# PARAMETRIC AND STATISTICAL ANALYSIS OF THE STIMULATION OF GEOTHERMAL WELLS THROUGH DEFLAGRATION: LEVEL 1

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## ABSTRACT

Stimulation through deflagration aims to use the energy generated from the combustion of a propellant to enhance permeability of a feed zone by generating fractures around the well bore. Given the success of the technology in oil and gas industry, this study was conducted to check if the technique has potential in addressing geothermal permeability issues. Both the short and long-term enhancement of production were investigated.

A radial model was developed using AUTOUGH2 and PyTOUGH to act as a deflagration simulator for testing different reservoir conditions and stimulation parameters. This simulator was satisfactorily calibrated to data from an actual well that had been deflagrated. Results showed that two-phase medium and high enthalpy reservoirs react more favorably to the deflagration stimulation compared to low enthalpy and vapour dominated reservoirs. In terms of sustainability, both the medium and high enthalpy reservoirs showed positive long-term permeability enhancement, while the vapour dominated and low enthalpy reservoirs returned to their pre-deflag conditions after less than five years of production. All cases showed a minimal change in enthalpy, indicating that deflagration does not significantly affect the enthalpy of the reservoir.

This paper focuses on the first of two levels of analysis (Level 1), which investigates combinations of different permeability, reservoir pressure and temperature, wellbore pressure, productivity index, and number of shots to determine the conditions suitable for deflagration. The second level of analysis that tests the sensitivity and robustness of the scenarios by checking the varying effects of Permeability Enhancement Factor and Radius of Influence which are both a function of the size/volume of propellant and the breakability of the rock around the well, will not be discussed in this paper.

## 1. INTRODUCTION

### 1.1 Background

Use of geothermal energy dates back for more than a century, but wide-scale power generation started up only after the 1950's with the development of flash steam technology in Wairakei, New Zealand. Geothermal energy has provided a low operating cost, stable baseload, low carbon, renewable resource for power production ever since. However, heat needs to be harnessed from the depths of the earth, and drilling towards a viable resource is critical in every geothermal project. In fact, drilling accounts for up to 40% of the total capital cost of a geothermal project (Thorhallsson & Sveinbjornsson, 2012). According to *Success of Geothermal Wells: A Global Study*, the rate of drilling success for fields in their exploratory phase starts at 50%, eventually picks up to 74% during the development phase, and then settles at 83% for operating fields (IFC, 2013). While this may seem like a relatively rapid improvement, it is still quite unacceptable considering that a typical deep well currently costs around NZ$10 million. This is the main reason why additional measures or stimulation activities are employed to attempt to improve productivity of wells, or at least mobilize a part of that otherwise lost investment.

Over the years, many stimulation techniques have been developed and proven useful for geothermal wells. Examples include matrix acidizing, perforation, deepening or sidetracking a well, and thermal stimulation - all to target additional feed zones or enhance existing ones. A number of new technologies, mostly adapted from the oil and gas industry are being experimented for application to geothermal conditions – one of which is the propellant based stimulation technology, also known as high energy gas fracturing or deflagration. While explosive fracturing is characterized by a high energy blasted over a short time interval, deflagration uses the energy generated from the combustion of propellant to enhance permeability of a feed zone by generating radial multiple fractures around the well bore. Aspiras, et al. has performed a comprehensive general study on the said technology. Deflagration of geothermal wells has been conducted in Reykjavik, Iceland, Soda Lake, USA, Taupo, New Zealand, and Leyte, Philippines with a varying degree of success.

Previous studies have evaluated the immediate post-deflagration results and primarily measure the improvement of permeability through the increase in the injectivity index (Bixley, Mclean, Lim, & Wilson, 2016). However, Bixley et al. (2016) conducted a study on one deflagrated well and found that in a multiple feedzone well with moderate permeability, a significant change in the injectivity index at a single feedzone only results in a small change in the overall well injectivity value, and thus, individual injectivity indices may not be the appropriate measure for evaluating the effects of deflagration. It was suggested that for production wells, the only definitive proof of improved permeability is the improvement in production flowrate which may not be apparent for several weeks, or months after a deflagration program.

### 1.2 Objective, Scope and Limitation

This main objective of the present analysis is to identify the ideal geothermal well and reservoir conditions for a deflagration job. To attain this objective, the study aims to develop a simple but realistic deflagration simulator to investigate a wide range of deflagration scenarios and evaluate these scenarios and come up with the most suitable conditions for the application of this technology. However, the current numerical model is only designed for production wells and is not applicable for reinjection wells. It is also designed for wells where the end-use product is steam and not hot water as is supplied to binary power plants. Also, the simulator is calibrated based on a specific set of data and assumptions and it may produce misleading results when applied to other situations. In terms of sustainability, the decline rates mentioned are natural decline rates of the well and do not consider possible recharge from the field to arrest such decline or acceleration of the decline due to scaling or well blockages that may form during production.

## 2. NUMERICAL MODEL DEVELOPMENT

Numerical models prove useful in seeking solutions for complicated sets of mathematical models which are difficult to solve directly through analytical means. In the case of subsurface geothermal reservoirs, mass and heat balances for multiple interconnected grids are simultaneously computed to mimic actual thermodynamic conditions in the reservoir. The simulator discussed here is based on TOUGH2, a general purpose numerical simulator for multiphase fluid and heat flow in porous and fractured media that has seen major application in geothermal reservoir engineering (Pruess, 1999). The version used in this study is AUTOUGH2 which was developed by the University of Auckland to incorporate critical features for geothermal simulations (Yeh, 2012). PyTOUGH (Croucher, 2014) uses the Python scripting language and enables complex TOUGH2 simulations to be conducted using a script. All visualizations were conducted using TIM, a new python based graphical interface for TOUGH2 also developed at the University of Auckland.

