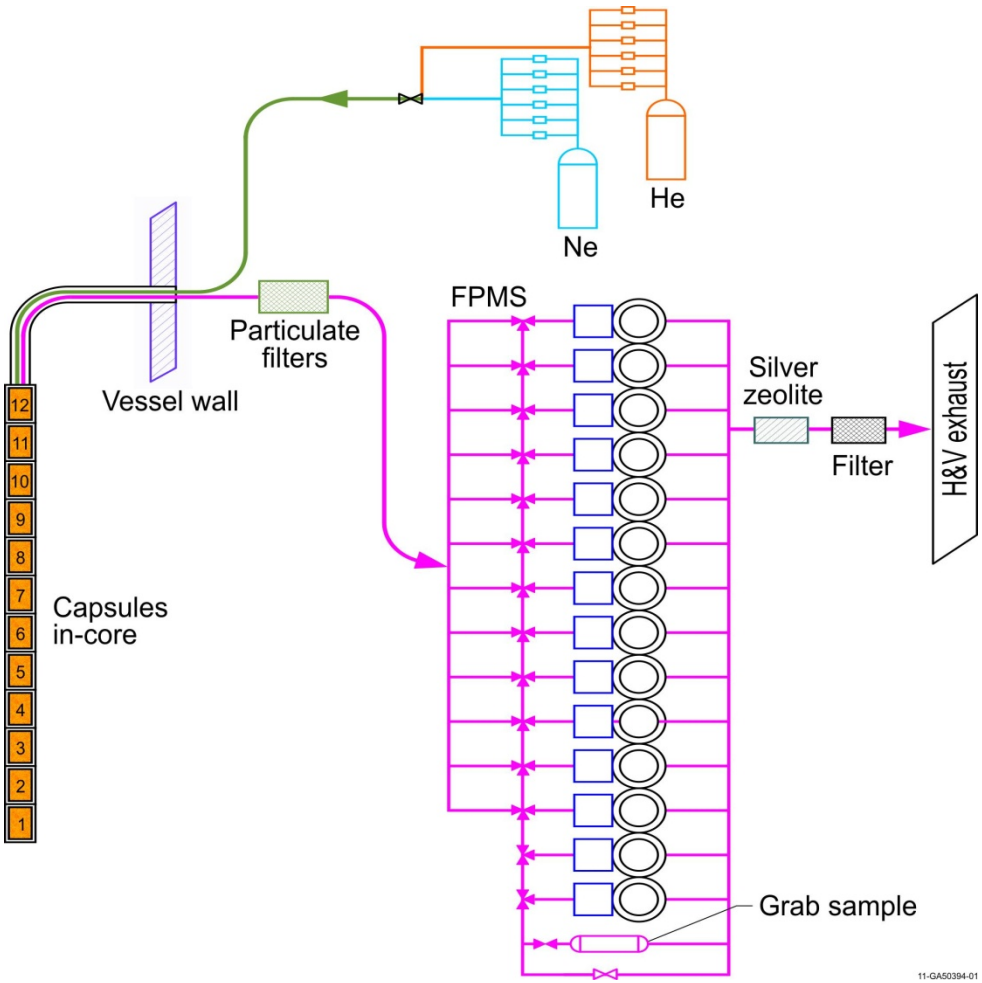


ATR Core Cross Section

- AGR-3/4 in NE flux trap
  - Ø 133 mm (5.25 in.) x 1.2 m (4 ft)
  - Max. room for fission product migration
  - Min. flux gradient across experiment
  - Corner lobe allows power level control
  - Double-up experiments
    - Use full height of ATR core
  - Neutron flux spectrum modified

The AGR-3/4 experiment began irradiation on December 14, 2011 and ended on April 12, 2014 for a total of 369.1 EFPD which spanned 10-ATR cycles and nearly 2.5 calendar years.

Temperature Control and Fission Product Monitoring Systems



AGR-3/4 Experiment Flow Path

- Individual capsule temperature control and fission product monitoring
- Temperature control system
  - Insulating gas gap in capsule
  - Helium (conductor) and neon (insulator)
  - Mass flow controllers
  - Type N capsule thermocouples
- Fission product monitors
  - Gross gamma NaI crystal scintillation detector
  - Liquid nitrogen (LN) cooled HPGe spectrometer
  - On-line back-up spare monitor(s)
  - Grab sample capability
- AGR-3/4 gas impurities anticipated in VHTR reactor
  - 50 ppmv CO
  - 50 ppmv H_2
  - 10 ppmv H_2O

Comparison of AGR-1, -2, and -3/4 Fuel

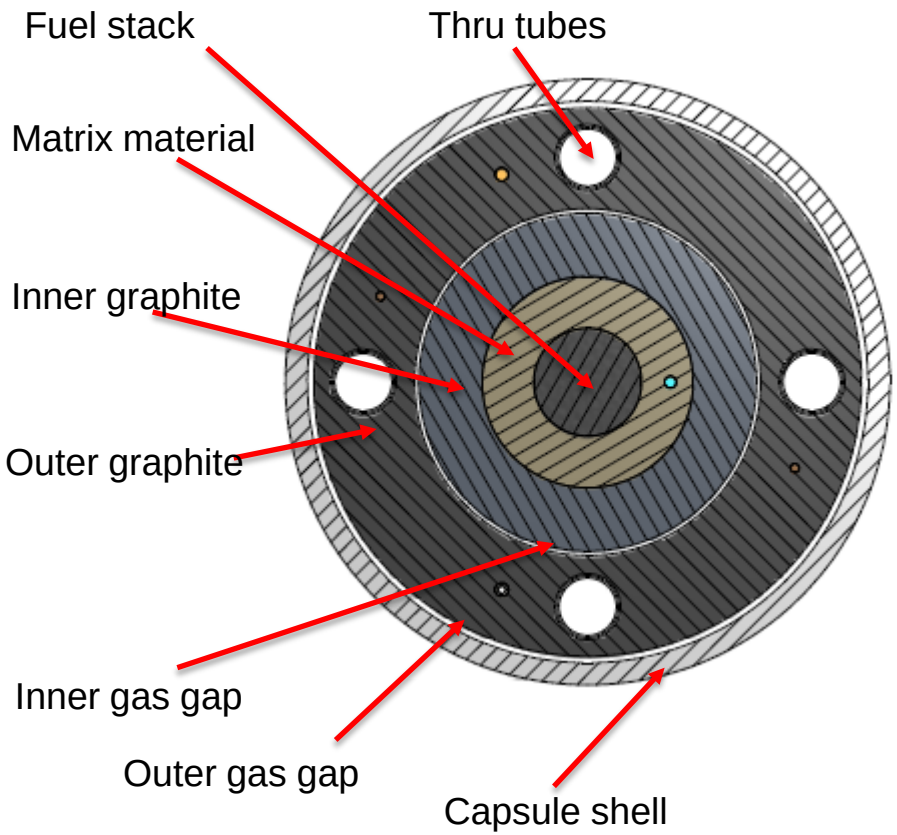
Experiment	Fuel Type	Particle Size	Enrichment	Particles/ Compact	Compact Size	Compacts /Capsule	Capsules
AGR-1	UCO	350 µm diameter fuel kernels 780 µm diameter particles	19.8%	4,150	12.4mm x 25.4mm	12	6
AGR-2	UCO	425 µm diameter fuel kernels 850 µm diameter particles	14%	3,176	12.4mm x 25.4mm	12	3
AGR-2 US	UO_2	510 µm diameter fuel kernels 940 µm diameter particles	9.6%	1,543	12.4mm x 25.4mm	12	1
AGR-3/4	**UCO (Driver)**	**350 µm diameter fuel kernels 820 µm diameter particles**	**19.8%**	**1,910**	**12.4mm x 12.5mm**	**4**	**12**
AGR-3/4	**UCO (DTF)**	**350 µm diameter fuel kernels 425 µm diameter particles**	**19.8%**	**20**	**N/A**	**N/A**	**N/A**

Comparison of AGR-1, -2, and -3/4 Operational Parameters

Experiment	EFPDs		Peak Burnup % FIMA		Peak Fluence $x10^{25}$ n/m^2		Peak Temp ^{O}C	
	Goal	Actual	Goal	Actual	Goal	Actual	Goal	Actual
AGR-1 (UCO)	725	620	>18	19.5	2.5-4.6	4.30	1080	1087
AGR-2 (UCO)	600	559	>10	13.15	2.2-4.0	3.47	1400	1296
AGR-2 (UO_2)	600	559	>10	10.69	2.2-4.0	3.53	1400	1062
AGR-3/4 (UCO)	**400**	**369**	**>5, <19**	**15.27**	**0.9-5.5**	**5.32**	**1300**	**1276**

AGR-3/4 Capsule Design

- Single fuel stack centered in capsule
  - Four compacts per stack
- Fuel compact matrix material surrounds fuel
- Nuclear grade (inner) graphite surrounds matrix material
- Fission product sink/trap surrounds matrix material
  - Nuclear grade (outer) graphite at lower temperature
- Thru tubes provide pathway for gas lines and TC's between capsules
- Commercial Type N thermocouples
  - In outer graphite at lower temperature
  - Two TC's/capsule (thru tube space)
  - Third TC in matrix material in three capsules

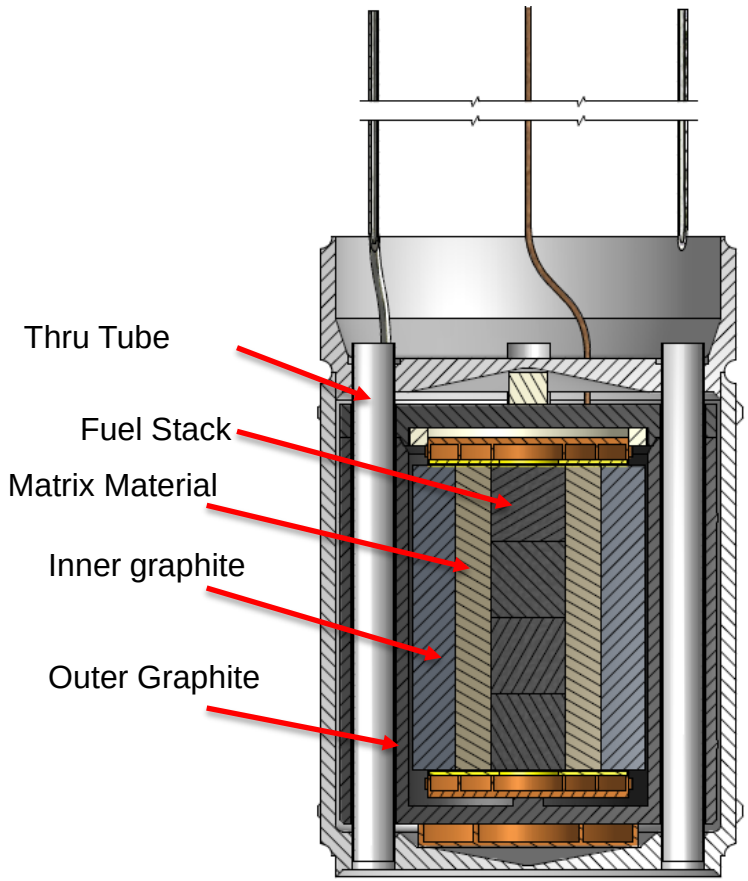


AGR-3/4 Capsule Cross Section

AGR-3/4 Capsule Types

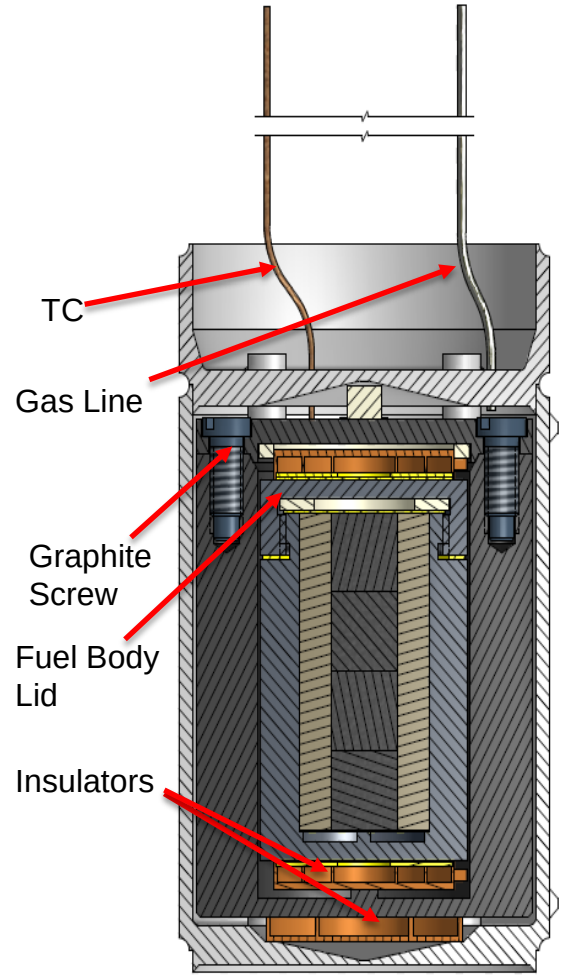
Standard Capsule

Reduces capsule height resulting in more capsules per experiment and/or taller fuel stack in each capsule



