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APPLICATION OF NONPARAMETRIC REGRESSION ON WELL HISTORIES AT MAHIAO AND MAHANAGDONG SECTOR OF LEYTE GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

J.D. Villacorte[1], R.C.M. Malate[1] and R. N. Horne[2]

[1]Energy Development Corporation, Energy Center, Merritt Road, Fort Bonifacio, 1201 Taguig City, Philippines
[2]Stanford Geothermal Program, Department of Energy Resources Engineering, 367 Panama St., Stanford, CA 94305-2220, USA
villacorte.jd@energy.com.ph, malate@energy.com.ph, horne@stanford.edu

ABSTRACT

Investigation on the applicability of the nonparametric regression ACE (Alternating Conditional Expectation) method was extended to different sectors of Leyte Geothermal Production field of Energy Development Corporation (EDC) in the Philippines. The method correlated chloride concentration history of production wells with brine injection rates to predict well-to-well connections which is useful in designing a strategy for brine injection, and determining where thermal breakthroughs are likely to occur. Good chloride history matches were obtained for some wells but well-to-well connection indices have some inconsistencies compared with tracer test data. The method was initially applied in Palinpinon-1 sector of Southern Negros Geothermal Production Field (SNGPF) and yielded good results.

1. INTRODUCTION

Different analytical approach has been very useful for the purpose of defining well-to-well connection and was presented in numerous works and in different mathematical forms. This was introduced in the classic paper of Harper and Jordan (1985) who quantified the rate of return of injection water at Palinpinon in the Southern Negros Geothermal Production Field (SNGPF) based on chloride histories. Other mathematical analysis of utilizing the same data of chloride histories was carried out by Urbino and Horne (1991) using a correlation method, and by Sullera and Horne (2001) who used wavelet decomposition. All three studies inferred well connections that were verified qualitatively by comparison with tracer tests results. However, these methods have shown a weakness in that an assumption of the mathematical form of the connection model is required. This could mean imposing reservoir relationships that may not be extrapolated validly into the future.

In 2007, Horne and Szucs investigated the use of nonparametric regression to deal with the limitation of the former methods. The approach aims to match the given data without making any assumptions about the underlying reservoir model. The method known as ACE (alternating conditional expectation) was chosen by Horne and Szucs (2007) for the purpose.

ACE is a nonparametric method developed and presented by Breiman and Friedman (1985) for transformation/regression. It provides nonlinear transform functions which minimizes error in both response and predictors. This method assumes that the optimal transform of a function is the sum of the optimal transforms of the independent variables. This means that ACE works by decomposing the signal of each variable in the following form:

$$g^{*}(y) = \sum_{i=1}^{p} f^{*}(x_i) + e^{*} \qquad (1)$$

The transform function for measuring well-to-well connectivity index is defined as:

$$I_i = \frac{1}{n}\sum_{j=1}^{n} \left| f_i(x_i(t_j)) \right| \qquad (2)$$

This is the equation that has been used by Horne and Szucs with Palinpinon-1 data. This has also been used in examining the data from Mindanao Geothermal Production Field, Palinpinon-2/SNGPF, Upper Mahiao and Mahanagdong. The computed indices showed the relative strength depicted by the bar length.

Using the ACE algorithm, different set of well history data was examined. This includes primarily data from Palinpinon-1, SNGPF which have shown remarkable consistency with tracer test results.

The succeeding sections that follow will present review of the results of the application with Palinpinon-1 presented in 2007. Two additional sets of data from Leyte Geothermal Production Field were examined to further validate the mentioned equation.

2. REVIEW OF RESULTS TO EARLIER APPLICATION WITH EDC GEOTHERMAL FIELDS

The nonparametric ACE approach has initially been applied to Palinpinon-1 chloride data. The same set of data which was used in previous "parametric" approach. Computed connection indices from a defined connectivity index transform function showed good agreement with actual tracer results.

With the successful outcome of the preliminary experiment, two other sets of chloride and injection history data from EDC fields were initially used to validate the approach. These sets of data were from Mindanao Geothermal Production Field and Palinpinon-2 of Southern Negros Geothermal Production Field (Villacorte, et. al, 2010). Results for both fields yielded good match with respect to chloride history, however, connection indices did not produced consistent results with their respective tracer tests.