### 2.1 Model Set Up

The general model set up is a single layer radial grid to mimic actual reservoir conditions. A radial model was chosen to represent the deflagration effect because multiple radial cracks emanating from an explosion centre have been observed in the experiments by Fourney et al. (1983). It is also supported by the study of Adushkin and Spivak (2004) where it was found that explosions in deep holes result in radial fracturing of rocks, with the greatest fragmentation occurring along the direction of natural fracturing, and as this radial distance increases, the damage decreases. A visual representation of the model is provided in Figure 1.

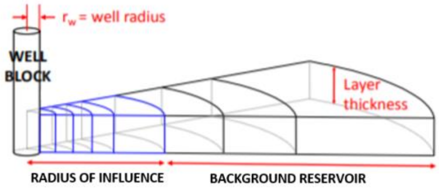


**Figure 1: Radial model (Modified from Mclean, 2015)**

### 2.2 Critical Parameters

Three parameters were introduced in the numerical model in order to represent the permeability enhancement effect resulting from deflagration treatment.

Radius of Influence - the maximum distance from the edge of the wellbore where permeability change occurs. Adushkin and Spivak (2015) published a study where experiments on underground nuclear explosions allowed the possibility of quantifying the behavior of rocks under intense dynamic loading conditions. Relevant to this study is how a deep-seated formation within a tectonic fault behaves in response to an explosion. From the actual data gathered from the experiments, a general relationship between differential block displacements and the amplitude of the external explosive loading was derived using the constant *k*, and theoretical yield of the explosives, given by:

$$Radius\ of\ influence\ (m) = \frac{k}{\sqrt[3]{yield, kt}}$$

a. *Crush zone* - Rocks within this range are pulverized with some inclusions of rock fragments no bigger than 3-4cm.

b. *Fracture Zone* - This zone is characterized by new fractures forming along the direction of the pre-existing fractures, structural elements and weakness zones. This fracturing is particularly intense along the planar tectonic discontinuities, which coincide with radial and tangential directions with respect to the explosion centre.

c. *Zone of irreversible deformation* - This zone is characterized by an increase in porosity and significant changes in permeability of the rocks. This is the main zone of interest because this accounts for the extent or the radius of influence where permeability change occurs in the model. Applying the relationship for local irreversible deformation and using the minimum factor of 800, a maximum upper limit of 37.6m was calculated and was imposed during the calibration. The calculation is given in Table 1 for a shot with a yield of 423.8MJ (13 x 3.6" OD propellant).

**Table 1: Radial effect (Modified from Adushkin, 2004)**

| Zones | k | Radial effect, m |
|---|---|---|
| Crush zone | 30-40 | 1.4-1.9 |
| Fracture Zone | 80-120 | 3.8-5.6 |
| Local Irreversible Formation | 800-1100 | 37.6-51.6 |

Permeability Enhancement Factor (PEF) - accounts for the degree of improvement in permeability within the radius of influence. The mechanisms by which the stimulation happens were summarized under 4 categories by Li, et al., 2000, namely: mechanical action, heat energy, chemical action, and oscillation pulse. In this study, all these effects are represented through the said single factor, which is just a multiplier for the existing permeability of the reservoir.

Productivity index Improvement Factor (PIF) - considers the possible increase in well deliverability due to the stimulation. This near wellbore enhancement is assumed to be experienced in addition to the permeability enhancement due to change in rock properties from the intense dynamic load experienced by the well.

### 2.3 Model Calibration

Well A was drilled to a total depth of 2338m and was completed with a 10 ¾" perforated liner from 878-1496m and 8 5/8" perforated liner from 1457-2338m. It had an initial steam flow of 3.6 kg/s which rapidly declined to less than 1 kg/s after only 2 years of production. The reduction in steam flow was suspected to be caused by scaling issues, which was confirmed by a go-devil survey. This well, however, even without its capacity decline, is a poor producer with an output that is considered low for this area; thus, it was selected for deflagration. The well underwent mechanical workover using a rig and deflagration was conducted using a wireline. The propellant sticks were housed inside a tandem gun carrier which carried 5 and 8 sticks at a time. Several target zones were chosen based on the temperature profile, spinner response and drilling losses and were fired with 1 shot each. A small injectivity test was conducted in between shots to attempt to measure the per-shot improvement in injectivity index, if any. There was minimal improvement in between shots and there was no difference between the pre- and post-deflagration completion test.

The numerical model was calibrated to Well A's measured steam flow and enthalpy through time. In the absence of continuous flow measurement system in Well A, tracer flow test data were used for matching. The tracer flow test data was adjusted to the same wellhead pressure of 1.2MPa for consistency as it can vary from 0.7-1.22MPa depending on required pressure during operation. Both steam flow and enthalpy were matched by adjusting twelve different parameters, keeping in mind the boundary conditions discussed previously and known well and field characteristics. Increasing the productivity index shifts the steam flow plot up and increases the enthalpy. Reservoir temperature and well bore pressure are already set, thus adjustments were made on the other parameters. Reservoir pressure with temperature dictates the reservoir characteristic and mostly controls the steam quality produced. Permeability and porosity are the parameters used to enhance the match as they influence the steam flow and temperature as well – the larger the value, the higher the steam flow, but the lower the temperature. After the pre-deflag output was calibrated, the radius of influence (RI), permeability enhancement factor (PEF), and productivity index increase factor (PIF) were then adjusted to estimate effect of deflagration on the steam flow and enthalpy. Together they dictate the steam flow increase and enthalpy change post-deflag. A PEF-RI combination increases steam flow and affects the enthalpy, while PIF shifts the whole plot up when increased. Enthalpy was matched to the nearest 50kJ/kg while steam flow was matched to the nearest 0.5kg/s. Acceptable results were obtained for both steam flow and enthalpy as shown in Figure 2.