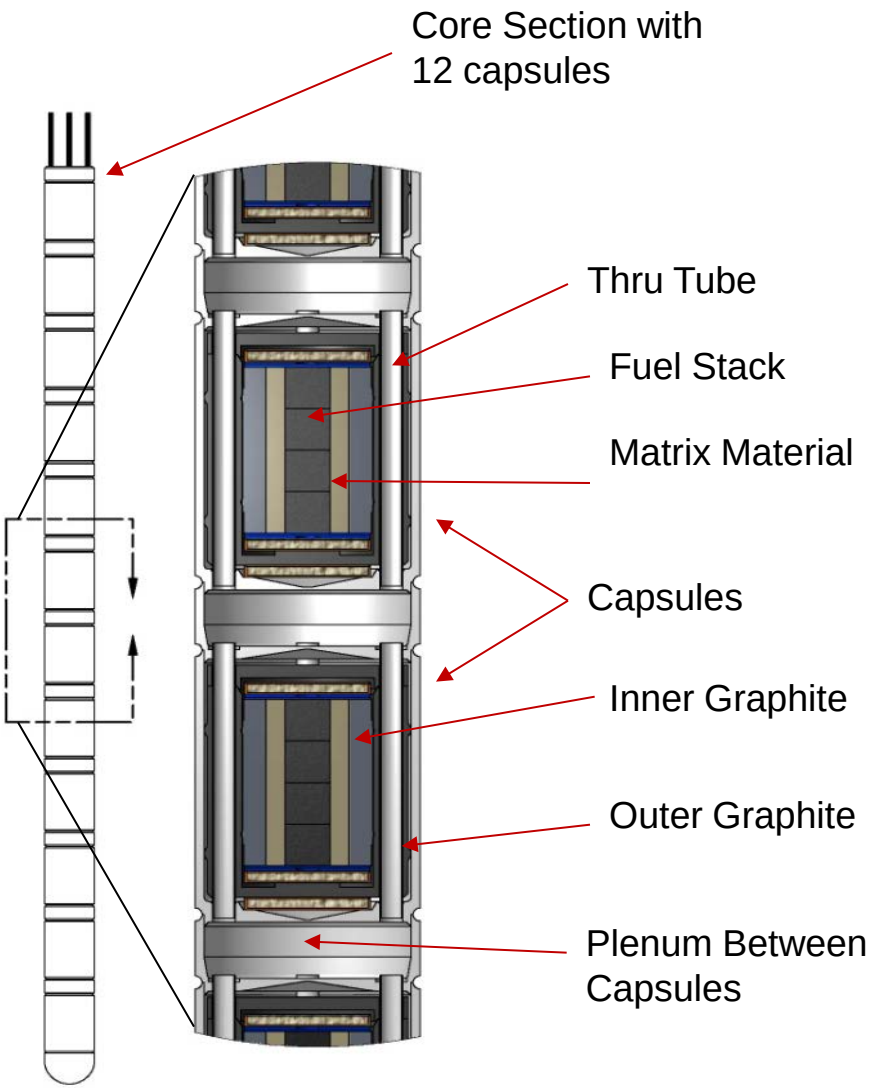
Fuel Body Capsule

Allows fuel, matrix and graphite to be heated together in PIE

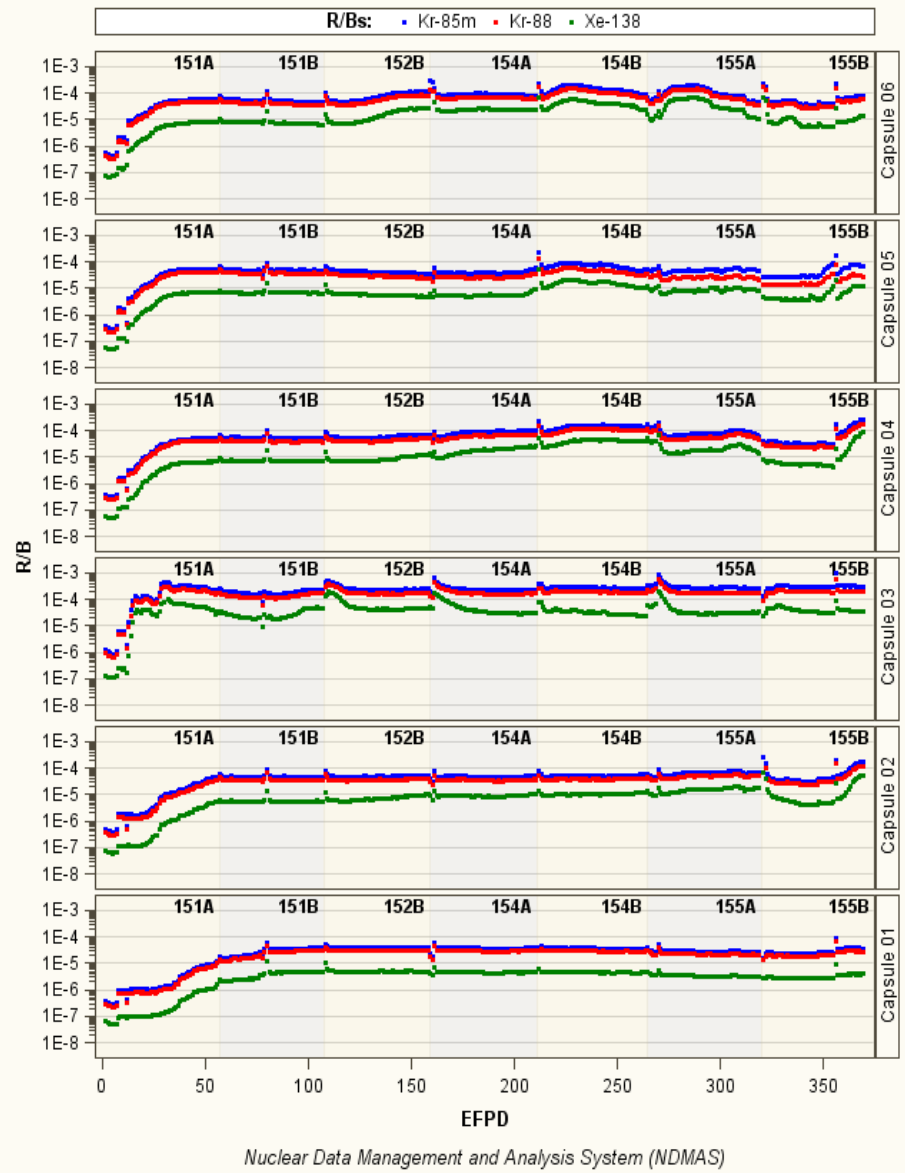


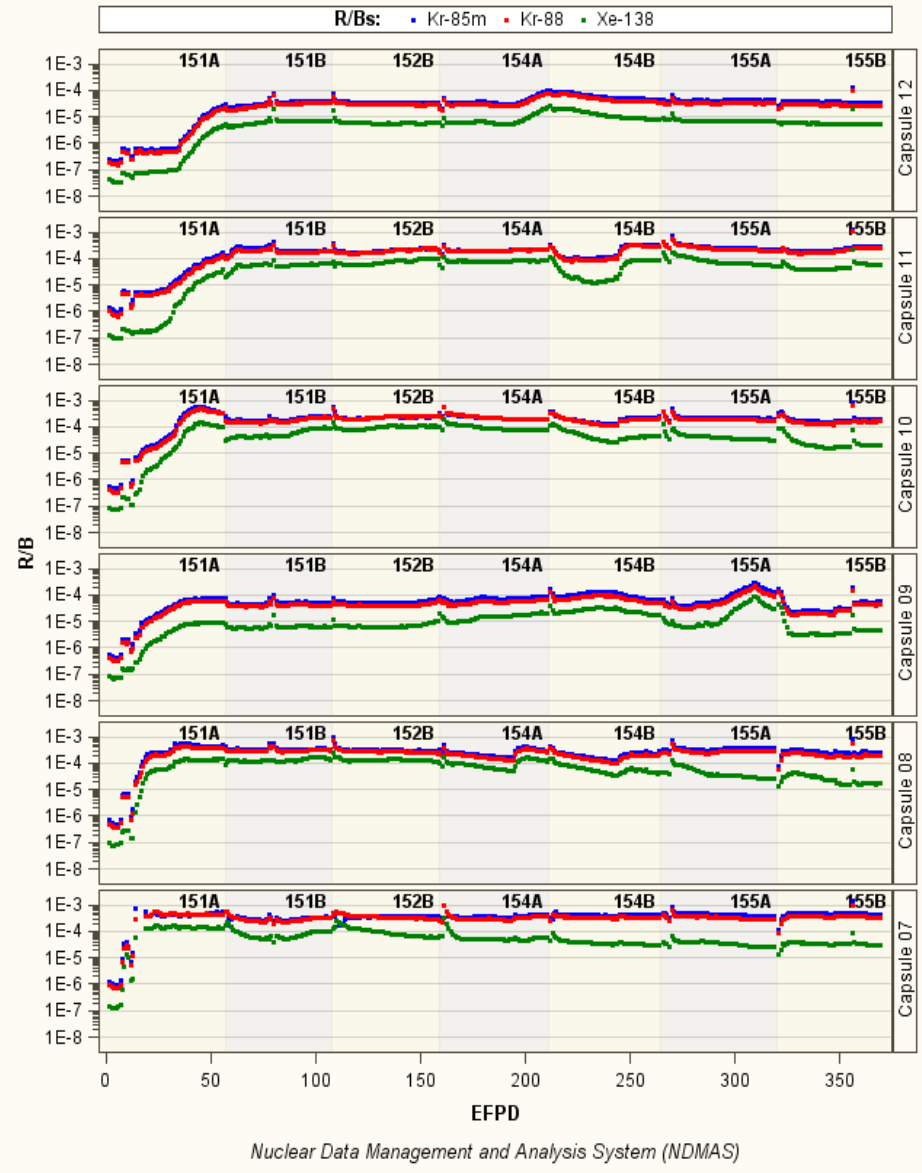
AGR-3/4 Test Train Design

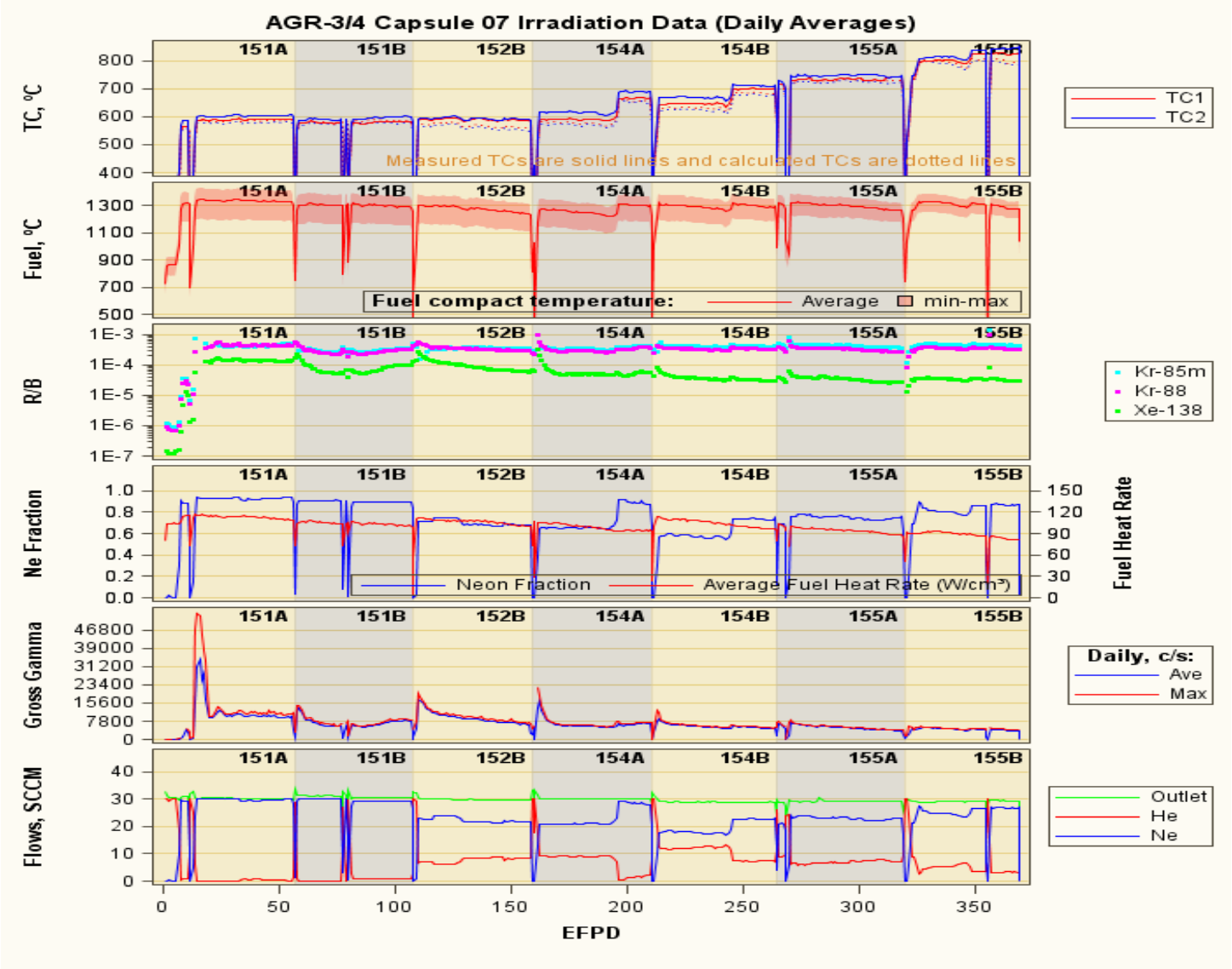
- Twelve capsules in test train
- Ø 70 mm (2.75 in.) × ~110mm (4.38 in.) pitch
- Plenums between capsules to route gas lines and TC's into capsules
- Individual temperature and gas flow control
- Individual fission product monitoring