Palinpinon-1, SNGPF

The data evaluated in the demonstration covers the period of 1983 to 1989. It is the same data examined using the previous parametric approaches. Typical results showed that the connection between wells was indicated by the magnitude of the positive values of the transform functions. An example is depicted in Figure 1 illustrating the transform functions generated for all injection wells relative to the production well OK7.

The corresponding indices were represented graphically in Figure 2. These connection indices show the probability that thermal breakthrough will occur and the indices strength is based on the magnitude of the bar segments.

Computed indices were compared to actual tracer tests results. The findings in PN1RD tracer tests were used to estimate well connectivity and have shown good consistency with the indices calculated using the ACE method. Connectivity values from PN9RD tracer test and data showed good agreement though not as the case of PN1RD.

3. APPLICATION TO CHLORIDE DATA FROM SECTORS OF LEYTE GEOTHERMAL PRODUCTION FIELD

Upper Mahiao, LGPF

The Upper Mahiao is part of the Tongonan Geothermal Production Field and hosted the hottest resource with a maximum temperature of 300°C. It currently meets the power plants requirements and the excess was supplied via steam highway to other sectors of the field.

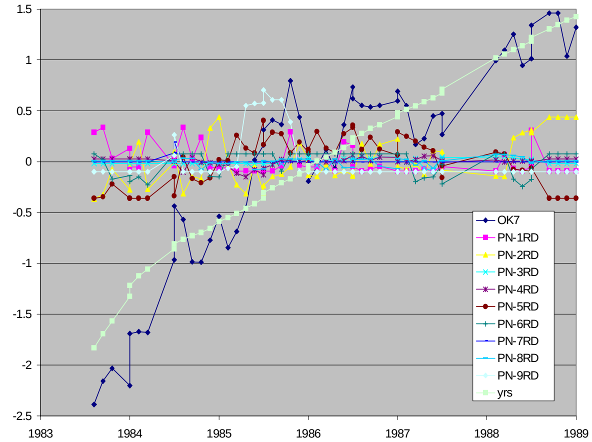

Figure 1: Extracted model function from OK7 data showing dependence on time and injection wells

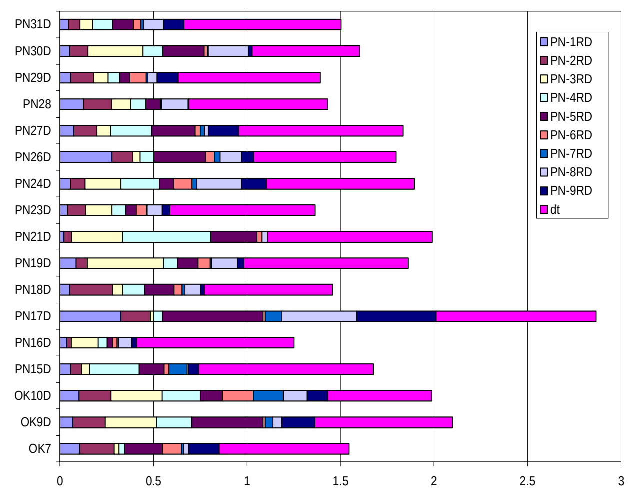

Figure 2: Summary of 'connection indices' based on ACE function magnitudes

The sector is supported by recharge from separated brine and plant condensate which amounted to a total mass of ~500 kg/s. This quantity is injected in pad 4RC and Pad 408 that started in December 2002 and August 2003, respectively.

An initial tracer test was conducted in June 2003 using 1,5-naphthalein disulfonate to probe pathway of condensate returns from injection well 4R11D to production wells in Pad 405 and then to 417D. After the results of the activity, the injection scheme was modified and optimized. The new configuration has minimized the effects of brine and condensate returns from the northwestern section as evident with the recovery of discharge enthalpies and chloride trends.

The latest tracer study, on the other hand, was carried out using a different isomer of NDS and injection well (4R3D). This activity aimed to validate the structural channels between the injection and production wells. Seven low-to-medium enthalpy wells were monitored and samples from which were analyzed using high performance liquid chromatography (HPLC).

Since the latest tracer test focused on seven production wells, it is the same set of wells that was evaluated using the ACE approach. Well histories of these wells were examined. Note that the approach processed the set of data independently respective of a production-injection well and not interdependent on production-production well. The study covered the period from 2003 to 2008.

