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Predicting the Number of Fuel Failures Using Chiron

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PROJECT TITLE: Predicting the Number of Fuel Failures using CHIRON

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

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PREDICTING THE NUMBER OF FUEL FAILURES USING CHIRON

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For Dr. Townsend

Senior Thesis

ABSTRACT

During Cycle 12 of TVA's Browns Ferry Unit 2, fuel failures occurred during operation. However, while the core is operating, visual inspection of the fuel rods is not an option. Therefore, computer modeling may be used to predict the number of fuel failures within a core. To predict the number of fuel failures, the offgas, or the chemical composition of the coolant as it leaves the core, is used to model the rise in fission products in the coolant. By using a modeling code, CHIRON, a prediction of the number of failed fuel rods can be made.

From May 2002 through July 2002, the failures summary results from CHIRON rose from an average of 1.2 failures with a standard deviation of 0.57 to an average of 6.4 with a standard deviation of 3.6. Therefore, it is expected that either the number of the fuel leakers or the size of the existing leakers increased from May 2002 through July 2002.

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INTRODUCTION

Browns' Ferry, a Tennessee Valley Authority owned and operated nuclear power plant, currently has two operating reactors with another reactor being returned to service. During Unit 2's most recent cycle, fuel failures occurred during operation. However, while the core is operating, visual inspection of the fuel rods is not an option. Therefore, computer modeling may be used to predict the number of fuel failures within a core.

Nuclear power plants operate by heating water using energy released by fissions and then extracting this heat to produce electricity. Fission occurs when a neutron bombards a nucleus of a fissile material such as Uranium. The neutron causes the nucleus to become unstable and to break apart. In addition to heat and neutrons, which will produce more fissions, the reaction produces elements known as fission products.

Fission products are contained within the fuel cladding under normal operations. However, a fuel failure, or a compromise within the cladding, will release these products into the local environment. For a failure occurring within an operating core, this environment is the coolant surrounding the fuel. The fission products emitted into the coolant can be used to characterize fuel failures. Many of these fission products are radioactive gases.

In order to predict the number of fuel failures within Browns Ferry Unit 2, the off gas, or the chemical composition of the coolant as it leaves the core, is used to model the rise in fission products in the coolant. By using a modeling code, CHIRON, a prediction of the number of failed fuel rods can be made.

The number of fuel failures given by CHIRON from samples during the summer of 2002 will then be compared to those estimated by the code prior to a mid-cycle outage in April of 2002. This comparison will help to normalize the results from CHIRON since the number of fuel failures in April was found to be four fuel assemblies.

SCOPE

In this work, I will analyze the results of off gas samples from Browns Ferry Unit 2 from May 2002 through July 2002. These results will then be compared to those prior to the mid-cycle outage in April.

To further understand the process, I will also discuss the CHIRON code. I will consider its primary inputs, outputs and theoretical basis.

BACKGROUND

DESCRIPTION OF FUEL

Each reactor's fuels assemblies are designed specifically for the cycle's needs and limits. For Cycle 12 of Browns Ferry Unit 2, a 9x9 fuel assembly was used. A diagram of a typical fuel assembly is shown in Figure 1. Within this 9x9 fuel assembly, 74 fuel rods, both full length (14 feet) as well as three-quarter length rods (10.5 feet), were inserted. In addition, water holes are also included in the assembly. Brown's ferry has 764 fuel assemblies in an operating core. Therefore, 56,336 fuel rods are being utilized within the operating core.

TYPES OF FUEL FAILURES

Although the fuel assemblies are constructed to satisfy stringent operation criteria, fuel failures do occasionally occur[1]. The types of failures are as follows:

- **Fuel Swelling:** A condition in which the fuel pellet within the fuel rod swells. This is primarily due to the generation of fission products. It is a concern with large, fast neutron fluxes.

- **Fuel Densification:** A condition caused by the density of the Uranium Dioxide fuel pellet increasing. This results in the reduction of the pellet diameter and length, thus creating gaps between pellets where the cladding might collapse.