AGR-3/4 Release to Birth Ratio's






AGR-3/4 Capsule 07 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
Measured TCs are solid lines and calculated TCs are dotted lines
TC1
TC2
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Fuel Heat Rate
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

Impure Gas

- Study the effect of an impure gas mixture on failed TRISO fuel
- The desired amounts of impurities in the flow to capsule 11 were: 50ppmv hydrogen, 50ppmv carbon monoxide, and 10ppmv of water, with 29.5sccm helium/neon
- Injection began on September 9, 2013

Peak Releases per Failed Particle for I-131

Capsule	Peak Release	Irradiation Cycle
7	18 ppm	1
8	11 ppm	1
11	61 ppm	5

No releases were detected for any of the other 9 capsules

Conclusion

- AGR-3/4 experiment was successful in keeping temperatures of the 12 capsules in the range of interest.
- Fission Product R/B ratios reached values in the10-4 to 10-3
- Final Burnup values on a per compact basis ranged from 4.85 to 15.27% FIMA
- DTF failed as expected
- No-known in-pile driver fuel failures
- Impurities added to the sweep gas did not appear to have an appreciable impact on fuel performance.
- AGR-3/4 will provide irradiated fuel performance data and data obtained from PIE and safety testing will improve the understanding of Fission Transport in HTGR's
- A greater understanding of the effects of sweep gas impurities on fuel performance and fission product transport will also be gained.

AGR-3/4 was a Success!!

Questions?

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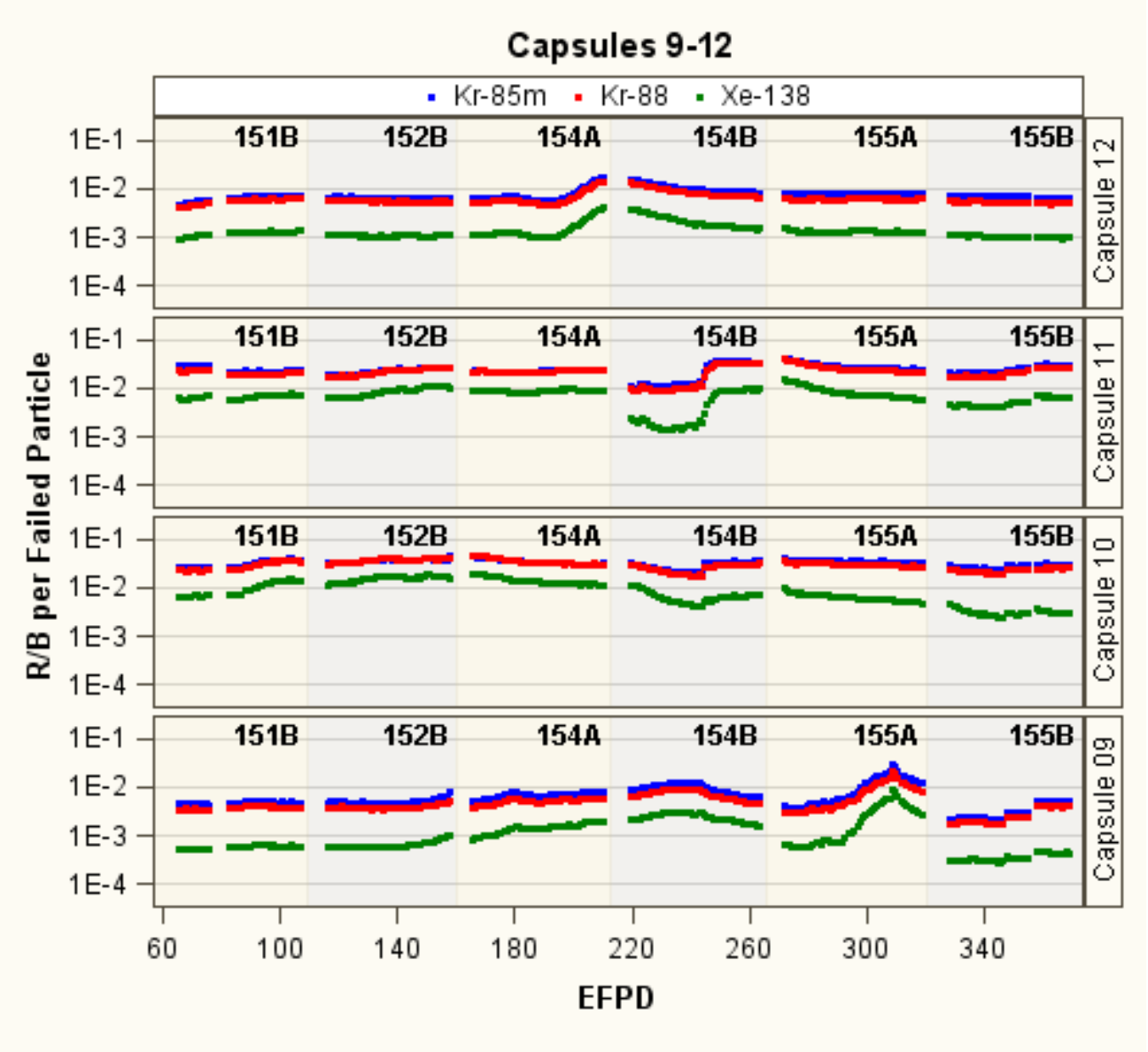
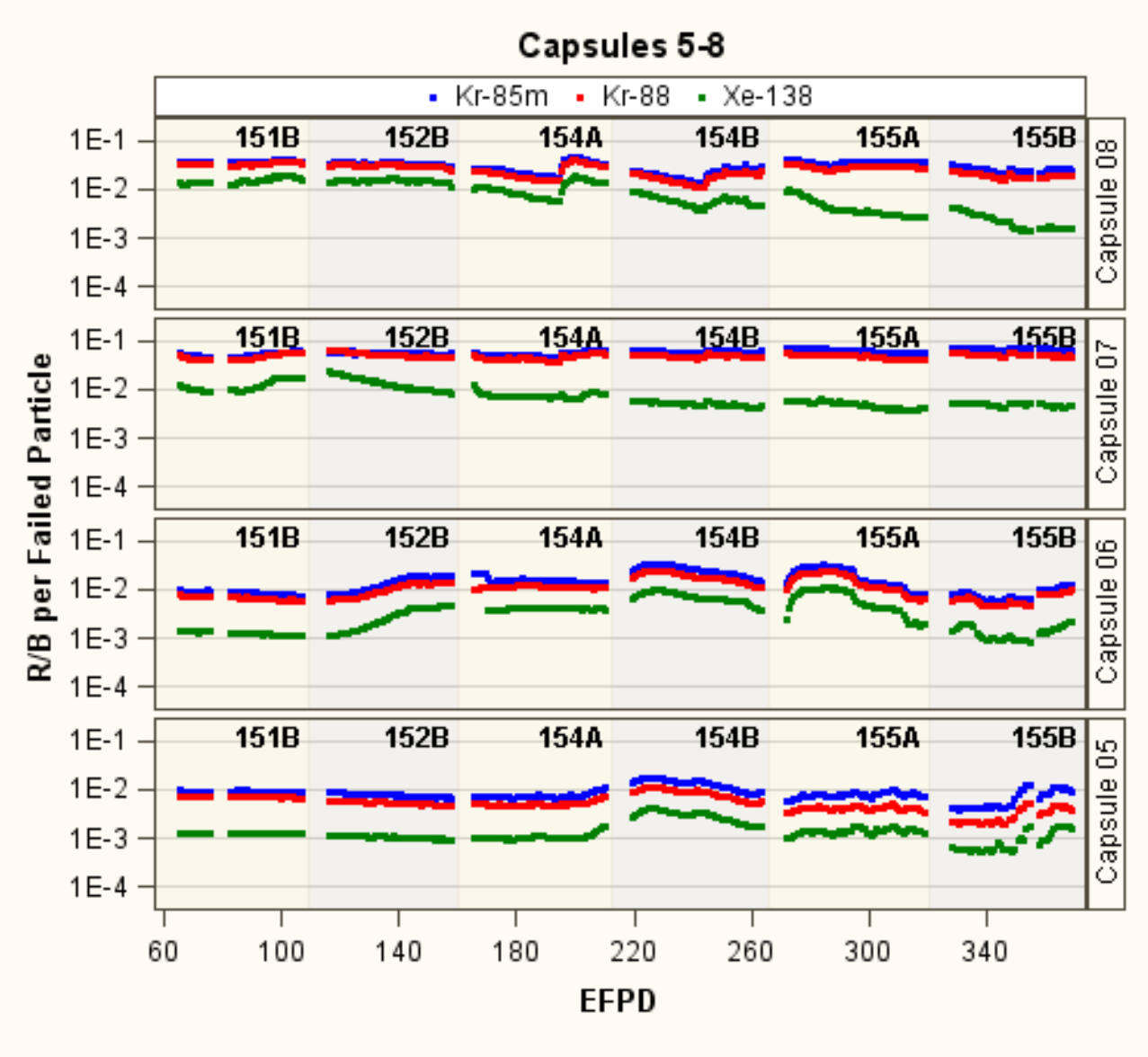
Spare Slides

R_p in AGR-3/4 Capsules 9-12

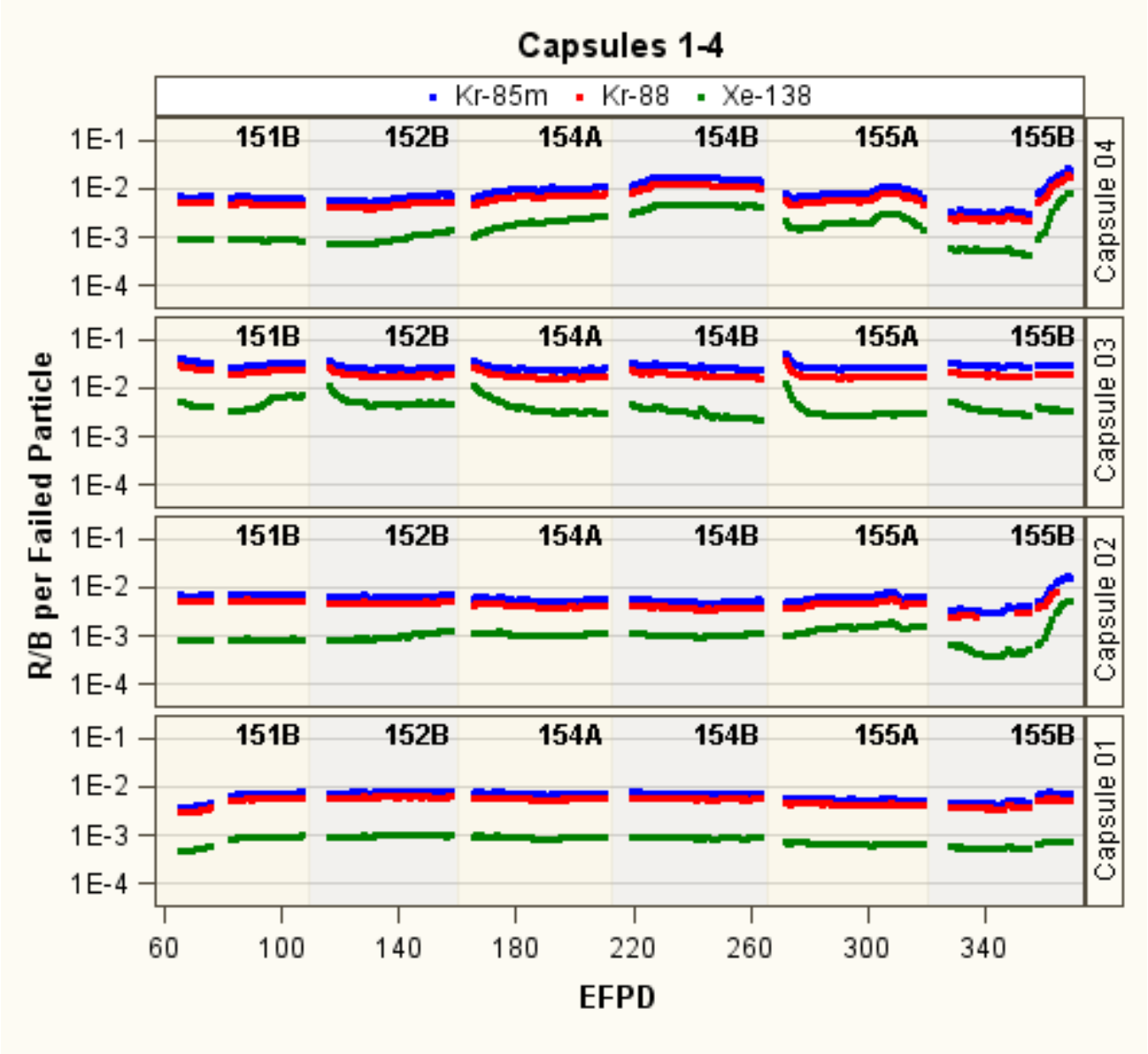
Daily R/B and best-estimated number of failed particles