From the steam flow data, it can be seen that the well was producing at expected levels for half a year but experienced scaling in the wellbore which led to a decline in the steam flow. The data also shows that the build-up of the scale was abrupt and does not follow a natural scaling profile, indicating that some undetermined reservoir process accelerated the scaling in the well. It was then scheduled for mechanical clearing and deflagration at Year 1.5 with the purpose of removing the well blockage and enhancing the output of the well. Deflagration was able to improve the flowrate of the well by almost 1kg/s, which only manifested half a year post deflagration. As pointed out by Bixley et al. (2016), well improvement from stimulation activities may take time before it is manifested, which is one of the reasons why post-completion injectivity indices may not serve as suitable measures of success for stimulation experiments. This delay in response may be caused by newly enhanced fractures requiring clearing first to establish a stable fluid flow. As described from the nuclear experiments (Adushkin and Spivak, 2004), there is a 1.9m-radius crushed zone extending out from the wellbore which may need time to clear out.

It can also be observed that production from the well was declining at a high rate even without considering the well blockage. This decline rate also showed up again after deflagration, so that steam flow is expected to return to pre-deflag levels in about 5 years. Based on these results, it appears that this well is also resource constrained, apart from having tight permeability and though deflagration was able to address the permeability issue, the improvement obtained may not be sustainable due to the resource limitation.

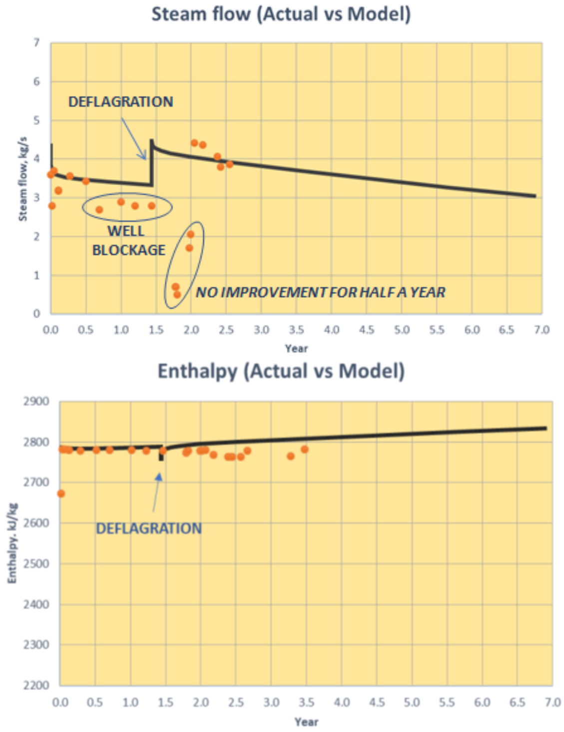


**Figure 2. Well A, Calibration Results**

## 3. LEVEL 1A: PARAMETRIC ANALYSIS

With a working deflagration simulator, typical geothermal scenarios were explored and subjected to deflagration. The aim was to answer the question: "Under what well and reservoir conditions will deflagration result in a favorable increase in steam flow?" Steam flow and enthalpy changes were investigated to determine the effect of deflagration.

### 3.1 Design of Parametric Analysis

Six main parameters with various levels were tested in this first phase of analysis. The first five factors define combined well and reservoir conditions, while the last factor represents the deflagration design. The combination of parameters would result to 576 scenarios, however only 432 runs were considered, as runs where wellbore pressure is greater than or equal to reservoir pressure were omitted from the analysis since the well will not produce without assistance.

In effect, 432 simulated deflagration jobs were evaluated – that is, 216 well and reservoir combinations were treated with both 1 shot and 2 shots of deflagration. The parameters investigated are summarized in Table 2.

**Table 2: Parameters for investigation**

| Factor | Levels | | | |
|---|---|---|---|---|
| Reservoir Pres, MPa | 5 | 7 | 9 | 12 |
| Reservoir Temp, °C | 240 | 280 | 304 | 320 |
| Productivity Index | 1e-12 | 1e-13 | 5e-13 | |
| Wellbore Pres, MPa | 3 | 5 | 7 | |
| Permeability, $m^2$ | 1.5e-14 | 1.5e-15 | | |
| No. of Shots | 1 | 2 | | |

Some parameters are of no primary concern at this stage, and thus were held constant. The values used were based from the calibration conducted during the model development.

**Table 3: Level 1 Parameters held constant**

| Factor/Parameter | Value |
|---|---|
| Permeability Enhancement Factor | 10 |
| Radius of Influence | 30m |
| Productivity Index Increase Factor | 1.0 |
| Conductivity | 1.0 |
| Rock Density | 2500 |
| Specific Heat | 1000 |
| Porosity | 40% |

### 3.2 Simulation Set-up and Procedure

The model was set-up to allow the well to produce for 2 years first to reach stable production temperature and steam flows. This also reflects real life scenarios where the operator is allowed a sufficient period to observe production levels, plan a stimulation activity, and mobilise logistics for the chosen stimulation, such that by Year 2, the chosen well intervention is conducted. It is assumed that for two-shot scenarios, the shots are conducted in one activity, allowing only 12hrs in between shots which is a typical deflagration operation. After the deflagration, the well is allowed to reach stable temperatures, so that after half a year, it is already assumed to be connected into the system and producing based on actual experience. The well is then allowed to continually produce for five years thereafter. The five-year evaluation was chosen as result of the calibration, which showed this to be the minimum period for producing incremental steam flows. Also, it coincides with a typical workover period for a geothermal well. A graphical representation of the process is given in the figure below.