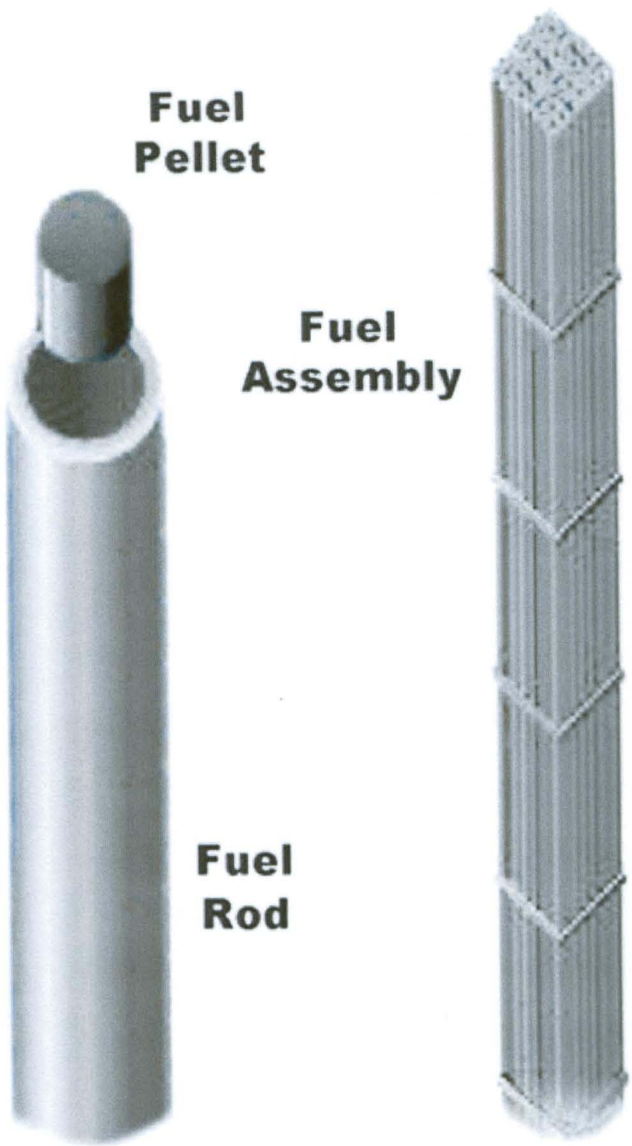

Figure 1. Structure of a typical Fuel Pellet, Fuel Rod, and Fuel Assembly.[5]

- **Thermal Expansion:** A condition in which the fuel pellets expand and/or deform. This is caused by nonuniform heating rates.

- **Pellet/ Cladding Interaction (PCI):** A failure of the cladding resulting from a power ramp after sufficiently high burnup. These types of fuel defects are caused by local stress loading as well as chemical reactions between the pellet and the cladding.

- **Formation of Hydrides:** A condition caused by the absorption of hydrogen within the zircaloy lattice, which may result in the embrittlement of the cladding.

IMPORTANCE OF FUEL FAILURES

Fuel failures are a major concern to the utility. TVA is expected to spend more than twenty million dollars to fix the problem at Browns Ferry[4]. The cost comes from the need to perform mid-cycle outages as well as to replace the fuel. In addition, fuel failures cause an increased radioactivity in the secondary loop in a Boiling Water Reactor (BWR). This increase in radiation leads to a shorter life of the secondary loop. Also, fuel failures are often treated with decreases in power production. Because less power is being produced from the reactor, the utility is losing income as well.

CURRENT SITUATION AT BROWNS FERRY

From the mid-cycle outage in April 2002, it was found that rods from four fuel assemblies had failed. Each of these assemblies was from the most recent batch of fuel inserted into the core. Thus, these rods had a low burnup of around 30 gigawatt-days per metric ton uranium (GWd/MTU). The burnup refers to the amount of energy generated by the nuclear fuel at the time of the sample. The location of the fuel assemblies within the core as well as the location of the failed rods is shown in Figure 2.