R_p in AGR-3/4 Capsules 5-8

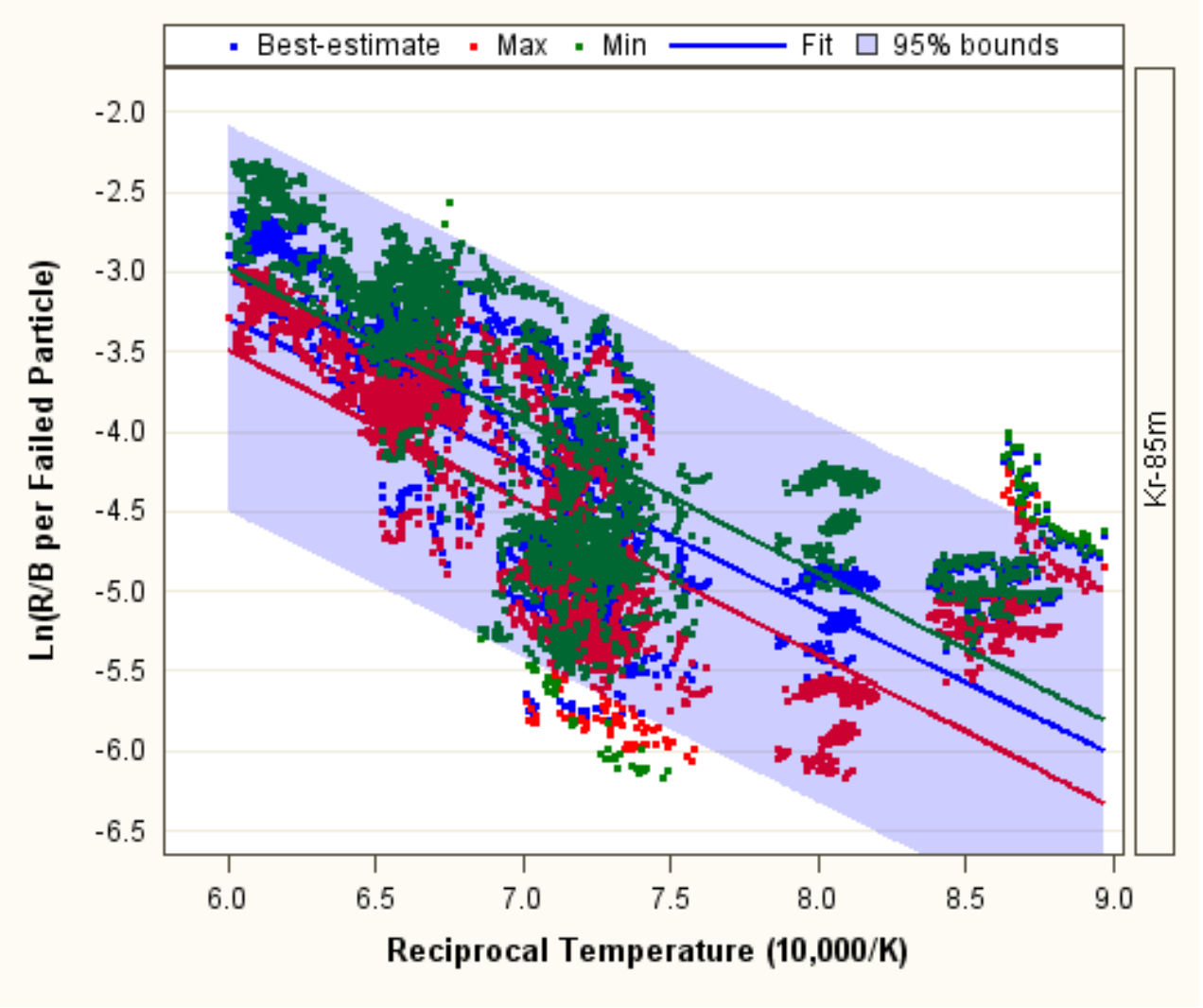


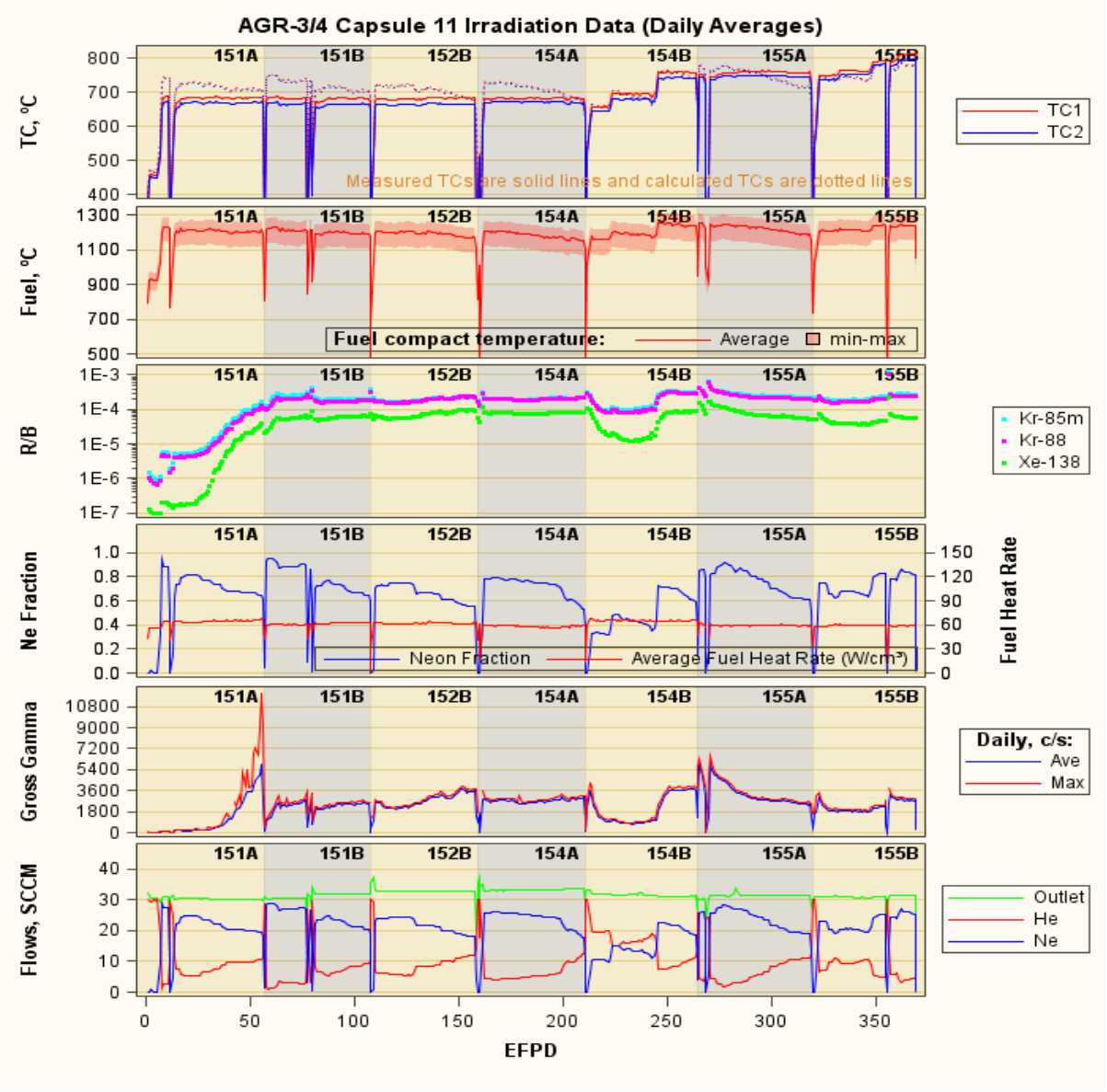
R_p in AGR-3/4 Capsules 1-4

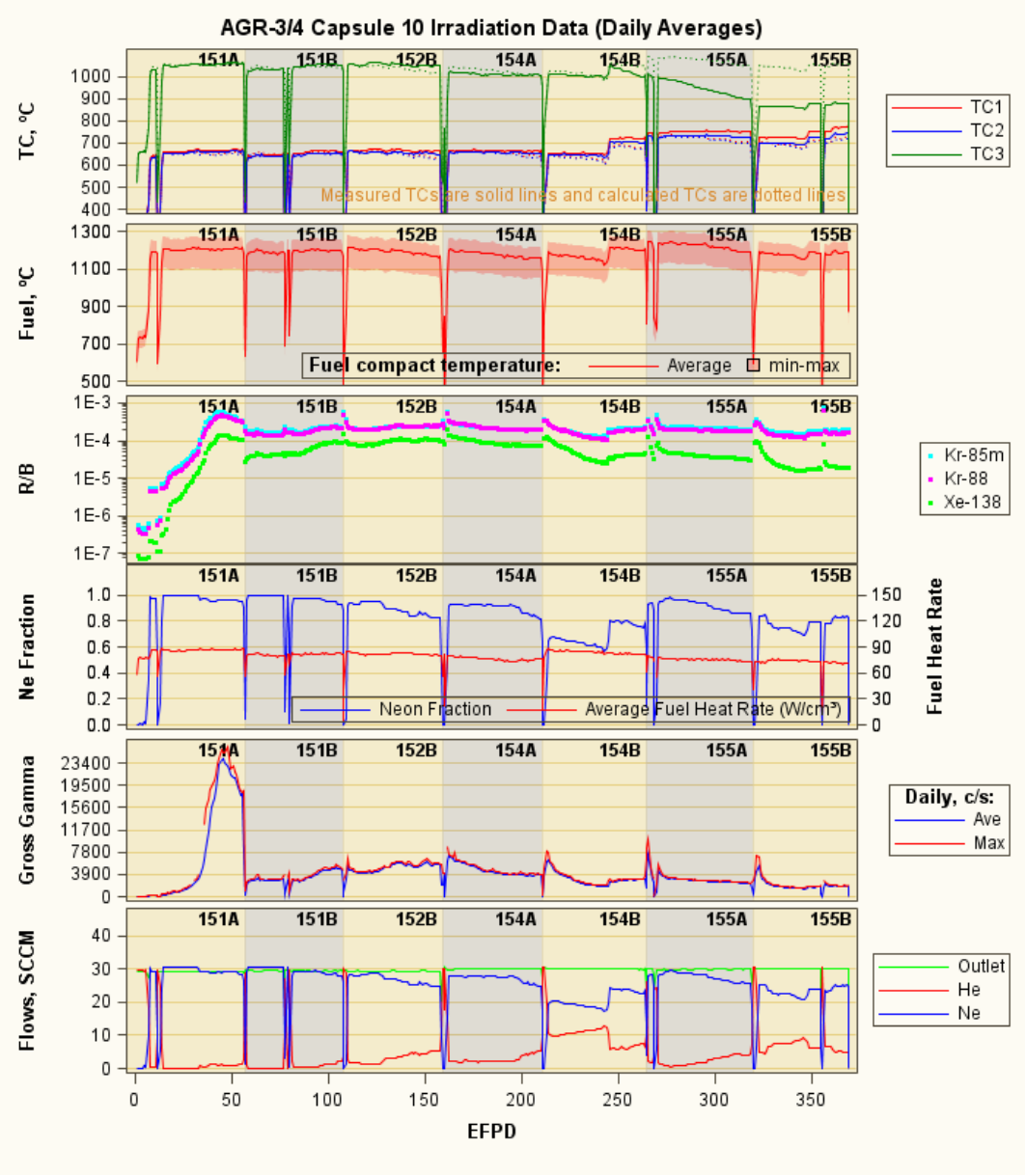


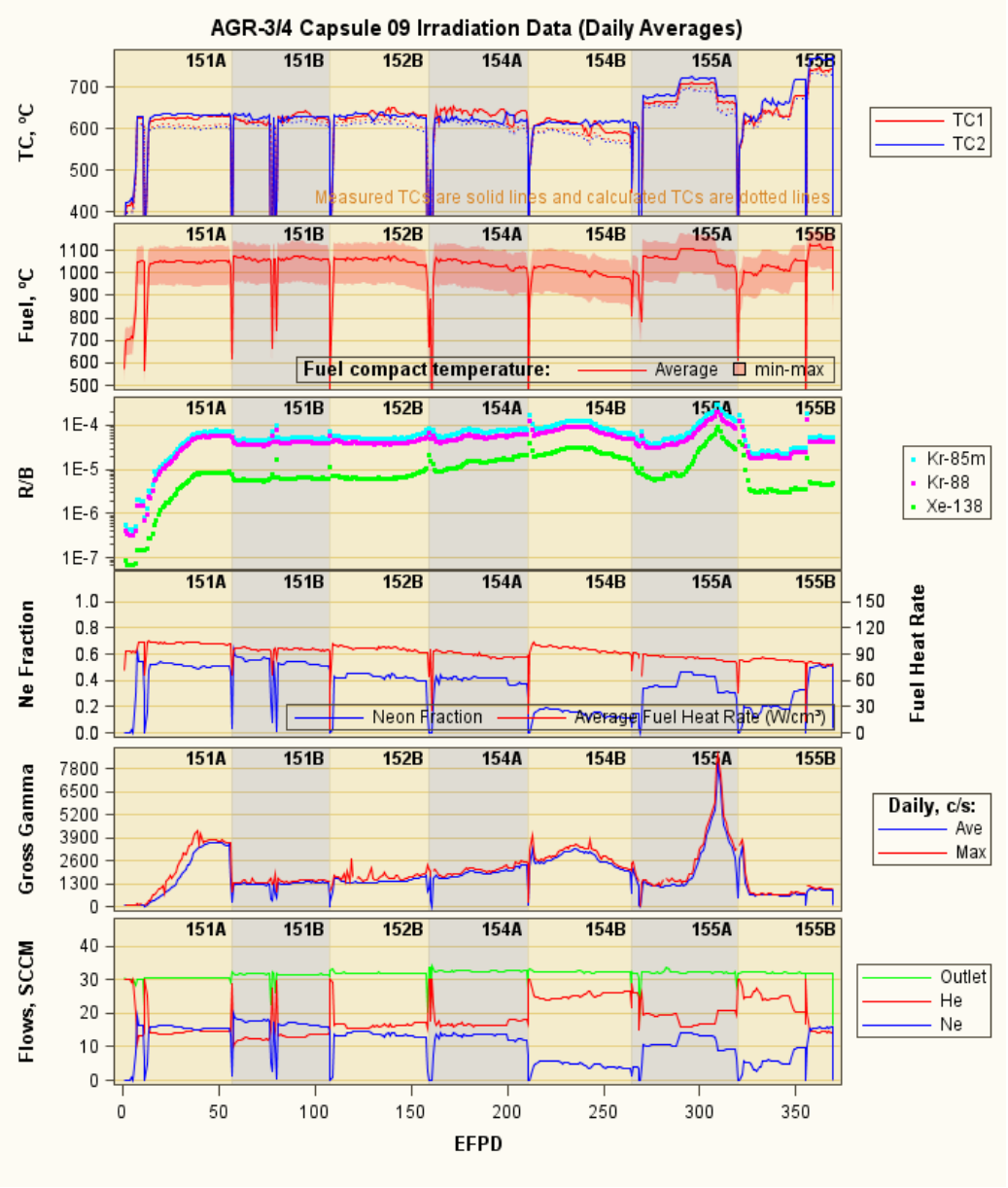
Regression Analysis Results for AGR-3/4

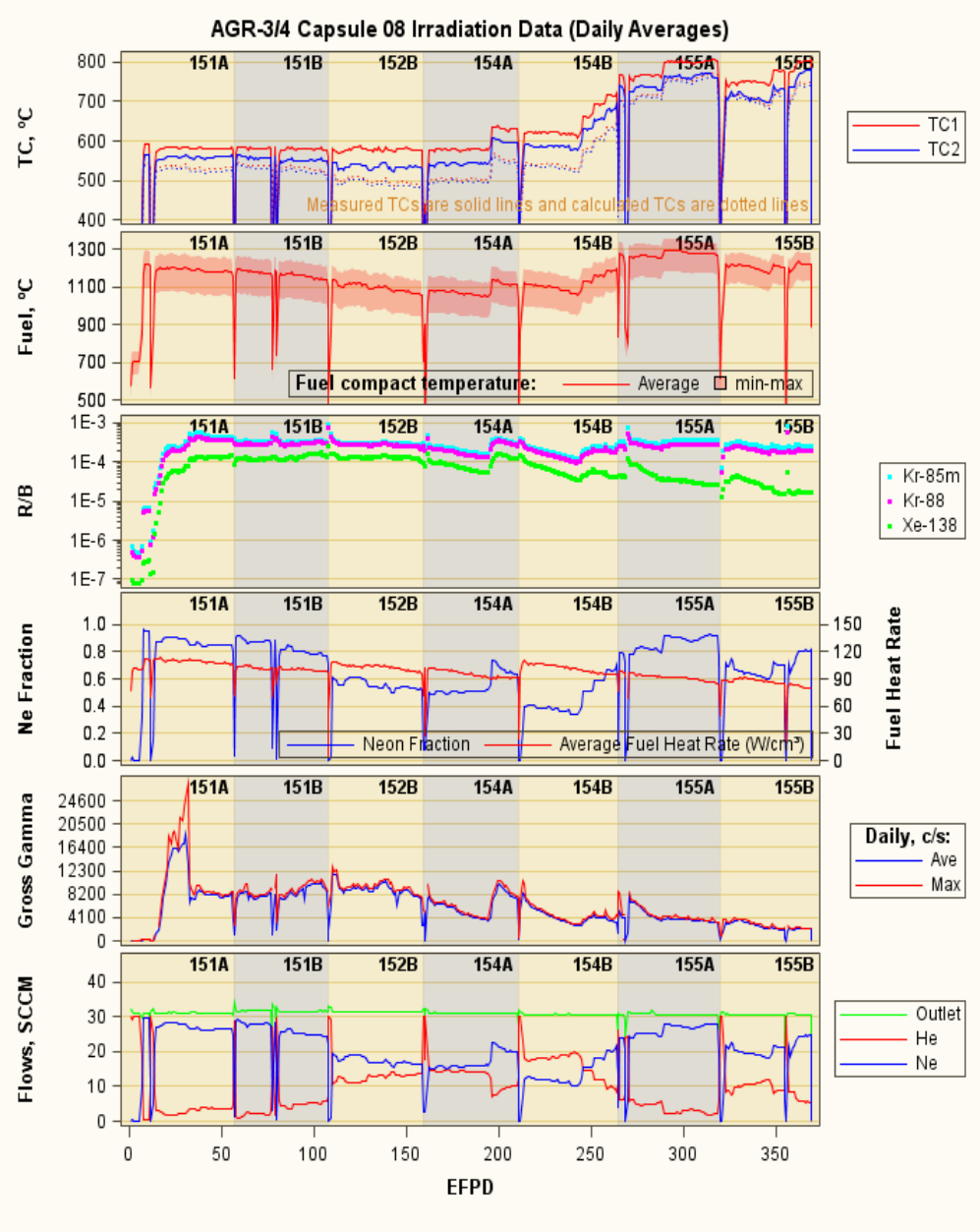
- Clear trend of exponential relationship between R/B and fuel temperature
- Insignificant impact of the failure count uncertainty:
  - Three fitted lines (blue, red and green) are fairly parallel to each other with a small shift
  - The shaded area representing 95% confidence bounds on the fitted line using best-estimate failure counts covers most of the 3 sets of R/B per failed particle