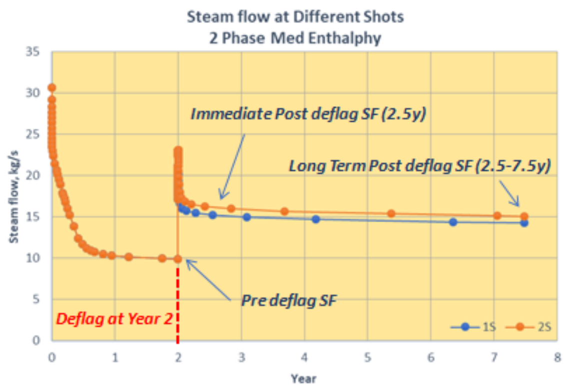


**Figure 3: Typical post-processed result per scenario**

The Level 1 analysis provides first elimination criteria for well and reservoir conditions that are uneconomical for deflagration. Each of the 432 scenarios is run individually in the model. Figure 3 shows a post-processed result reflecting single and double shot scenarios for the particular well and reservoir condition. Steam flow and enthalpy data results from individual scenarios are consolidated under a Level 1 master data file for further data analysis. Definition for steam flow notation is presented in Table 4 to standardize the characterization.

As this study seeks to measure improvements derived from the application of the technology, incremental steam flows and enthalpies are used as basis for evaluation, as they indicate changes regardless of initial value. The criteria used for the results categorization were specified by the researcher based on economics and practical reasons. An immediate incremental steam flow hurdle of at least 2 kg/s is set as baseline to correspond to at least 1 MW increase assuming a steam rate = 2.0 MW/kg/s. Any value less than this may be construed as within measurement error limits. For the 5Y incremental steam flow, a breakeven with pre-deflag levels is required, when the well may be slotted for a typical workover. The rest are deemed not economical enough for deflagration as a stimulation activity. In geothermal scenario, a five-year period interval for workover is typical.

**Table 4: Steam flow notation**

| Notation | Definition of measurement | Other notations |
|---|---|---|
| Pre-deflag SF | Steam flow of the well immediately prior deflagration shot is applied | Original, unstimulated |
| Immediate Post deflagration SF | Steam flow of the well 0.5 yrs after deflagration shot is fired | 0Y SF, post-deflag SF, short-term |
| 5-year Average SF | Average steam flow of the well after 5 years of production post deflag | 5Y SF, long-term SF |

### 3.3 Results

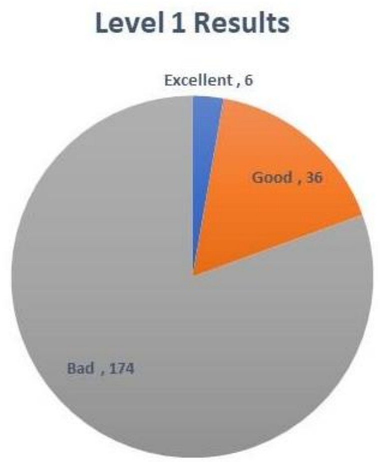


**Figure 4: Level 1 Analysis Results**

Out of the 216 combined reservoir and well conditions, 42 exhibited "Excellent" conditions for deflagration stimulation, six of which have sustainable long-term improvement greater than 5 kg/s, or an increase of approximately 2.5MW. The rest, which are categorized as "Good", have a positive five-year incremental steam flow (5YIncSF) and an immediate incremental steam flow (0YIncSF) of at least 2kg/s. Of the positive results, 95% are from 2-phase medium to high enthalpy liquid dominated reservoirs. From the results, it appears that reservoir fluid pressure support coupled with moderate to high temperature is necessary when stimulating wells using deflagration. This confirms the requirement for good resource potential first, prior to any stimulation activity.

#### 3.3.1 Excellent

Six scenarios resulted with the most favourable results with a mean immediate incremental increase of 8.7kg/s and mean long-term increase of 7.3kg/s. At 2.0 kg/s/MW steam rate, this corresponds to a 3.6-4.3MW increase, equivalent to typical sized production well. Four out of six comes from a 2-phase high enthalpy reservoir. The most obvious commonalities for these excellent wells are the reservoir pressure, high productivity index, and high temperatures. Initial well PI for this category averages at 2.0kg/s/MPa. Obviously, wells with these characteristics are already self-producing with acceptable output, which usually rules them out as candidates for stimulation in the first place. This is reflected from the runs as 80% already produce 5-10MW without deflagration, with the mean of 7.5MW, which is above the global average of 5.5MW (IFC, 2013). However, as seen in the results, deflagrating these types of wells may stimulate a 50% increase in well productivity, and may possibly result in a 3-4MW increase (83% of the time) which is equivalent to one typical deep well, generating millions of dollars in savings. The wellbore pressure ranges from low to medium, which suggests a target zone that is not too deep to be overpowered by high wellbore pressure. The good pressure difference allows a natural flow from the reservoir to the wellbore. Increase in permeability from the deflagration seems adequate when coupled with the other parameters.

### 3.3.2 Good

Around 85% of the scenarios that yielded positive results are within the Good category; and thus, represent most of the potential for deflagration application as these wells are most likely to be marginal producers. This can be observed in the average PI for these wells at only 0.9 kg/s/MPa. Mean steam flow is 5.5kg/s (2.7MW), with a mean immediate and long term incremental increase of 3.6kg/s (1.8MW) and 2.6kg/s (1.3MW), respectively. Based on the data, ~67% of the 'Good' wells have initial steam flow less than 6kg/s(3MW), which is 2.5MW lower than the global average. Deflagration modelling results show a 64% chance of increasing the output by 1-2MW. However in the long-term, the well has ~31% chance of reverting to pre-deflag levels, where it can again be stimulated, in time for a regular workover to garner additional output. In the optimistic side, it has ~53% possibility of 1-2MW increase in the long run. The well PI can further increase by 0.6kg/s/MPa upon stimulation. As with the 'excellent' scenarios, almost all wells produce from a two-phase high enthalpy liquid dominated reservoir. The pressure support and high temperature seems to be the most relevant reservoir characteristics based from both results. This indicates the best reservoir conditions for deflagration.