Resulting transform functions for wells 415D and 410 are shown in Figures 3 and 4, respectively. Both plots showed good matched of time dependency of well chloride histories and is not linear in form. Interactions of these production wells with 4R3D have noticeable high positive values indicating its strength.

Well-to-well connectivity indices were computed using the same previously defined equation used in earlier applications. These indices were tabulated and presented in Table 1 and plotted in Figure 5. The longer bar, the more likely the connection strength and the likelihood of a thermal breakthrough.

Mahanagdong, LGPF

The next set of data will be the well histories from Mahanagdong sector of LGPF. This sector is a different geothermal system and has distinct heat source from the Tongonan area. An impermeable and cold barrier separates the two production sectors. This is called the Mamban block.

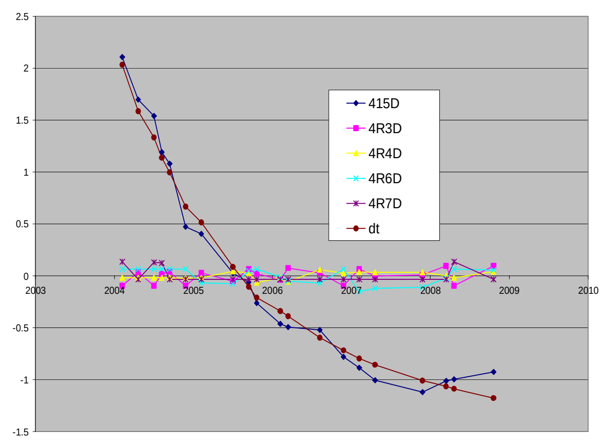

Figure 3: Extracted model function from well 415D data showing dependence on time and injection wells

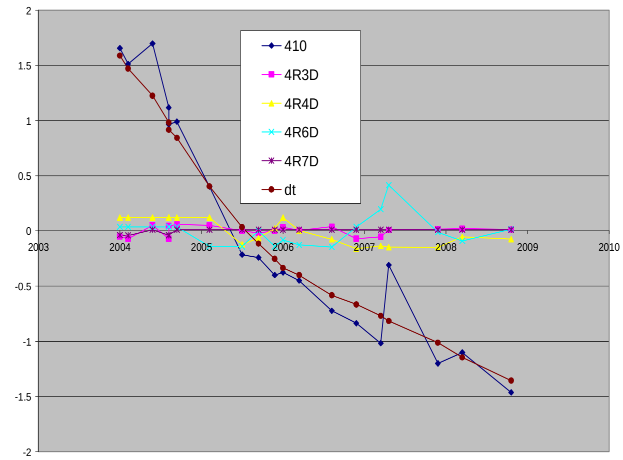

Figure 4: Extracted model function from well 410 data showing dependence on time and injection wells

Table 1. Connection indices at Upper Mahiao based on the average absolute magnitude of the ACE functions shown in Figure 5.

	4R3D	4R4D	4R6D	4R7D	dt
417D	0.15	0.32	0.27	0.51	0.34
415D	0.06	0.03	0.07	0.05	0.83
410	0.04	0.10	0.09	0.02	0.79
404	0.09	0.14	0.19	0.10	0.96
405	0.27	0.76	0.30	0.35	0.65
4R10D	0.30	0.23	0.25	0.18	0.54
4R9D	0.24	0.36	0.13	0.29	0.60

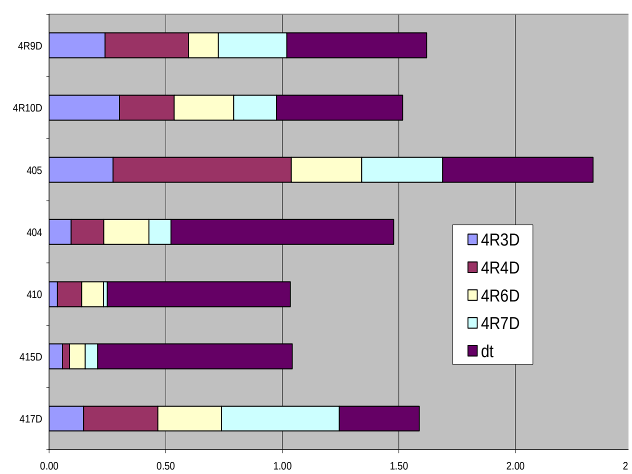

Figure 5: Summary of 'connection indices' based on ACE function magnitudes for Upper Mahiao wells

The field is divided into two areas namely the Mahanagdong-A and Mahanagdong-B which has a 132 MWe and 66 MWe, respectively. Both have a main plant and a topping unit. The total mass is extracted from a total of 21 production wells. The rate of extraction gradually increased and as a consequence, pressure decline of as much as 5 MPa was experienced in the central portion of the field.