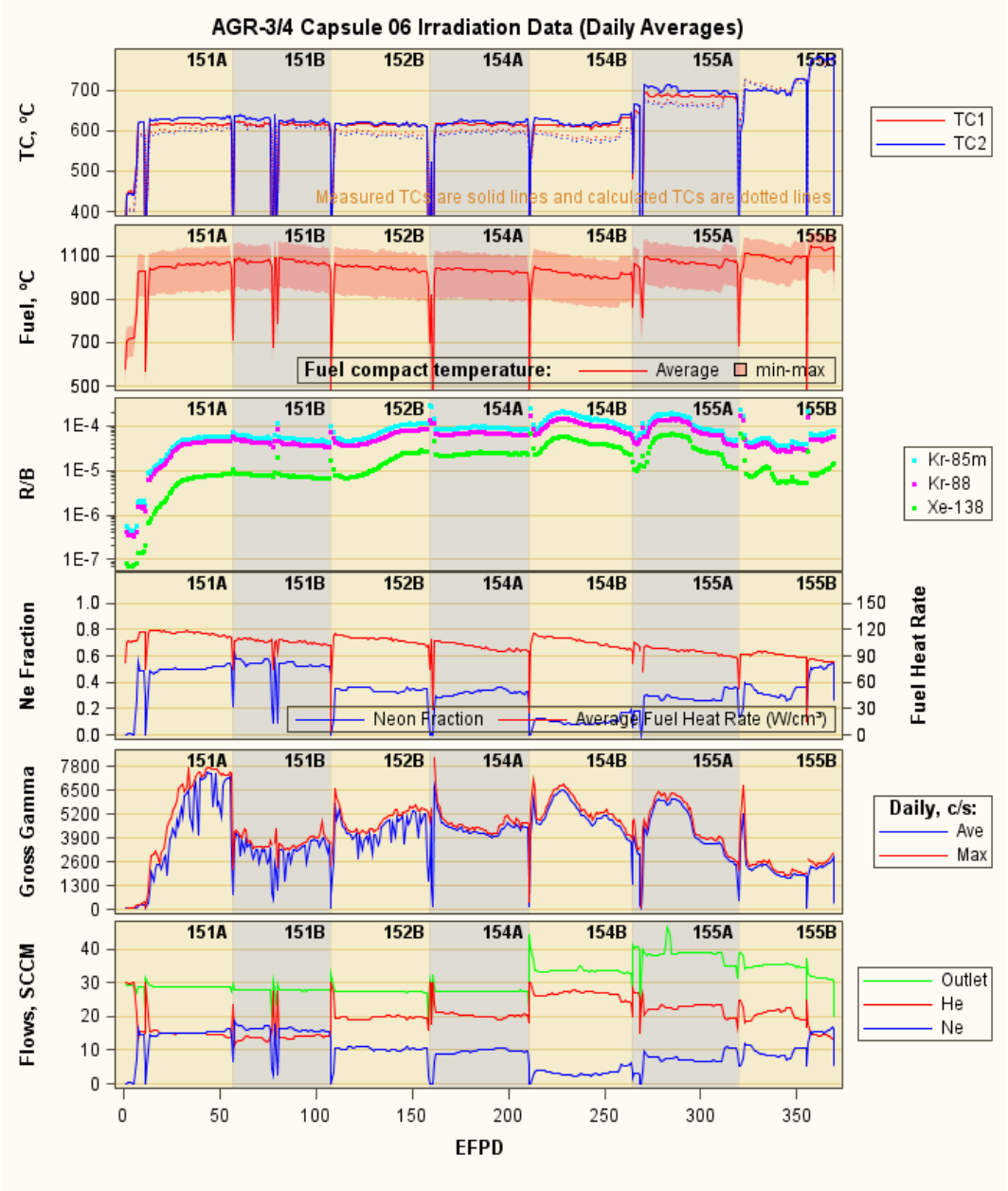


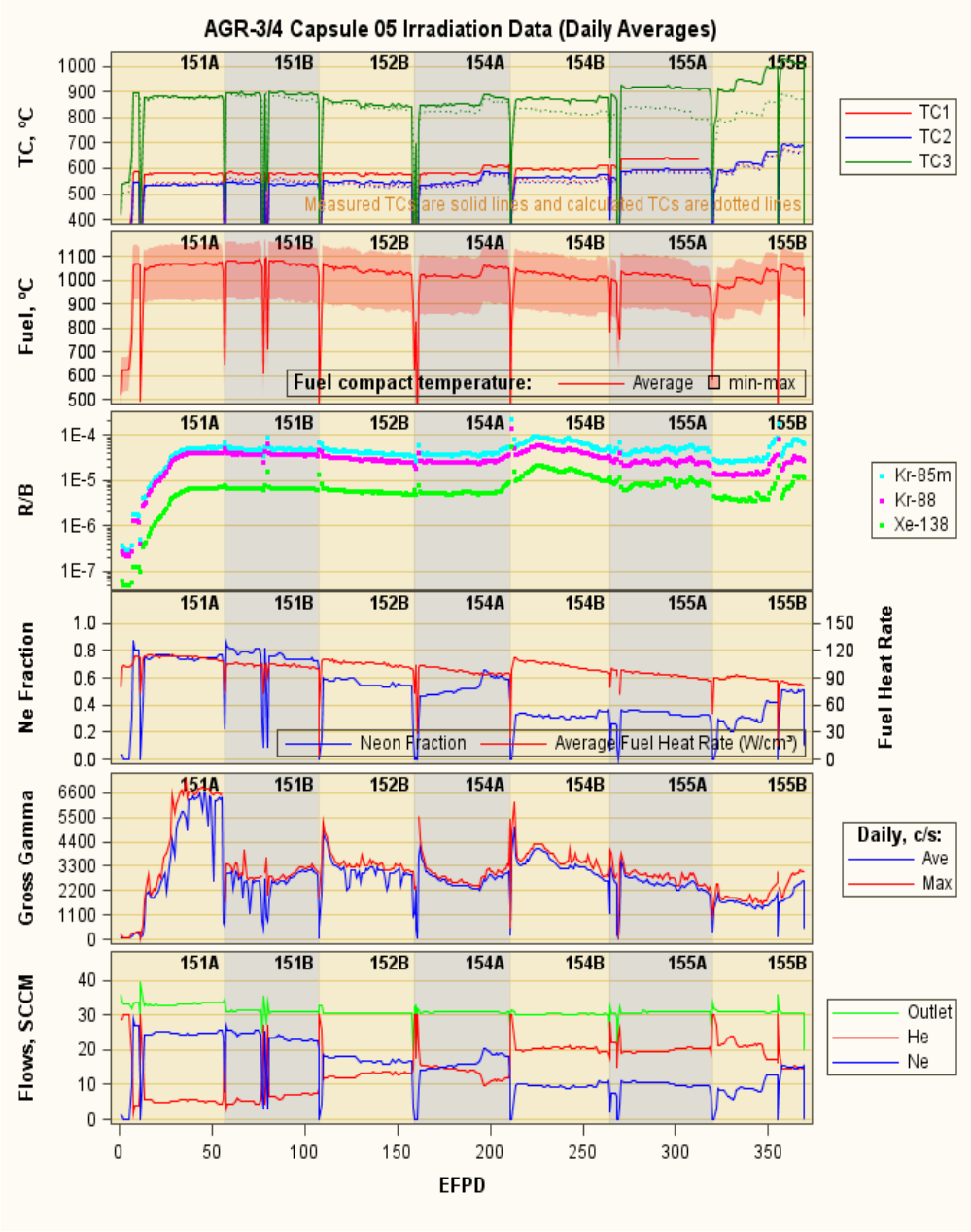

AGR-3/4 Capsule 11 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

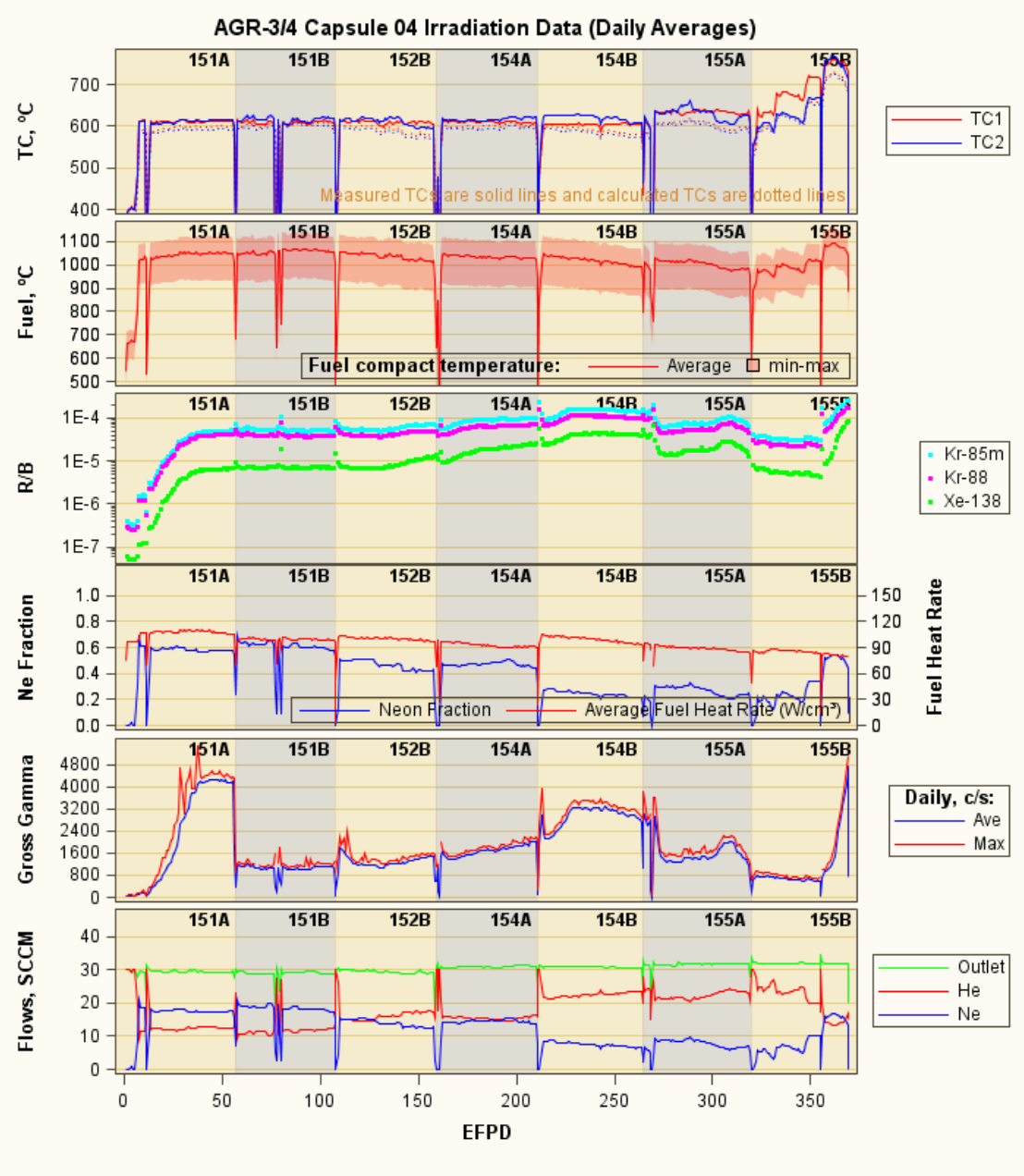

AGR-3/4 Capsule 10 Irradiation Data (Daily Averages)
TC, °C
Fuel, °C
R/B
Ne Fraction
Gross Gamma
Flows, SCCM
151A
151B
152B
154A
154B
155A
155B
TC1
TC2
TC3
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel compact temperature:
Average
min-max
Kr-85m
Kr-88
Xe-138
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Fuel Heat Rate
Daily, c/s:
Ave
Max
Outlet
He
Ne
EFPD