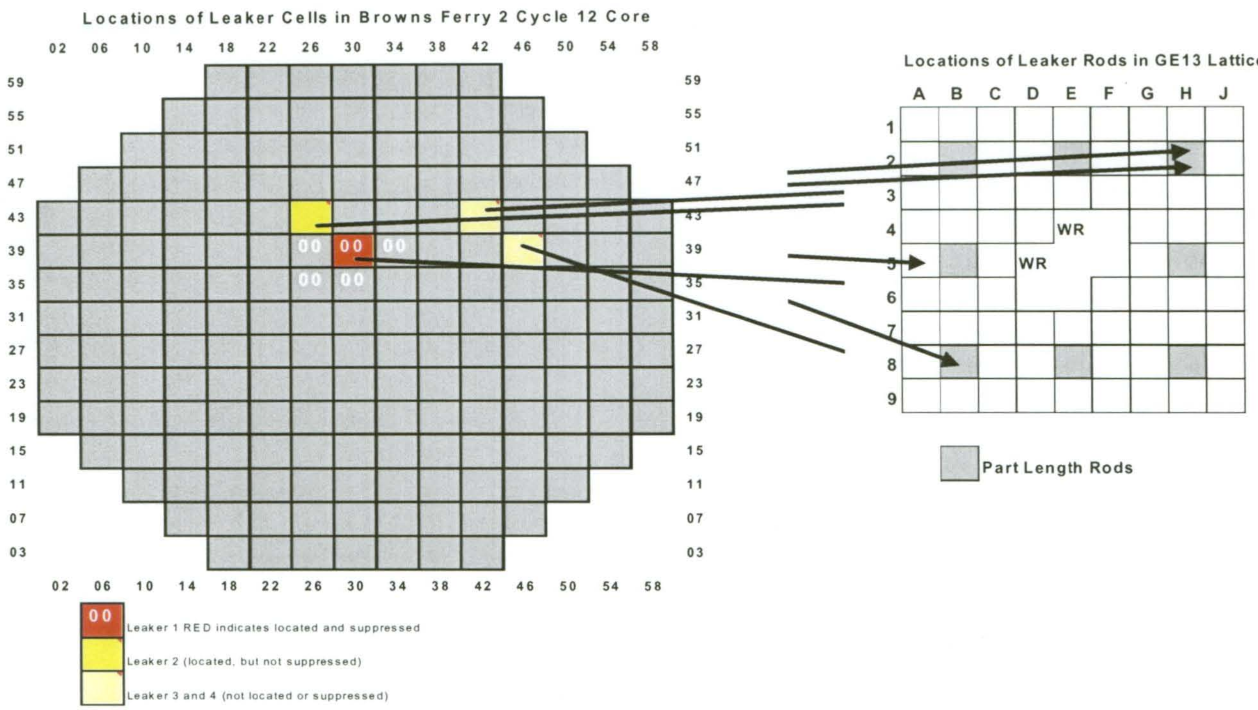

Figure 2. Location of fuel failures found from mid-cycle outage April 2002.[2]

PROCEDURE: HOW IS CHIRON USED?

The microcomputer code CHIRON is a DOS based, PC compatible nuclear code. CHIRON's primary function is to estimate the number of fuel failures in a core based on the coolant's chemistry data. This robust code is useful for both pressurized water reactors (PWR) as well as boiling water reactors (BWR). The model is able to predict the number of failures, within a factor of two, for approximately 90% of the cases. To improve the estimation results provided by CHIRON, long-term, steady-state coolant data is required. [3]

To better understand CHIRON, it is important to be familiar with (i) the theoretical basis, (ii) the key inputs, and (iii) the key results.

THEORETICAL BASIS

The results of CHIRON[3] are based up the solutions to the multivariate non-linear fit for the fuel diffusion equation, which is shown in Equation 1. The release to birth ratio can be broken into its individual parts. Release refers to the activity of each of the isotopes released from the fuel failure. Birth refers to the activity of each of the isotopes formed after the release. Therefore, these isotopes that are produced after the release are thought to be "born" within the coolant. The three coefficients, a, ε , and C, can be obtained using a least squares analysis.

$$(R/B)_i = \frac{a\varepsilon}{\lambda_i^{3/2} + \varepsilon\lambda_i^{1/2}} + n_i C \qquad \text{Eqn. 1}$$

Where:

R/B = Release to Birth Ratio

i = ith isotope

λ = Decay constant for an isotope

a = Fitted Coefficient (Escape rate from fuel pellet)

ε = Fitted Coefficient (Escape rate from gap to coolant)

C = Fitted Coefficient (Constant "Recoil" release)

n_i = Tramp (recoil) correction term

KEY INPUT

Since CHIRON's analysis can be performed for a variety of nuclear core designs, it is imperative that the program be configured for the core in question[3]. A variety of required plant parameters are listed under core data. In addition to general core design information, specific coolant data is mandatory to analyze the number of fuel failures.

