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Development of Diverter Systems for EGS and Geothermal Well Stimulation Applications

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In the creation of an EGS system the reservoir rock must be stimulated to allow for circulation of fluids from the injection well to the production wells. Key to optimizing an EGS system is the creation of multiple stimulated fractures from one wellbore. This has proven to be a difficult task as most EGS injection wells are completed open hole and there are few mechanical tools or systems that can reliably provide the needed hydraulic isolation in a geothermal environment to do multiple zone stimulation.

The development of diverter systems was undertaken to overcome the problem of hydraulic isolation and multiple zone stimulation. Diverter systems were developed specifically for open hole application under geothermal well conditions. One of the performance parameters that were set for diverter development was a material that would remain intact during stimulation treatment and then dissolve into non-damaging degradation products after the stimulation. This makes it possible to apply this technology without the need for a drilling rig during or after the stimulation. The elimination of a drilling rig greatly reduces the cost of stimulation treatments as well as significantly reduces the risk of damaging the well during the process.

Included in this work will be an explanation of how particular diverter systems were developed and why they were chosen over other chemical systems. Test methods for development will be described along with test results from a number of materials evaluated for this application. Also, degradation versus temperature data, decay kinetics results, and laboratory fracture sealing tests will be provided. Some brief description of the successful application of diverters in field applications will also be provided along with description of planned future development.

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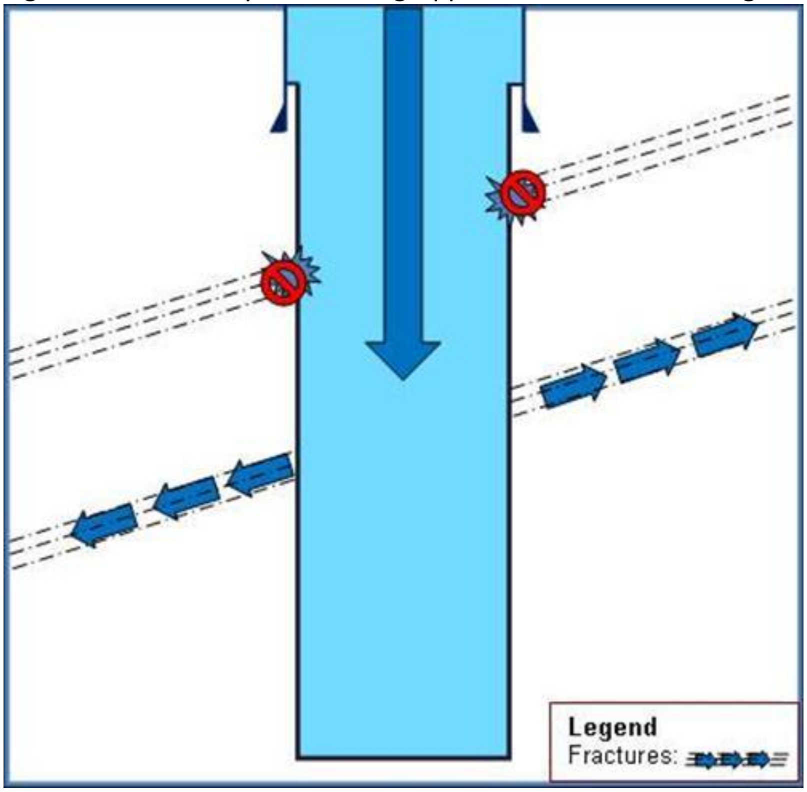
Introduction

Enhanced Geothermal Systems (EGS) could provide additional geothermal power from resources that currently cannot be developed using conventional geothermal completion methods. For the creation of an EGS working reservoir the existing rock must be fracture stimulated to allow for circulation of water from an injection to a production well. EGS projects in the past have been limited to the amount of reservoir rock that can be stimulated by simply pumping fluid from the surface. Whatever fractures will accept water while pumping are the only fractures that are stimulated. Using this method large portions of the reservoir rock remain un-stimulated and therefore unproductive.

In order to stimulate multiple fractures in and EGS reservoir some means of hydraulic isolation is needed whereby a portion of the reservoir rock can be stimulated, subsequently isolated, and then additional reservoir rock can be stimulated. One potential means of achieving hydraulic isolation for the purpose of multiple zone stimulation would be the use of some type of mechanical isolation device like a packer. While this has been tried it was unsuccessful and led to disaster and the loss of the well. The mechanical packer was stuck in the open hole and was not drillable. Any mechanical system that would be considered for multiple zone stimulation would introduce some additional risk to the process due to the nature of drilling operations. It would also cause additional cost for the drilling rig to be on location and operating during the stimulation operations.