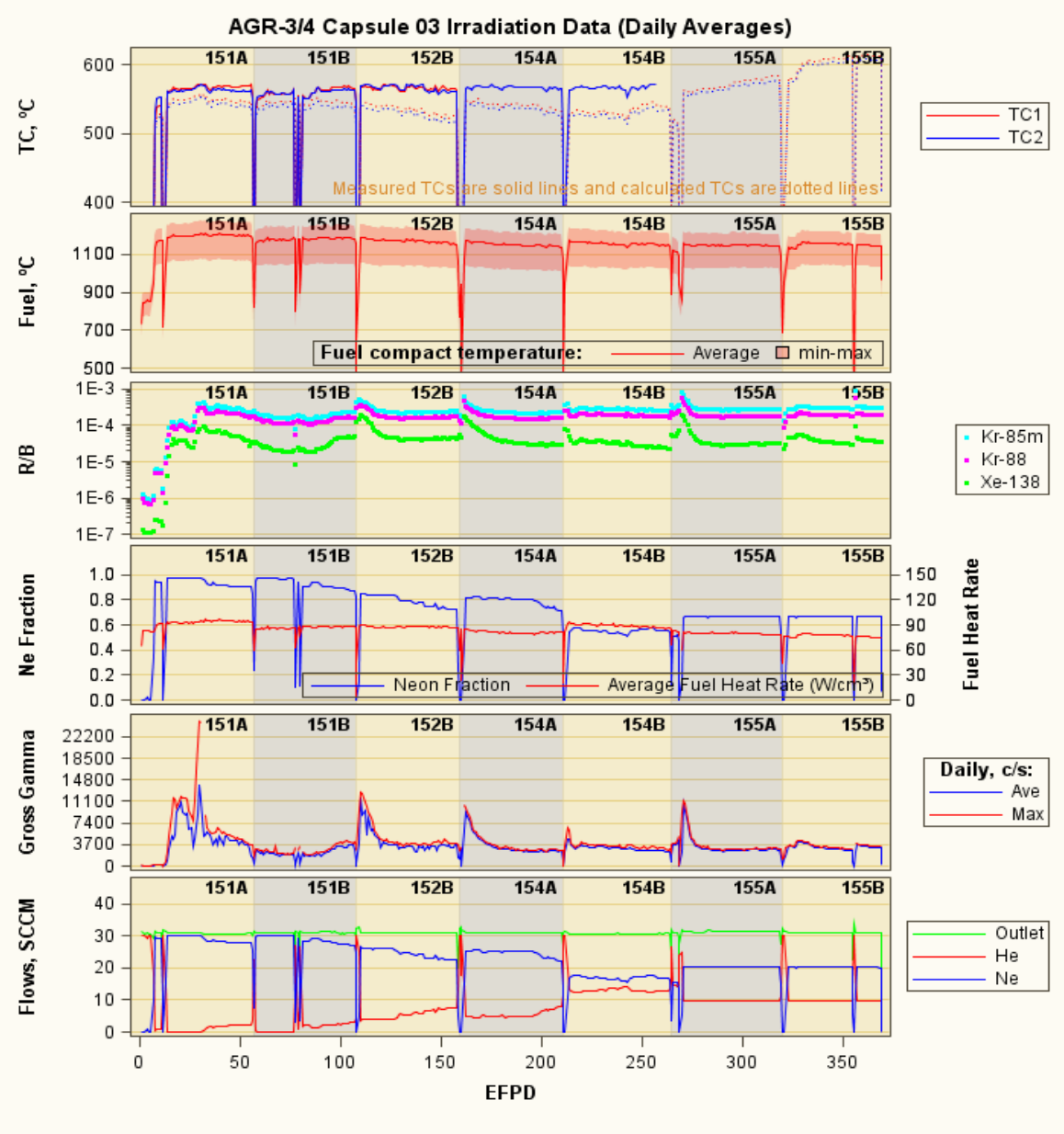

AGR-3/4 Capsule 09 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

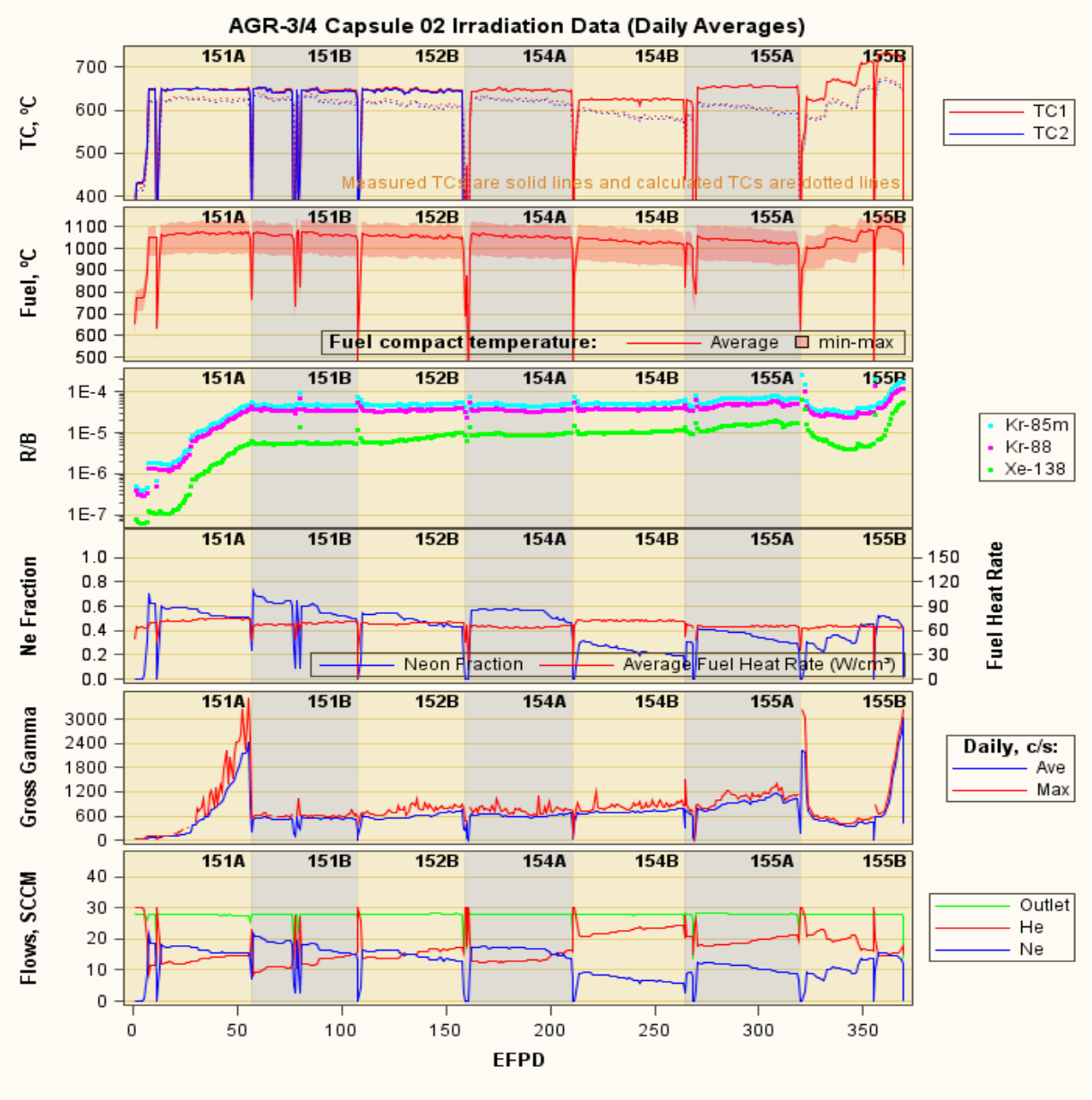

AGR-3/4 Capsule 08 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

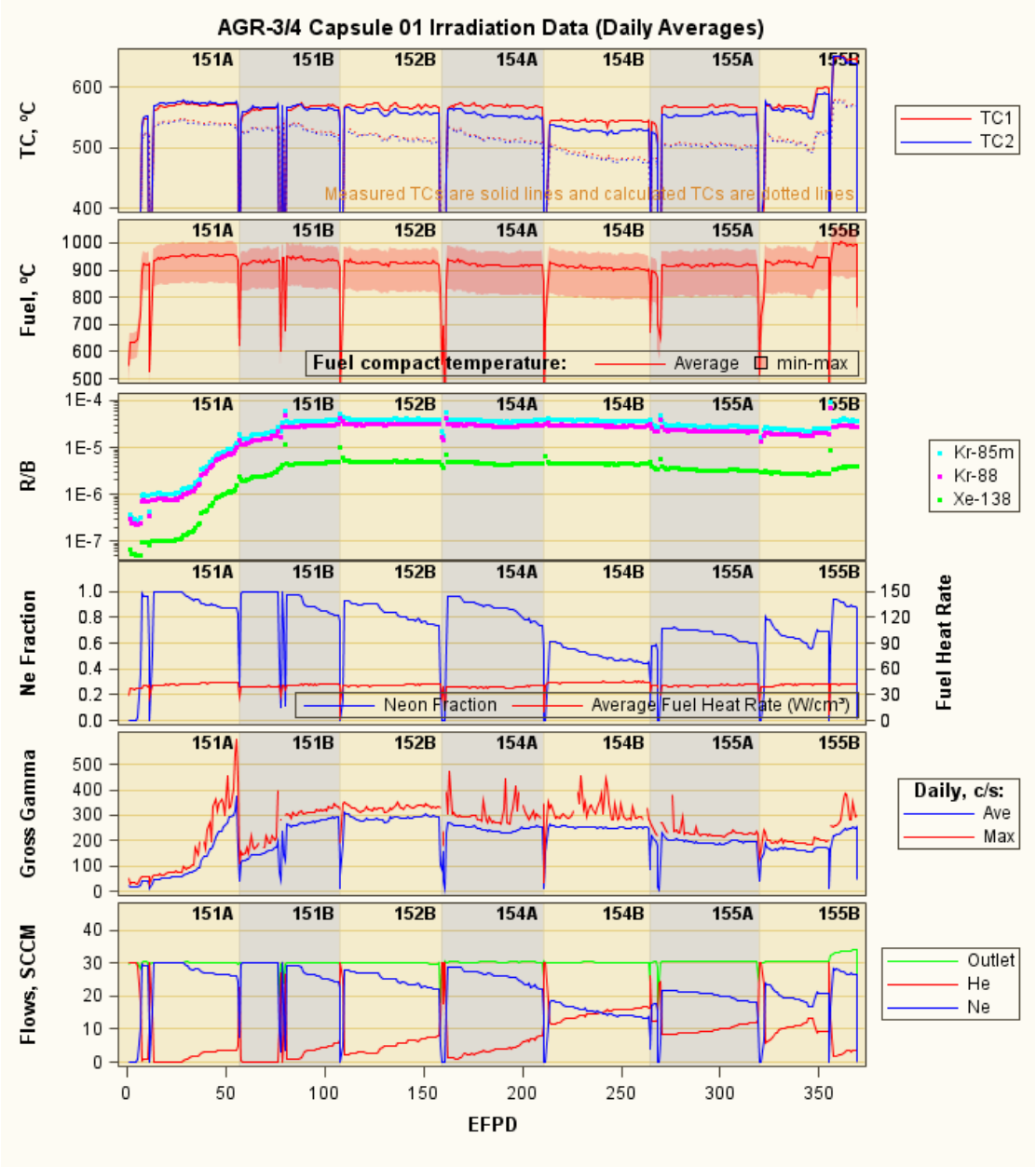

AGR-3/4 Capsule 06 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Fuel Heat Rate
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

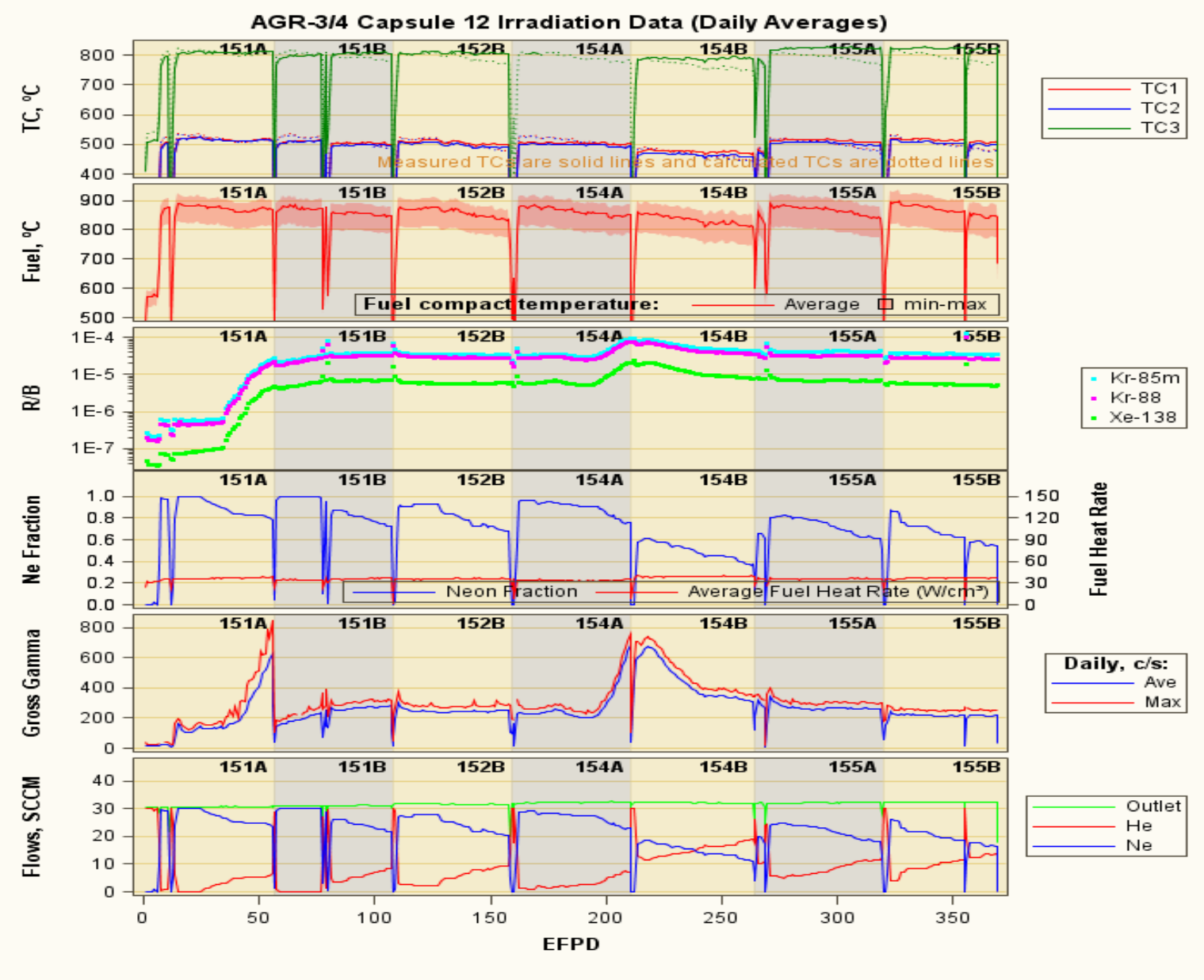

AGR-3/4 Capsule 05 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
TC3
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD


AGR-3/4 Capsule 04 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD

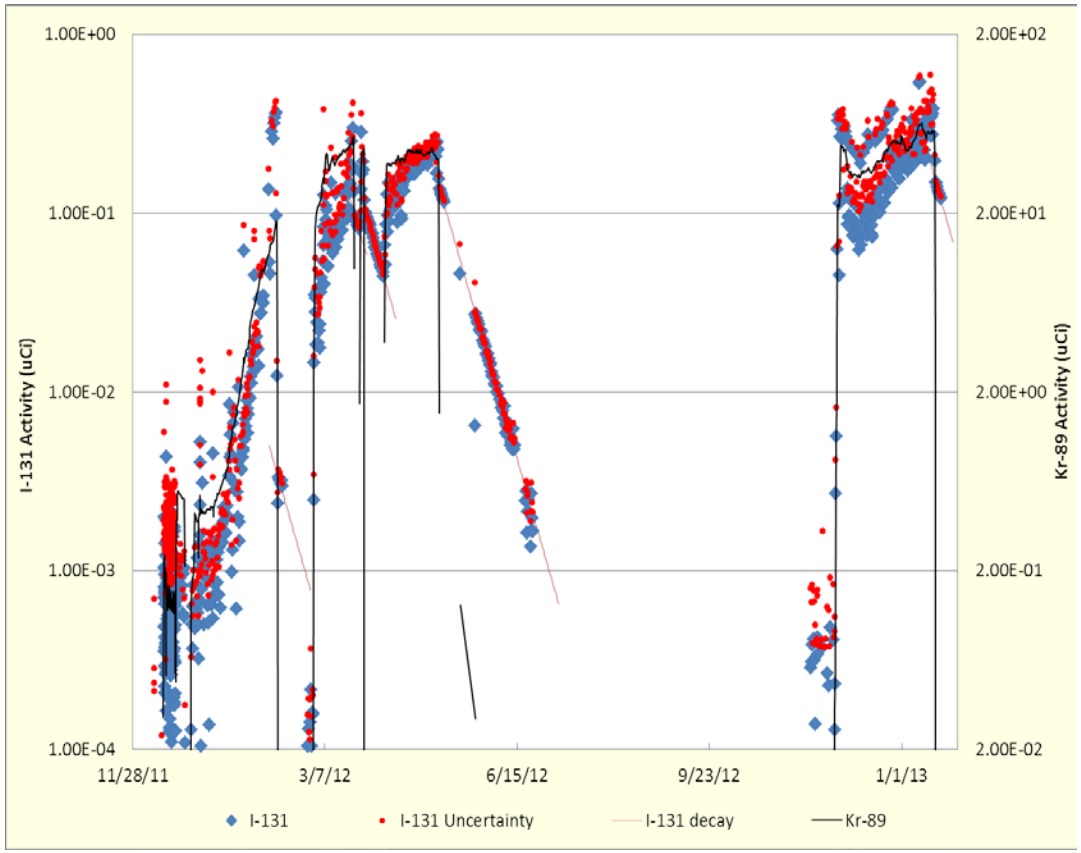

AGR-3/4 Capsule 03 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
600
500
400
Measured TCs are solid lines and calculated TCs are dotted lines
TC1
TC2
Fuel, °C
1100
900
700
500
Fuel compact temperature:
Average
min-max
R/B
1E-3
1E-4
1E-5
1E-6
1E-7
Kr-85m
Kr-88
Xe-138
Ne Fraction
1.0
0.8
0.6
0.4
0.2
0.0
Neon Fraction
Average Fuel Heat Rate (W/cm³)
150
120
90
60
30
0
Fuel Heat Rate
Gross Gamma
22200
18500
14800
11100
7400
3700
0
Daily, c/s:
Ave
Max
Flows, SCCM
40
30
20
10
0
Outlet
He
Ne
0
50
100
150
200
250
300
350
EFPD