CORE DATA

In order to analyze the core data, the plant specific parameters must first be input into the core. Plant configuration inputs include **Reactor Type** (BWR / PWR), **Reactor Rated Power** (in Megawatts thermal), **Number of Fuel Rods in Core**, **Active Length** (in centimeters), **Water Volume** (in cubic centimeters), and **Reactor Water Density** (in grams per cubic centimeter). Other parts of the general configuration menu that are set to default values include (i) Model Options, (ii) Conversion Parameters, (iii) Files and Titles, and (iv) General Configuration.

COOLANT/ CHEMISTRY DATA

Important case specific data include the date and time of the sample. Also core data such as the power level and the burnup are also needed. In addition to the case specific data, the isotopic activity is also entered. The activity can be given in either micro-Curies per cubic centimeter or micro-Curies per second. The three isotopic groups include (i) noble offgas, (ii) iodines, and (iii) reactor water solubles. Contributing isotopes for each of the groups are as follows:

- **Noble offgas:** Xe-133, Xe-135, Xe-135m, Xe-138, Kr-85m, Kr-87, Kr-88
- **Iodines:** I-131, I-132, I-133, I-134, I-135
- **Reactor Water Solubles:** Ba-139, Ba-140, Ba-141, Cs-134, Cs-137, Cs-138, Mo-99, Np-239, Sr-89, Sr-90, Sr-91, Sr-92, Tc-99m Tc-101, Te-129m, Te-132

Up to ten cases can be simultaneously solved for the estimated number of fuel rod failures

KEY OUTPUTS

The primary result from performing a CHIRON analysis is the estimated number of leaking fuel rods within the core at the time of sample[3]. Due to the variety of leakers that could be present, the predicted number of failures is within a factor of two for approximately 90% of the cases. Therefore, the standard deviation of the failed rods is also included in the report summary. Figure 3 shows a sample report summary. As shown below, the final report highlights the **Failure Summary,** the **Activity Summary,** and the **Fit Coefficients.** The Failure Summary includes the estimated number of leakers as well as the failure error. The Activity Summary compares the input values of the isotopic activity to the activity that the model predicted. The Fit Coefficients refer to the solution coefficients found for the multivariate non-linear fit for the fuel diffusion equation of which the model is based upon.

GRAPHICAL RESULTS

Other outputs contain the graphical representations of the solutions for the fuel diffusion equation. These graphs include the following:

- **R/B vs. Lambda:** Displays the release to birth ratio (R/B) found for each of the isotopes as a function of the decay constant.
- $F(\varepsilon)$ vs ε : Displays the function of the escape coefficient in comparison to the escape rate
- **Failure Correlation**

- **Cs Burnup:** Displays the ratio of Cesium-134 to Cesium-137 as a function of Burnup (GWD/MT).

```
                     FIT TYPE: Offgas          R² = 0.56982
Plant: TEST      Sample ID: Sample         Sample Date: 01/15/85    12:01:00

           ACTIVITY SUMMARY uCi/sec              FAILURE SUMMARY
 Isotope      Measured      Predicted         Method: EPRI Dec 90
   Xe-138    1.160e+005    1.146e+006   ■     Failed Rods:       26   (25.79)
    Kr-87    1.940e+004    8.689e+004         Fail Error 1σ:  22.16
    Kr-88    1.870e+005    5.592e+004
   Kr-85M    6.520e+003    1.297e+004       Power:  P/Pr =  0.980 (x 1.04 RPF)
   Xe-135    2.790e+004    3.371e+004         Fission/Sec/Rod:     1.756e+015
   Xe-133    1.180e+004    1.180e+004         U-235/Pu-239 yld:  1.000  0.000
TOTALS       3.686e+005    1.347e+006         Burnup GWD/MT: User: N/A  Cs = N/A
RECOIL       3.648e+005    1.333e+006
Non-Recoil   3.784e+003    1.383e+004       Fit coefficients:
                                                aε:                3.640e-009
                                                ε:                 0.000e+000
                                                c (Recoil Term):   4.722e-001


                                              No. Iterations :       5
                                              Converge Criteria:  1.000e-004
                                              Converge Error:     2.203e-005
                                                        S. Levy Inc.
                      Press any key to continue
```

Figure 3. Sample CHIRON failure report [3]

FRI AND OFFGAS DATA

The Fuel Reliability Index, or FRI, as well as off gas chemistry data are monitored for indications of fuel failures. Failures are indicated by changes in Iodine and Noble gas activities. Browns Ferry Unit 2 Cycle 12 FRI is given in figure 4.