The initial response of the field with the drawdown was boiling as evident with the increase in enthalpy in some of the wells. The succeeding years was marked by change in the hydrological flow of the field. Injection returns was manifested in the fluid chemistry in the different production wells of the field starting 1999 while in 2001, groundwater inflow have been discernible in four of the production wells.

Due to these occurrences, an NDS tracer study was performed in January 2003. Three different types of isomers were respectively in three injection wells that best represent the source of fluids of interest. Results were accounted and presented during the annual conference sponsored by EDC in 2005.

Results for well MG7D and for MG27D are illustrated in Figures 6 and 7, respectively. The figures showed relatively good match of chloride history for MG27D but a rough estimate of the trend for MG7D. It could be seen that large positive magnitude of the transform functions could be noted in each of the injection wells showing their respective connection.

Meanwhile, connection indices of these wells were likewise computed using the derived equation previously presented and used in treatment of the data. Results showed that MG28D has the biggest cumulative bar implying that it is likely to be affected by thermal breakthrough. Comparison with tracer results will be discussed in the succeeding section.

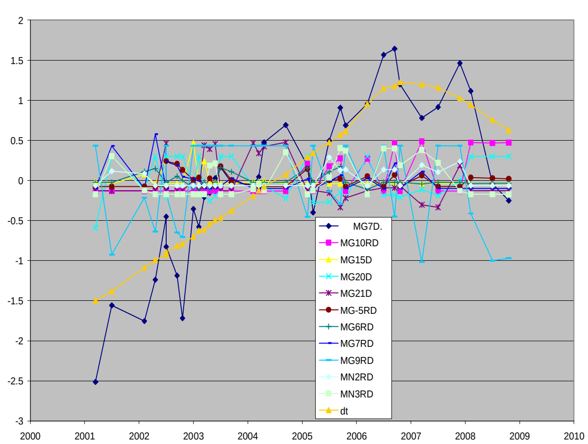

Figure 6: Extracted model function from well MG7D data showing dependence on time and injection wells

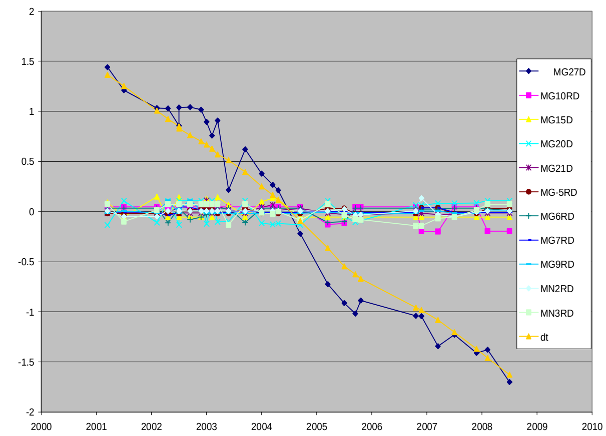

Figure 7: Extracted model function from well MG27D data showing dependence on time and injection wells

4. COMPARISON TO TRACER RESULTS

The computed connection indices presented in the Table 1 and Table 2 below. These were compared to results of their respective tracer tests to determine the physical significance and to calibrate the equation as well.

As mentioned, only seven low to medium enthalpy wells were monitored during the tracer test conducted in Upper Mahiao sector last August 2006. These wells were only the ones included in the treatment of the ACE approach. The injection well chosen in the test was Well 4R3D. Findings of the tracer showed that the chemical reached the fastest to well 417D while least for 4R9D. In addition, the chemical compound used was recovered in considerable quantity in well 417D. The results of the tracer test were compared to the indices calculated based on the ACE method and is presented in the Figure 8. The computed indices showed that the most affected was well 4R10D while 417D ranked only fourth. Meanwhile, the well with the shortest bar is well 410 which placed third in the most affected wells based on tracer.