### 3.3.3 Bad

174 out of 216 reservoir and well conditions did not yield positive results, which is around 80%, which interestingly adheres to the Pareto principle. Their initial average productivity index is low at only 0.3 kg/s/MPa with a potential increase of only 0.1 kg/s/MPa. Mean initial steam flow is 1.4kg/s (<1MW), with insignificant average immediate and long-term increase. Investigation of the well data showed 83% of those scenarios with discouraging results were initially producing a steam flow of less than 1kg/s or ~0.5MW, considerably non-commercial, with only 17% potential steam flow increase of 1-3kg/s (~1MW). Employing 2 shots of deflagration to further enhance the well only increased the occurrence of 1 kg/s increase to 26%. As discussed previously, the technology appears not to be applicable for vapour dominated and two-phase low enthalpy systems given that 44% of the poor results are from wells producing from vapour dominated reservoirs and 31% 2-phase Low enthalpy reservoirs. This is unfortunate, not only for the vapour dominated reservoirs such as the Geysers and Lardarello, but also for those wells that produce mostly from the shallow steam zone. This shows that shallow, dry, major feedzones are not good targets for deflagration.

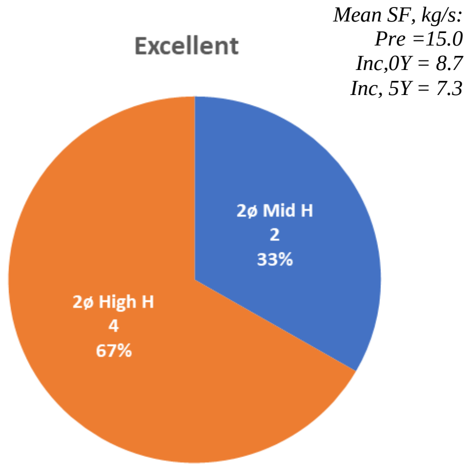


**Figure 5: Level 1 Parametric Results: Excellent**

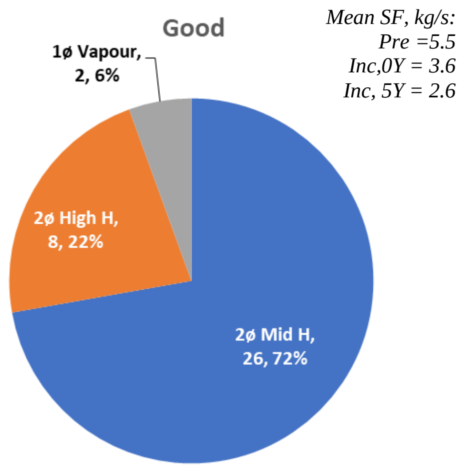


**Figure 6: Level 1 Parametric Results: Good**

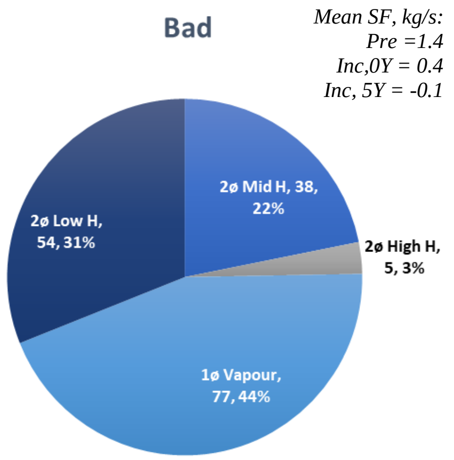


**Figure 7: Level 1 Parametric Results: Bad**

## 4. LEVEL 1B: STATISTICAL ANALYSIS

In the previous part, the critical 20% of the data which matters was determined. All results underwent statistical analysis with incremental steam flows as the response variables, while the reservoir pressure, temperature, wellbore pressure, productivity index, permeability, and number of shots were the factors considered.

### 4.1 One-way ANOVA

In this section, the One-way Analysis of Variance (ANOVA) test is used as a statistical check on whether three or more different sets of data are significantly different from each other. It takes the mean and spread of the data and computes its ability to detect differences between the groups at a set error $\alpha=0.05$. Minitab® uses Welch's method which is applicable for datasets with unequal variances, and thus there is no need to test for this requirement. It will help determine whether (1) Incremental steam flows between one-shot or two-shots per feedzone are significantly different, and whether (2) Incremental steam flows between immediate and five-years thereafter are significantly different. The findings will aid in the design of deflagration jobs in securing the required number of shots per feed-zone, which affects the cost of the experiment. The second question seeks to determine the sustainability of the permeability enhancement. This can be calculated using the difference between the incremental steam flows at immediate and long times.

#### 4.1.1 Long Term vs Short Term Effect

Presented in Figure 8 are the results of the test conducted on 216 samples. Here, 4 sets of data underwent ANOVA, Immediate 1 shot (1S-0Y), Immediate 2 shots (2S-0Y), 5-year 1 shot (1S-5Y), and 5-year 2 shots (2S-5Y) results. Based on the results, in both 1 shot and 2 shot scenarios, there is a significant difference between the incremental steam flows recorded in the short term and long term. It is reflected by the non-overlapping '5Y' and '0Y' intervals in the means comparison chart. Clearly, the natural decline over the 5-year period is relevant and should be noted when deciding to go for a deflagration activity. It is thus safe to say that deflagration is not a long-term solution in enhancing well output but when designed properly, will pay off for itself and bring in some savings.

#### 4.1.2 No. of Shots

Based on the results, as seen in Figure 8, for both immediate and long-term scenarios, there is not enough evidence to imply a significant difference between the incremental steam flows generated from 1 shot or 2 deflagration shots. Instinctively, it would be assumed that the incremental steam flow from a 2-shot deflagration would be generally higher due to the weakened rocks from the first shot; however, as data suggests, there is no significant additional benefit that can be gained from a 2nd shot for the scenarios tested. The statistical model has a 90% chance of detecting 0.8 kg/s incremental steam flow difference and 60% chance for 0.48kg/s steam flow difference.