The data used for the variable input deck of CHIRON is a result from plant chemistry testing that was found in the BFR2 CI-705 reports: Off gas and Iodine Isotopic Results. A table of the variable input data is attached as Appendix A.

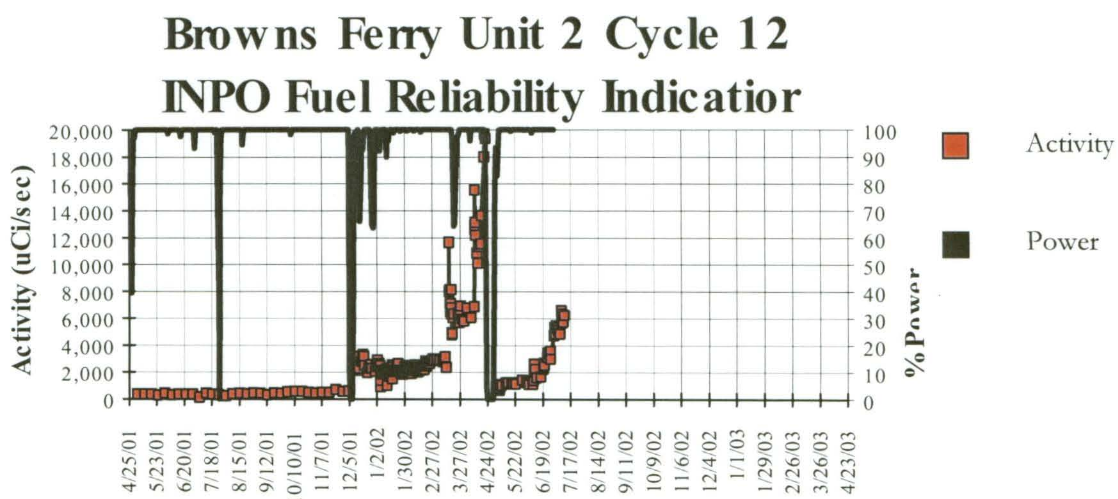

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Figure 4. Graphical representation of BFU2 CY12 power and FRI through July 2002 [2]

From May 2002 through July 2002, the failures summary results rose from an average of 1.2 failures with a standard deviation of 0.57 to an average of 6.4 with a standard deviation of 3.6. Figure 5 displays the increase in the predicted number of fuel failures.