AGR-3/4 Capsule 02 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
TC1
TC2
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel, °C
Fuel compact temperature:
Average
min-max
R/B
Kr-85m
Kr-88
Xe-138
Ne Fraction
Fuel Heat Rate
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Gross Gamma
Daily, c/s:
Ave
Max
Flows, SCCM
Outlet
He
Ne
EFPD


AGR-3/4 Capsule 01 Irradiation Data (Daily Averages)
151A
151B
152B
154A
154B
155A
155B
TC, °C
600
500
400
Measured TCs are solid lines and calculated TCs are dotted lines
TC1
TC2
Fuel, °C
1000
900
800
700
600
500
Fuel compact temperature:
Average
min-max
R/B
1E-4
1E-5
1E-6
1E-7
Kr-85m
Kr-88
Xe-138
Ne Fraction
1.0
0.8
0.6
0.4
0.2
0.0
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Fuel Heat Rate
150
120
90
60
30
0
Gross Gamma
500
400
300
200
100
0
Daily, c/s:
Ave
Max
Flows, SCCM
40
30
20
10
0
Outlet
He
Ne
0
50
100
150
200
250
300
350
EFPD


AGR-3/4 Capsule 12 Irradiation Data (Daily Averages)
TC, °C
Fuel, °C
R/B
Ne Fraction
Gross Gamma
Flows, SCCM
151A
151B
152B
154A
154B
155A
155B
TC1
TC2
TC3
Measured TCs are solid lines and calculated TCs are dotted lines
Fuel compact temperature:
Average
min-max
Kr-85m
Kr-88
Xe-138
Neon Fraction
Average Fuel Heat Rate (W/cm³)
Fuel Heat Rate
Daily, c/s:
Ave
Max
Outlet
He
Ne
EFPD

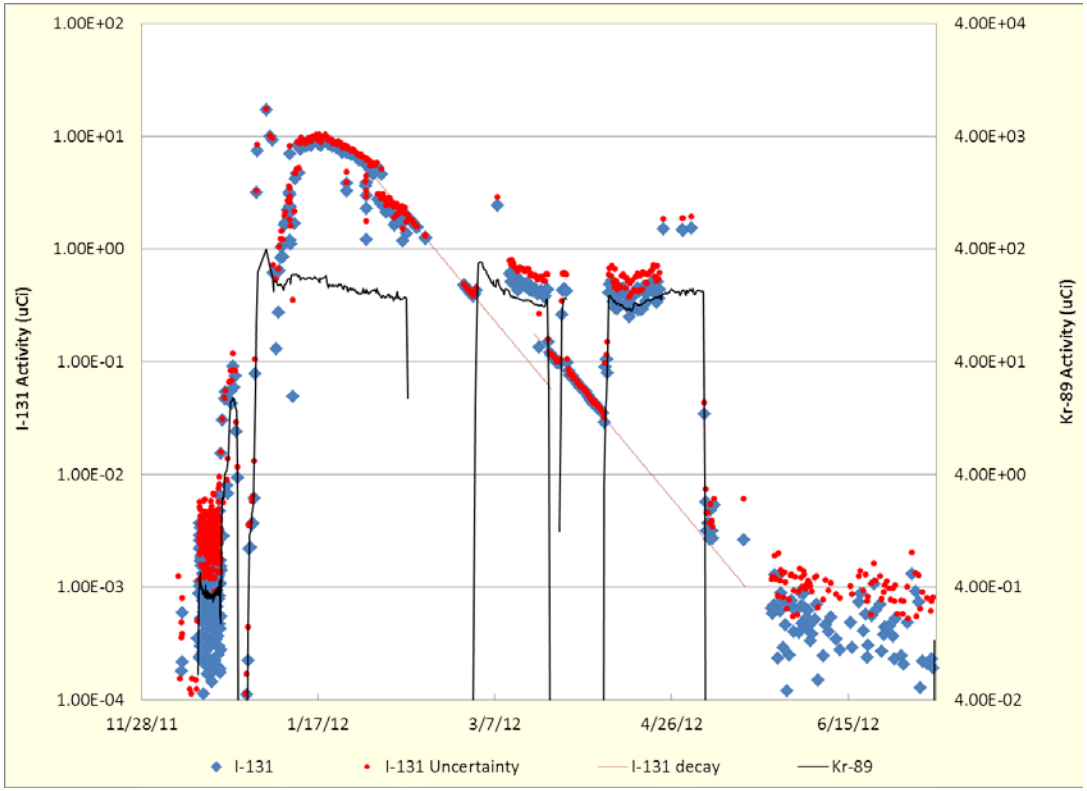
I-131 Accumulation AGR-3/4 Capsule 11



- ^{131}I was present in the sample chamber of FPM 11 as early as irradiation cycle 2
- An activity level of approximately 0.10 uCi was measured when the reactor was scrammed around mid-cycle on March 22 and again on March 27, 2012
- An activity level of approximately 0.14 uCi was measured at the end of the cycle on May 5, 2012

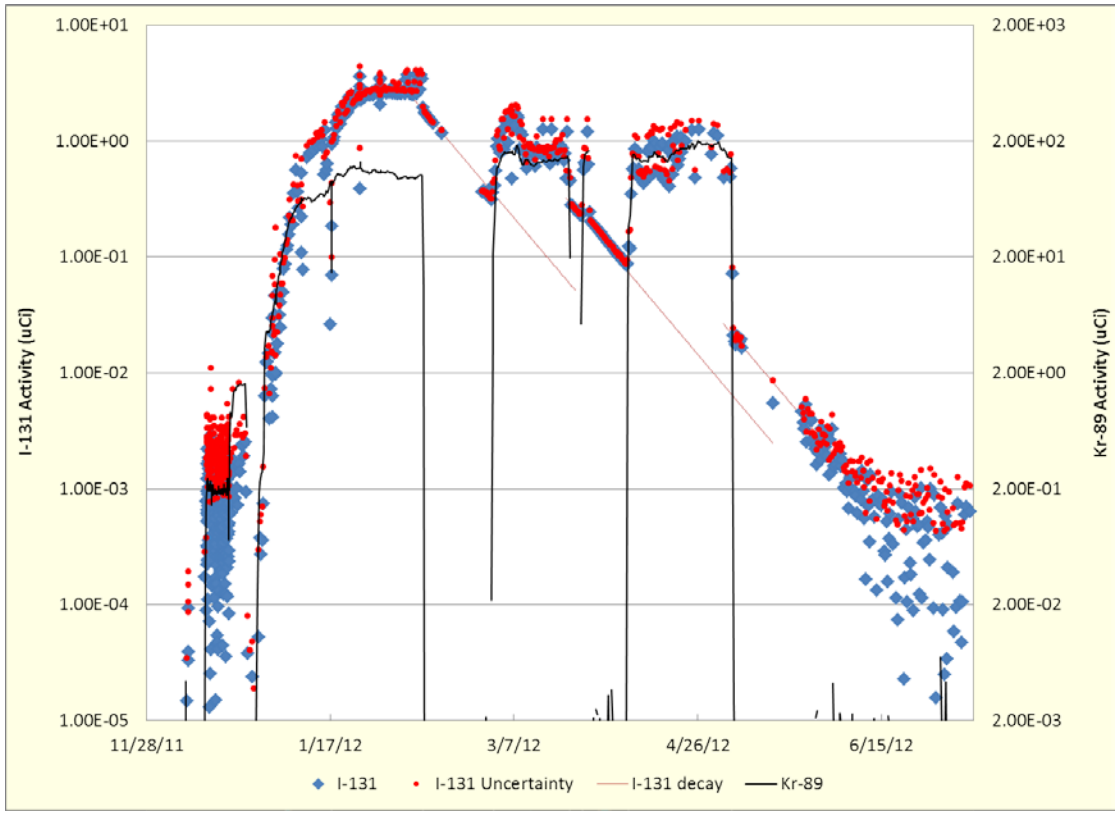
The question arises, is this iodine specie flowing through the chamber like the krypton and xenon isotopes or is it stuck to the surface of the chamber?

I-131 Accumulation AGR-3/4 Capsule 7



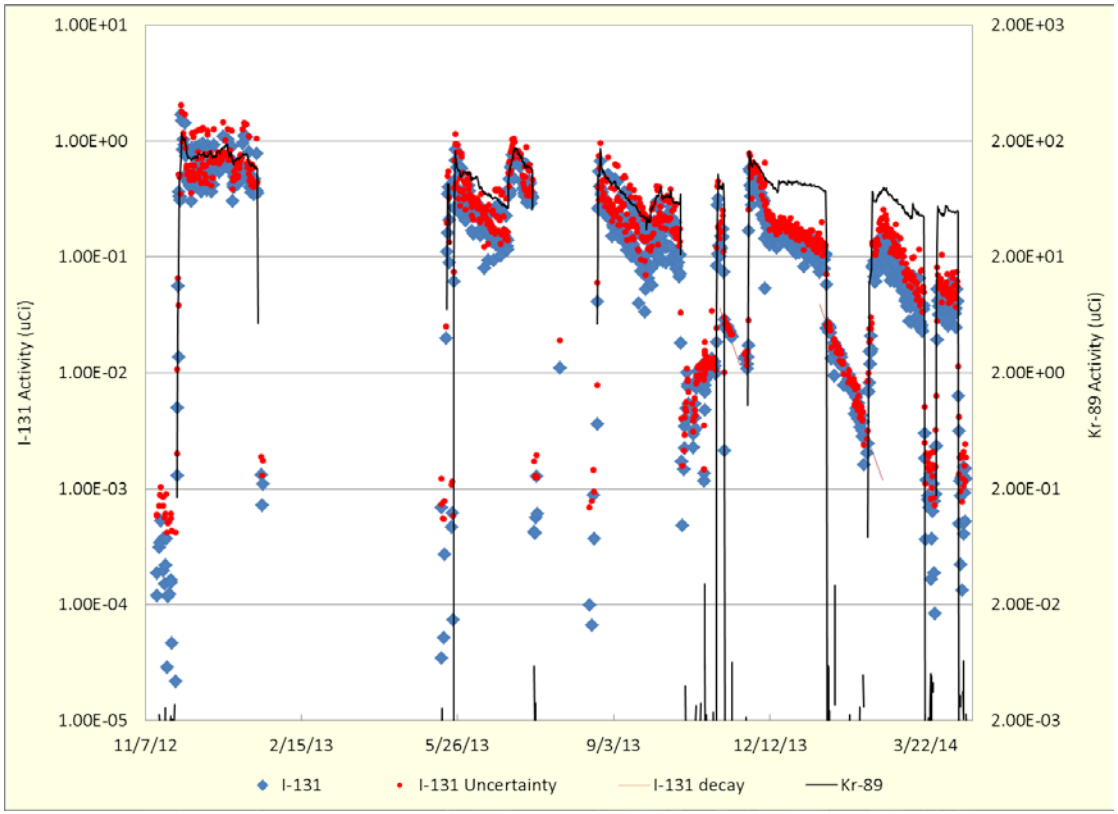
- ^{131}I accumulation in FPM 7 for the first 2 irradiation cycles of AGR-3/4
- FPM 7 had an inventory of 1.9 mCi at the end of the first irradiation cycle
- There was evidence for small additions to the sample chamber inventory early in cycle 2, at the mid cycle shutdowns on March 22 and March 27, 2012, about 0.06 and 0.02 uCi respectively
- I-131 was not observed after irradiation cycle 2

I-131 Accumulation AGR-3/4 Capsule 8



- ^{131}I accumulation in FPM 8 for the first 2 irradiation cycles of AGR-3/4
- FPM 8 had an inventories of 1.8 uCi at the end of the first irradiation cycle
- By the end of the second irradiation cycle the inventory was 0.31 uCi

I-131 Accumulation AGR-3/4 Capsule 8 (cont.)



- ^{131}I accumulation in FPM 8 for the last 5 irradiation cycles of AGR-3/4
- FPM 8 had an inventory of 0.05 uCi at the end of the 6th irradiation cycle
- Amounts to 4 ppb of the capsule inventory and 0.4 ppm of the failed particle inventory for capsule 8

Moisture was initially present in the graphite of these two capsules and off-gassed during the first few irradiation cycles providing mobility to the iodine inventory.