The productivity indices post 1 shot (PI After 1S) and 2 shots (PI After 2S) were also compared using the same method and produced the same results as shown in Figure 9. It should also be considered that the data used included 216 samples, 144 of which had negative results. Thus, to confirm consistency in results, the ANOVA analysis was repeated for both steam flows and PI post 1 shot and 2 shots for the positive 42 scenarios. This would help check whether the number of shots is significant for the scenarios which had a positive response to deflagration. Results show that there is still not enough evidence to say that steam flows and productivity index post 1 shot and 2 shots have significant difference.

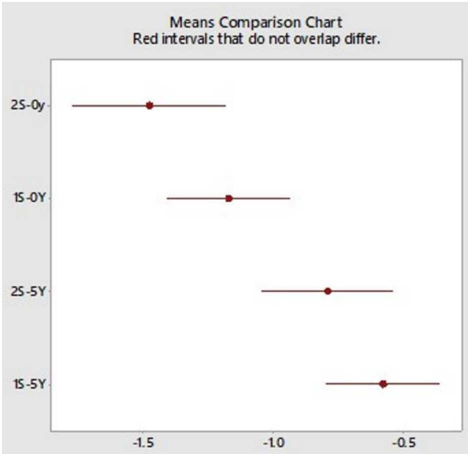


**Figure 8: Level 1 ANOVA Steam flow Results**

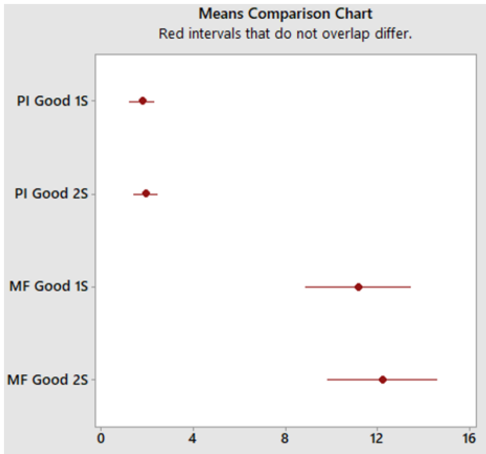


**Figure 9: Level 1 ANOVA PI and SF Results**

### 4.2 Factorial Analysis

After identifying the scenarios which reacted positively to deflagration stimulation, it is important to be able to identify the critical factors which influence the increase in steam flow for better candidate well and target selection. This can be achieved by running the factors together with the results under a factorial analysis. Design of experiment (DOE) factorial analysis automatically assigns dimensionless coded variables for each level and computes for its main effects and interaction effects using these variables. Minitab® was used to conduct DOE factorial analysis.

#### 4.2.1 Factorial Design

The 42 well and reservoir conditions were subjected to a factorial analysis in order to determine the factors which are critical to the results of the model. Design parameters are shown in Table 5.

**Table 5: Factorial Analysis Design Parameters**

| Name | Levels | | |
|---|---|---|---|
| **Factors** | | | |
| Permeability | 1.5 e-14 | 1.5 e-15 | |
| Reservoir Pressure | 7 MPa | 9 MPa | 12 MPa |
| Productivity Index | 5.0 e-13 | 1.0 e-12 | |
| Wellbore Pressure | 3 MPa | 5 MPa | 7 MPa |
| Reservoir Temp | 280 | 304 | 320 |
| **Block** | | | |
| Timing | Immediate | Long term | |
| **Response Variable** | | | |
| Inc Steam flow | 1 shot | 2 shots | |

### 4.2.2 Factorial Analysis

Factors, with all the possible interactions, were tested against incremental steam flows, and their effects were plotted in the graph in Figure 10. All terms which cross the critical value denoted by the red line significantly affect the incremental steam flows by decreasing magnitude. The model has an R-sq of 86.69% which is acceptable.

Wellbore pressure, productivity index, reservoir temperature, and pressure all significantly influence the results. Permeability, though it does not directly affect the results, when paired or combined with reservoir pressure and productivity index, result in a significant effect. This means that the primary determinant for the successful application of deflagration, or any stimulation activity, is to have a good resource potential first, so that when the permeability is enhanced, their interaction produces a favourable result. The main effects plot in Figure 10 further shows the effect on the mean of incremental steam flow per factor. Here it can be more clearly seen that permeability, by itself does not affect the deflagration success, but when coupled with other factors, especially Reservoir Pressure as shown in the Pareto chart, does affect the incremental steam flow. Furthermore, based on the main effects plot, lower wellbore pressure, higher temperature, and higher productivity index would generally yield to better deflagration success.

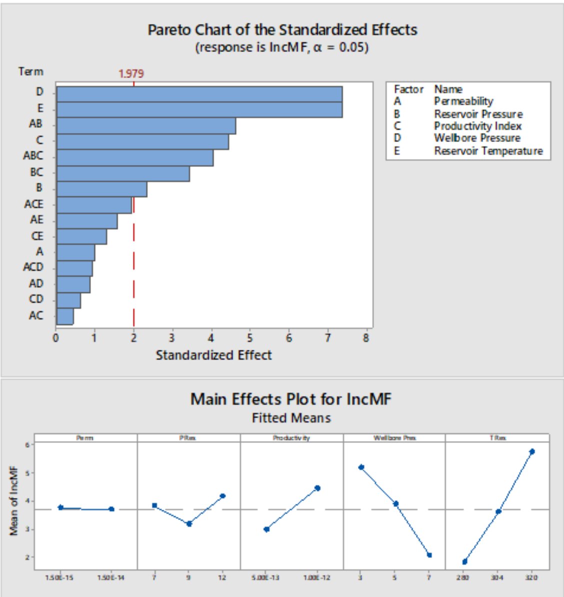


**Figure 10: Level 1: Factorial Analysis Results**

## 5 GENERAL DISCUSSION

Presented in Figure 11 are the steam flows and enthalpies of different reservoir system subjected to a single shot deflagration. As discussed in the results of the parametric tests, 2-phase medium and high enthalpy react favorably to the deflagration stimulation as compared to low enthalpy and vapour dominated reservoirs. The plot also shows the differences in the decline rates, which determines the sustainability of the stimulation experienced by the different reservoirs. Both the medium and high enthalpy show positive long-term contribution, while the vapour dominated and low enthalpy returned to their pre-deflag levels within 4 and 1 year of production, respectively. Enthalpy behavior does not appear to be affected from pre- to post- deflagration and also between different shots. Enthalpy was quickly recovered in runs where enthalpy drop was experienced, which means that the increased permeability invited reservoir fluid to rush into the wellbore, thereby reducing the enthalpy temporarily.