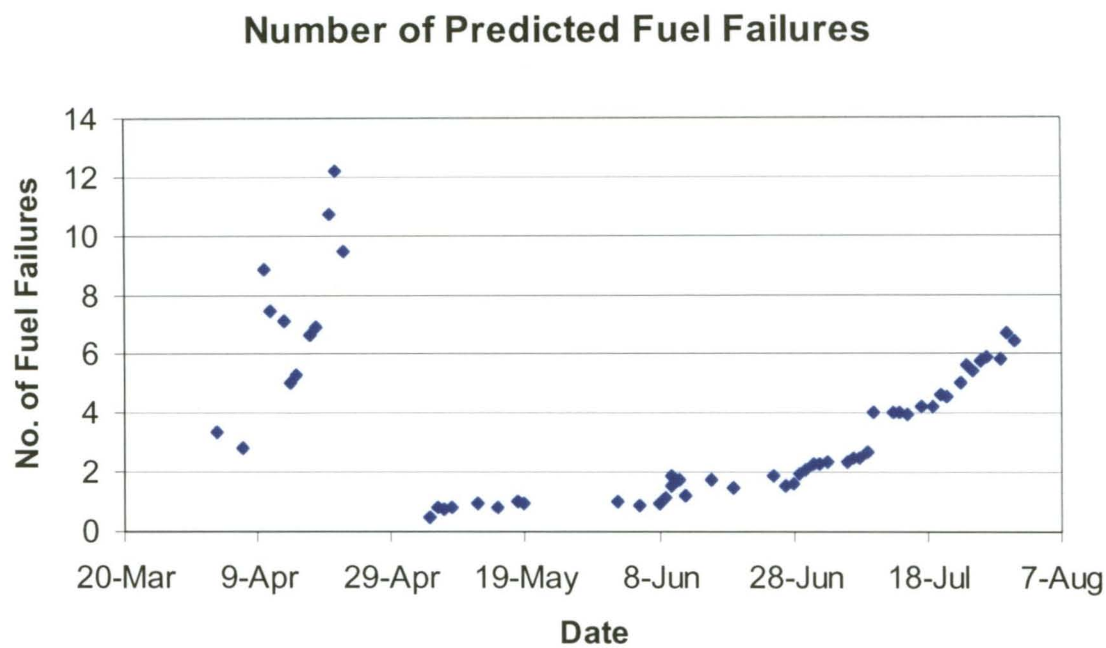

Figure 5. Predicted Number of Fuel Failures as a function of time.

As shown in Figure 5, the failure summary prior to the mid-cycle outage, which began on April 23, 2002, is also given. Thus the summer results could be compared to those prior to the outage. The estimated number of fuel failures on April 21, 2002 was 12.18 with a standard deviation of 11.12. During the mid-cycle outage, the actual number of leaking fuel rods was found to be four.

CONCLUSIONS AND RECOMMENDATIONS

From the increase in both the FRI as well as the CHIRON failure results, either the number of the fuel leakers or the size of the existing leakers increased from May 2002 through July 2002. Browns Ferry underwent another mid-cycle outage to remove leakers at end of October. Although the exact number of leakers could not be determined prior to the outage, plans to remove 49 fuel assemblies were in place. Most of the planned removals are for preventative measures.

The large margin of error from the CHIRON code is due to the methods of the code. Since the data used are from the offgas samples, which are a collection of radioisotopes from throughout the core, a few, large leakers cannot be distinguished from several, small leakers. Therefore, CHIRON should be used for estimation purposes only.

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3. Michaels, Wayne, Brian Paulson, Kenneth Watkins, and Niels Kjaer-Pedersen. 1992. CHIRON User Manual. Palo Alto: S. Levy Incorporated.

4. Scalice, John. 32nd International Nuclear Fuel Performance Conference. 2002.

5. www.nrc.gov/what-we-do/regulatory/emer-resp/pellet-assembly.html. Retrieved April 30, 2003. Last updated September 18, 2002

APPENDIX A

Attached: Input information through June 2002

Date	Time	MWth	gpm	Mlb/hr	GWD/ST
3-Apr	8:00	3457	261	14.1	26
7-Apr	7:46	3457			
10-Apr	8:48	3459	260	14.1	26.8
10-Apr	19:31	3449	260	14.1	26.8
10-Apr	21:28	3449			
11-Apr	3:39	3458			
11-Apr	15:26	3457	250	14.1	26.9
12-Apr	0:08	3453	250	14.1	26.9
13-Apr	8:55	3454			
14-Apr	4:12	3454			
15-Apr	4:16	3454			
17-Apr	8:48	3450	253	14.1	27
18-Apr	4:42	3454			
20-Apr	15:05	3456	260	14.1	27.1
21-Apr	9:22	3456	260	14.1	27.1
22-Apr	4:45	3455			
23-Apr	9:00	0			
2-May	0:58		248	9.5	27.3
5-May	22:33	3454			
6-May	8:24	3446			
6-May	9:45	3454			
2-Jun	9:19	3454			
5-Jun	8:25	3461	260	14.1	28.2
8-Jun	15:07	3458			
9-Jun	9:37	3456			
10-Jun	4:50	3460			
10-Jun	6:57	3458			
11-Jun	7:54	3461	260	14.1	28.2
12-Jun	8:05	3454	260	14.1	28.3
16-Jun	13:29	3456			
19-Jun	8:02	3457	259	14	28.5
25-Jun	13:29	3456			