As for the case of the Mahanagdong wells, findings of the tracer test were tabulated below and presented in Table 2 with corresponding Figure 9. The compound injected into MG21D showed relatively fast arrival to production wells from 2 to 11 days. The highest return concentration was perceived in MG3D being the nearest to the source well. On the other hand, the chemical compound in MG5RD established connection with wells located in the southern part of the field. The fluid traveled moderately fast speeds with the compound detected starting from 20 days to nearly 2 months. Tracer compounds were first seen in wells MG7D and MG16D followed by MG2D and MG22D.

Computed indices with respect to MG21D and MG5RD were shown in Figures 10 and 11, respectively. It could be seen that though the production wells affected by MG21D roughly matched those in which have longer bars in the figure, the highest of which is MG28D should not be included. On the other hand, wells affected by MG5RD based on tracer results were poorly predicted by the connection indices.

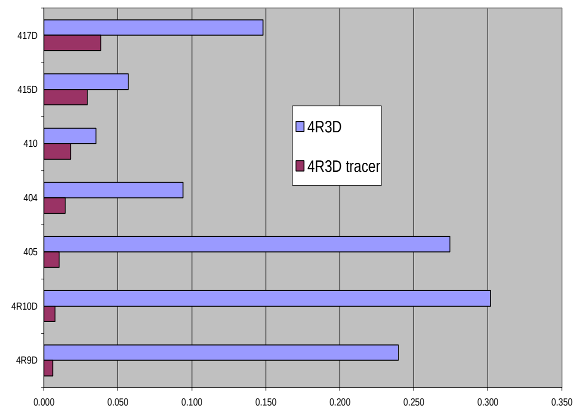

Figure 8: Comparison of indices for injector 4R3D, compared to tracer test results into 4R3D

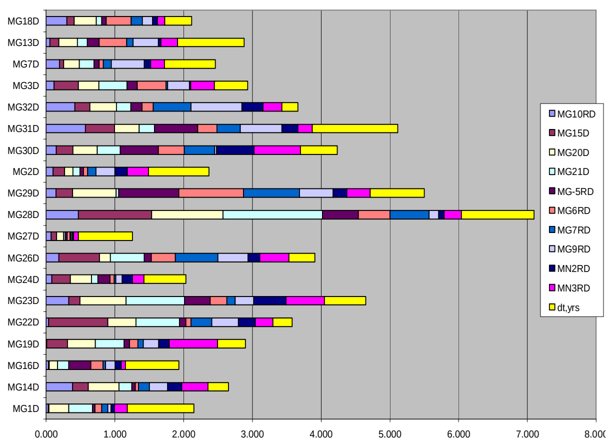

Figure 9: Summary of 'connection indices' based on ACE function magnitudes for Mahanagdong wells

5. DISCUSSION

The successful outcome of the initial demonstration of the nonparametric ACE approach to Palinpinon-1 well history data paved the way of validating the applicability to other geothermal fields. Well-to-well connectivity defined for the set of data seems to be very consistent with tracer results.

Another set of data were examined using the derived equation for the well-to-well connectivity index. These data were from the two sectors of the Leyte Geothermal namely, Upper Mahiao and Mahanagdong. The results of the transform functions showed good matched with chloride history for most of the wells. However, consistency with tracer results has likewise been poorly achieved. This would increase the possibility that the proposed equation for the well connectivity index is specific to certain set of data. This would require definition of a new equation that would be calibrated with tracer test results. Upon calibration, the derived equation maybe applied in predicting long term hydrological movement in the field.