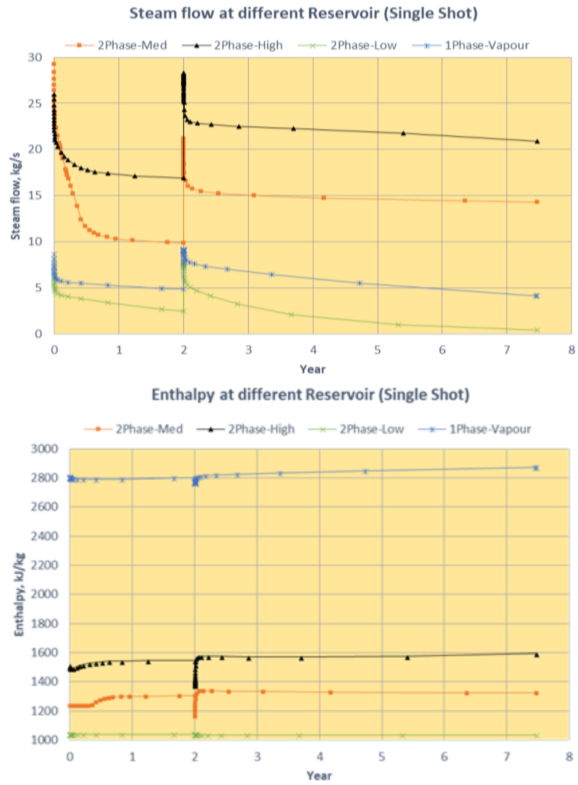


**Figure 11: Steam flow and Enthalpy per Reservoir**

### 5.1 Two Phase High Enthalpy

**Table 6: Two-phase high enthalpy simulation results**

| | Steam flow, kg/s | | | | |
|---|---|---|---|---|---|
| **Category** | **Initial** | **1SInc** | **5YInc** | **Decline p.a** | **2SInc** |
| Excellent | 15.0 | 9.1 | 7.5 | 0.31 | + 1.9 |
| Good | 7.0 | 4.6 | 3.8 | 0.17 | + 1.2 |
| Bad | 2.9 | 0.9 | 0.7 | 0.03 | + 0.1 |
| **Average** | **7.7** | **4.5** | **3.7** | **0.16** | **+1.1** |

On average, a two-phase high enthalpy well producing at an initial steam flow of 7.7 kg/s (3.8MW) may incur an additional 4.6 kg/s (2.3MW) and 3.8 kg/s (1.9MW) increase in the short term and long term, respectively. An additional shot can only contribute 1.9kg/s at best and 1kg/s on the average. Furthermore, the decline rate for the 'Excellent' category is almost twice as much as that in 'Good' category. The enthalpy did not change significantly between prior or after deflagration and between shots.

### 5.2 Two Phase Medium Enthalpy

**Table 7: Two-phase med enthalpy simulation results**

| | Steam flow, kg/s | | | | |
|---|---|---|---|---|---|
| **Category** | **Initial** | **1SInc** | **5YInc** | **Decline p.a** | **2SInc** |
| Excellent | 14.9 | 8.0 | 7.0 | 0.20 | +1.4 |
| Good | 5.1 | 3.3 | 2.4 | 0.18 | +0.9 |
| Bad | 2.2 | 0.5 | -0.2 | 0.14 | +0.2 |
| **Average** | **3.8** | **1.9** | **1.1** | **0.16** | **+0.5** |

It can be observed that less than 50% of two-phase medium enthalpy scenarios resulted in a positive result; thus additional effort must be undertaken to ensure a suitable choice of a candidate well. On the average, wells from this reservoir exhibits an initial steam flow of 3.8 kg/s (1.9MW) with a potential short-term and long-term increase of 1.9kg/s (0.9MW) and 1.1kg/s (0.5MW), respectively. Best case, deflagration may result to an incremental steam flow increase of 8kg/s (4MW). A second shot contributes an additional 0.5kg/s on the average and 1.4kg/s, at best, both under 1MW. Relative to the high enthalpy case, the decline rates for 'Excellent' and 'Good' for the medium enthalpy case appear to be consistent with an average of 0.16kg/s/yr.

### 5.3 Two Phase Low Enthalpy

**Table 8: Two-phase low enthalpy simulation results**

| | Steam flow, kg/s | | | | |
|---|---|---|---|---|---|
| **Category** | **Initial** | **1SInc** | **5YInc** | **Decline p.a** | **2SInc** |
| Bad | 1.5 | 0.3 | -0.6 | 0.17 | +0.1 |
| **Average** | **1.5** | **0.3** | **-0.6** | **0.17** | **+0.5** |

Low enthalpy wells are not suitable for deflagration for the purpose outlined in this study. The deflagration simulator is designed for an end use product of steam because steam flows discussed here are the steam component only. As shown in the results from the simulator, deflagration was not able to significantly improve the steam flow from low enthalpy reservoirs as increasing the permeability only invites more fluid into the system thereby reducing the steam component. The wells had an average initial steam flow of only 1.5kg/s (<1.0MW) and this is considered to be non-commercial for flash plant operation. Deflagration may be able to improve the well by 0.3kg/s, with an additional 0.1kg/s if another shot is added. Interestingly, decline rate is almost the same with high and medium enthalpy scenarios.