Date	Time	Xe-138	Kr-87	Kr-88	Kr-85m	Xe-135	Xe-133
3-Apr	8:00	3939.17	685.71	750.7	246.7	860.78	309.03
7-Apr	7:46	3569.44	558.71	66.46	210.99	819.24	233.88
10-Apr	8:48	3699.3	778.8	826.83	267.39	985.18	330.99
10-Apr	19:31	6332.45	1199.25	1332.5	459.65	1564.77	1760.37
10-Apr	21:28	6593.84	1048.78	1349.92	449.11	1622.5	1843.16
11-Apr	3:39	7436.36	1629.02	1529.3	537.59	1738.81	2658.85
11-Apr	15:26	7066.92	1474.48	1358.54	455.71	1694.52	1106.11
12-Apr	0:08	6218.05	1486.33	1316.84	446.97	1535.27	1202.12
13-Apr	8:55	5116.4	1290.58	1366.95	472.76	1668.5	970.65
14-Apr	4:12	5457.41	1305.84	1102.57	356.02	1342.79	572.84
15-Apr	4:16	6565.52	1288.56	1129.02	380.43	1362.19	630.78
17-Apr	8:48	6091.4	1338.36	1275.82	436.53	1463.44	954.36
18-Apr	4:42	7148.3	1739.46	1549.01	501.52	1790.25	925.6
20-Apr	15:05	9204	1963.52	1840.8	602.56	2380.77	2000.34
21-Apr	9:22	9483	2265.88	2062.07	732.52	2684.49	2445.72
22-Apr	4:45	10204.14	1228.55	2067.8	697.84	2628.46	1427.03
23-Apr	9:00						
2-May	0:58						
5-May	22:33	481.6	40.48	40.92	17.71	33.7	59.45
6-May	8:24	467.92	69.98	92.37	38.86	64.31	98.96
6-May	9:45	535.64	68.99	83.06	35.48	63.04	87.62
2-Jun	9:19	805.04	106.03	103.62	41.97	91.91	111.5
5-Jun	8:25	699.46	108.14	104.85	38.05	82.4	90.07
8-Jun	15:07	727.9	93.47	94.59	36.6	85.92	58.12
9-Jun	9:37	755.96	159.91	175.77	60.53	145.38	91.72
10-Jun	4:50	1364.69	339.46	346.31	113.75	292.92	169.73
10-Jun	6:57	1044.39	257.33	255.97	87.88	220.38	134.96
11-Jun	7:54	1138.84	286.08	298.4	99.24	268.28	154.67
12-Jun	8:05	874.99	201.26	191.44	64.18	170.58	97.07
16-Jun	13:29	800.62	74.16	277.08	94.56	305.6	130.69
19-Jun	8:02	1244	276	269	86.7	284	103.6
25-Jun	13:29						

Date	Time	I-134	I-132	I-135	I-133	I-131
3-Apr	8:00	3.06E-05	4.29E-06	6.02E-06	1.77E-06	5.86E-06
7-Apr	7:46					
10-Apr	8:48	4.38E-05	5.55E-06	7.71E-06	1.13E-05	1.53E-05
10-Apr	19:31	2.42E-05	4.03E-06	5.74E-06	6.47E-06	1.22E-05
10-Apr	21:28					
11-Apr	3:39					
11-Apr	15:26	2.95E-05	4.31E-06	5.60E-06	1.22E-05	3.39E-05
12-Apr	0:08	2.93E-05	4.32E-06	6.36E-06	1.07E-05	3.35E-05
13-Apr	8:55					
14-Apr	4:12					
15-Apr	4:16					
17-Apr	8:48	3.74E-05	5.14E-06	6.80E-06	2.74E-06	7.16E-06
18-Apr	4:42					
20-Apr	15:05	4.41E-04	6.37E-06	2.89E-05	2.22E-04	4.64E-04
21-Apr	9:22	2.25E-05	3.86E-06	8.46E-06	3.55E-05	5.70E-05
22-Apr	4:45					
23-Apr	9:00					
2-May	0:58	1.18E-04	3.81E-05	3.95E-05	1.32E-05	6.26E-03
5-May	22:33					
6-May	8:24					
6-May	9:45					
2-Jun	9:19					
5-Jun	8:25	3.67E-05	5.76E-06	1.02E-05	8.41E-06	5.57E-06
8-Jun	15:07					
9-Jun	9:37					
10-Jun	4:50					
10-Jun	6:57					
11-Jun	7:54	2.96E-05	3.87E-06	9.04E-06	8.27E-06	5.92E-06
12-Jun	8:05	3.60E-05	3.14E-06	9.26E-06	8.93E-06	5.59E-06
16-Jun	13:29					
19-Jun	8:02	3.39E-05	3.77E-06	9.07E-06	8.77E-06	5.98E-06
25-Jun	13:29					