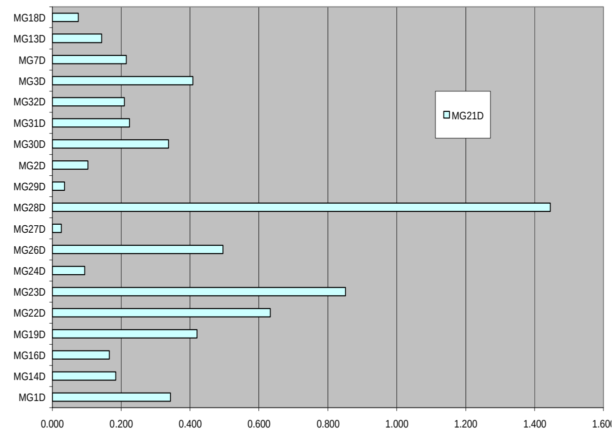

Figure 10: Computed indices for injector MG21D

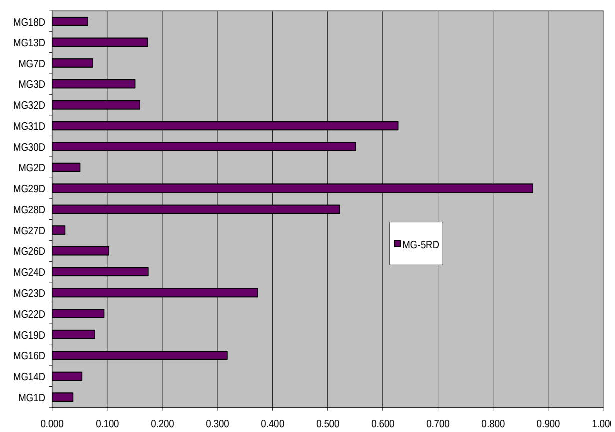

Figure 11: Computed indices for injector MG5RD

CONCLUSION

The nonparametric ACE method has been used in predicting well connectivity of production and injection wells by estimating their indices. It has been successful upon application to Palinpinon-1, SNGPF.

Further examination of the applicability of the ACE method using two sectors of LGPF showed the limited functionality of the derived equation for connection indices. Though good matches of well parameter history could be achieved, this not necessarily leads to consistent connection indices.

The derived equation showed limited application and may not reflect effects of other reservoir processes.

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Table 2. Connection indices at Mahanagdong based on the average absolute magnitude of the ACE functions shown in Figure 11.

	MG10RD	MG15D	MG20D	MG21D	MG-5RD	MG6RD	MG7RD	MG9RD	MN2RD	MN3RD	dt,yrs
MG1D	0.030	0.011	0.290	0.343	0.038	0.095	0.090	0.043	0.055	0.187	0.967
MG14D	0.384	0.231	0.447	0.184	0.055	0.044	0.159	0.264	0.203	0.383	0.297
MG16D	0.035	0.012	0.119	0.165	0.318	0.179	0.040	0.136	0.089	0.061	0.779
MG19D	0.007	0.302	0.405	0.420	0.077	0.124	0.077	0.225	0.151	0.704	0.406
MG22D	0.035	0.860	0.411	0.633	0.094	0.076	0.299	0.387	0.245	0.256	0.279
MG23D	0.330	0.161	0.673	0.851	0.373	0.238	0.125	0.272	0.467	0.560	0.598
MG24D	0.082	0.271	0.306	0.094	0.175	0.063	0.022	0.094	0.151	0.165	0.612
MG26D	0.186	0.591	0.156	0.496	0.103	0.347	0.619	0.440	0.169	0.423	0.381
MG27D	0.074	0.076	0.104	0.027	0.023	0.043	0.014	0.021	0.018	0.069	0.785
MG28D	0.467	1.066	1.042	1.446	0.521	0.462	0.569	0.139	0.079	0.249	1.061
MG29D	0.142	0.244	0.634	0.036	0.872	0.942	0.814	0.490	0.200	0.337	0.787
MG2D	0.100	0.166	0.124	0.103	0.050	0.061	0.118	0.277	0.180	0.308	0.878
MG30D	0.146	0.244	0.354	0.337	0.551	0.379	0.441	0.029	0.544	0.672	0.538
MG31D	0.570	0.426	0.356	0.224	0.628	0.279	0.341	0.605	0.231	0.211	1.244
MG32D	0.416	0.220	0.388	0.210	0.159	0.168	0.549	0.735	0.308	0.277	0.231
MG3D	0.115	0.353	0.299	0.408	0.150	0.419	0.024	0.316	0.021	0.344	0.484
MG34D	4.434	0.359	0.661	0.168	1.810	2.388	0.347	5.219	0.058	1.143	0.492
MG7D	0.194	0.060	0.229	0.215	0.074	0.060	0.115	0.484	0.092	0.202	0.740
MG13D	0.056	0.130	0.271	0.143	0.173	0.400	0.094	0.365	0.039	0.240	0.970
MG18D	0.301	0.106	0.324	0.075	0.064	0.365	0.166	0.147	0.069	0.108	0.391