### 5.4 Vapour Dominated System

**Table 9: Vapour Dominated simulation results**

| | Steam flow, kg/s | | | | |
|---|---|---|---|---|---|
| **Category** | **Initial** | **1SInc** | **5YInc** | **Decline p.a** | **2SInc** |
| Good | 4.5 | 2.2 | 0.7 | 0.30 | +0.4 |
| Bad | 0.9 | 0.5 | 0.3 | 0.03 | +0.1 |
| **Average** | **0.9** | **0.5** | **0.3** | **0.04** | **+0.1** |

Only 2 out of 79 vapour dominated scenarios resulted to a positive response, both having an aggressive decline rate of 0.30 kg/s/year; thus, it can be generalized that deflagration stimulation is not suitable for vapour dominated systems and for wells whose major feedzones are above the water level. Additional shot only adds 0.1 kg/s on the average and 0.4 kg/s at best. While deflagration does not improve these wells significantly, it still results to a minimal increase even in the long term which is quite different with the low and medium enthalpy reservoirs, where their long term incremental increases are negatives.

## 6. CONCLUSION

The radial model developed using TOUGH2 was able to demonstrate the effect of deflagration on steam flow in long term; consequently, it was able to act as a simulator for the different test parameters. From the objectives laid out, the study was able to determine the geothermal well and reservoir conditions suitable for deflagration that can provide economical improvement to well performance. Analysis of variance was used to analyze statistical difference between means which was useful in determining the effect of number of shots, and determining long term vs short term effects of enhancement. On the other hand, factorial analysis was able to identify significant factors affecting the improvement. Out of the 216 reservoir and well conditions simulated, 42 exhibited positive conditions for deflagration stimulation, 95% of which are 2-phase medium to high enthalpy liquid dominated reservoirs. Six scenarios resulted with the most favorable results with a mean immediate incremental increase of 8.7kg/s (2.4MW) and mean long-term increase of 7.3kg/s (3.6MW), while the rest had immediate incremental steam flow of greater than 2kg/s (1MW) and five-year average improvement of 0-5kg/s (0-2.5MW).

In both immediate and long-term scenarios, there is not enough evidence to show significant difference between the incremental steam flows and productivity indices generated from 1 shot or 2 deflagration shots, thus in general, there is no need for an additional shot. Natural decline over the 5-year period is also found to be significant and should be noted when deciding to go for a deflagration.

Overall, results showed that two-phase medium and high enthalpy reservoirs react more favorably to the deflagration stimulation versus low enthalpy and vapour dominated reservoirs. Wellbore pressure, productivity index, reservoir temperature, and pressure all significantly influenced the Level 1 post-deflagration results. Permeability, though it does not directly affect the results, when paired or combined with reservoir pressure and productivity index, result in a significant effect

## REFERENCES

Aspiras, A., Braganza, J., Morente, C., Austria, J. J., Jumawan, J., & Whittome, A. (2015). Selection of candidate geothermal wells for deflagration; Paper presented at the New Zealand Geothermal Workshop, Taupo, New Zealand.

Adushkin, V., & Spivak, A. (2004). Changes in properties of rock massifs due to underground nuclear explosions. *Combustion, Explosion, and Shock Waves*, *40*(6), 624-634. CESW.0000048263.34894.58

Adushkin, V., & Spivak, A. (2015). "Underground explosions".

Bixley, P., Mclean, K., Lim, Y. W., & Wilson, D. (2016). (2016). Assessing the effectiveness of deflagration in multi-feedzone wells. Paper presented at the *New Zealand Geothermal Workshop*, Auckland, New Zealand.

Croucher, A. (2014). Introduction to python. Retrieved from https://github.com/acroucher/PyTOUGH/wiki/Introduction-to-Python

Fourney, W. L., Barker, D. B., & Holloway, D. C. (1983). Model studies of well stimulation using propellant charges. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, *20*(2), 91-101. 10.1016/0148-9062(83)90330-3 Retrieved from https://www.sciencedirect.com/science/article/pii/0148906283903303

International Finance Corporation. (2013). *Success of geothermal wells : A global study* Washington, DC. Retrieved from http://hdl.handle.net/10986/16493

Katie McLean, & Sadiq J. Zarrouk. (2015). (2015). Standardized reservoir model design for stimulating pressure transients in geothermal wells. Paper presented at the *New Zealand Geothermal Workshop,* Taupo, New Zealand.

Li, W., & Xue, Z. (2000). A review of gas fracturing technology. Paper presented at the 10.2118/58980-MS Retrieved from https://www.onepetro.org/conference-paper/SPE-58980-MS

McLean, K., & Zarrouk, S. J. (2017). Pressure transient analysis of geothermal wells: A framework for numerical modelling. *Renewable Energy, 101*, 737-746. 10.1016/j.renene.2016.09.031 Retrieved from https://www.sciencedirect.com/science/article/pii/S0960148116308205

Precise propellant stimulation. (2010). Retrieved from http://www.precisepropellant.com/Index-2.html

Pruess, K. (1991). *TOUGH2: A general-purpose numerical simulator for multiphase fluid and heat flow*. (). United States: DOE; USDOE, Washington, DC (United States). 10.2172/5212064 Retrieved from http://www.osti.gov/scitech/biblio/5212064

Thorhallsson, S., & Sveinbjornsson, B. M. (2012). (2012). Geothermal drilling cost and drilling effectiveness. Paper presented at the * "Short Course on Geothermal Development and Geothermal Wells",* Santa Tecla, El Salvador. Retrieved from http://data.theeuropeanlibrary.org/BibliographicResource/1000097927013

United States. Congress. Office of Technology Assessment. (1989). *The containment of underground nuclear explosions.* ().United States. Congress. Office of Technology Assessment. Retrieved from http://digital.library.unt.edu/ark:/67531/metadc39939/

Yeh, A., Croucher, A., & O'Sullivan, M. (2013). (2013). Tim – yet another graphical tool for tough2. Paper presented at the *New Zealand Geothermal Workshop*, Rotorua, New Zealand.