Due to the risk and cost associated with mechanical systems a “chemical” solution was considered for providing hydraulic isolation. Ideally any chemical system could be used that would provide hydraulic isolation of previously stimulated fracture(s) allowing for further stimulation of additional fractures. This chemical system would stop or limit flow into a stimulated fracture by pumping it in place at the end of a given stimulation treatment allowing for applying additional pressure to a given wellbore and subsequent stimulation of additional fractures (See Figure 1). Ideally this chemical sealant would remain effective during the time of the additional stimulation treatments and then degrade into non-damaging soluble by products, leaving all stimulated fractures open for flow of geothermal fluids.

Figure 1: Chemical System Sealing Upper Fracture and Allowing Stimulation of Lower Fracture



Diverter Development

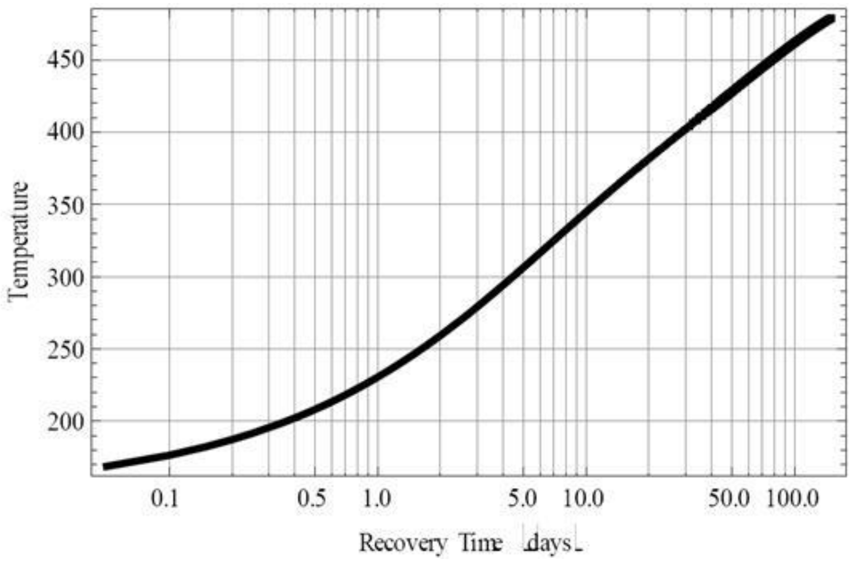
A number of systems were considered for providing the needed hydraulic sealing of fractures for EGS stimulation applications. The original premise was that the system would seal by being injected into the stimulated fracture and then provide hydraulic isolation by the material having or increasing in viscosity or simply setting up after injection. If the sealant was injected into the fracture then it would need to hold up at the geostatic temperature during the time of subsequent stimulation treatments and then be removed and/or break down thermally or chemically. This is due to the fact that any cooling of the rock in the formation would last only a short time (hours) once fluid injection is terminated due to (temporary) sealing.

Viscous gel systems were considered as it was thought that the increased viscosity of the gel would increase the injection pressure of the fracture being stimulated and cause additional fractures to begin to open up and be stimulated. There were a number of disadvantages and challenges with this idea, including:

- Finding a gel system that would remain viscous and maintain a seal for the long time periods necessary for additional stimulation after the fractured rock heated back up to geostatic temperatures of a geothermal reservoir
- Estimating the volume of gelled fluid needed to increase the injection pressure sufficiently to open up additional fractures without the use of drill pipe or coiled tubing during the operation

Other multiple systems were considered but technical and operational challenges made their implementation difficult or impossible. One of the big challenges was finding a material or system that would be effective both while injecting it into the well while it was relatively cool from the cold stimulation water and then remain effective once the fractures had been sealed by material and the formation rock began to heat back up again. Temperature modeling studies indicated that while very high temperature rock could be cooled during stimulation, it would heat back up again rapidly once stimulation fluid no longer was being injected into the fracture. Figure 1 below illustrate this phenomena.

Figure 2: Temperature (in degrees F) Recovery in 246 °C Rock after 7 days of Injection with 66 C Injection water.



It was then determined that if a particulate material were used to seal off fractures through bridging at or near the wellbore that the temperature problems and challenges associated with other diverter systems could be greatly reduced. This would be accomplished by first sealing off the fracture at the wellbore face. Packing of the particles near the wellbore would prevent further flow into the wellbore. At the same time the cold temperature stimulation fluid (water) would keep the temperature of the particles relatively low during subsequent stimulation treatments as long as the newly stimulated fractures were below the fractures that were being sealed by the chemical sealant particles. Once the stimulation treatment was over the diverter particles could be removed by either falling to the bottom of the well once the differential pressure holding them in place was removed, by flowing back with fluid from the fractures once the well was opened up and flowed, and/or due to thermal degradation as the well rapidly heated back up to geostatic temperatures once the injection of the cold stimulation fluid ended.

The advantages of a particulate diverter system include:

- Ability of sealing fractures at the wellbore face so that the material will remain relatively cool from injection of cool stimulation being pumped into the well during subsequent fracture stimulation treatments
- The material can be placed without stopping pumping during the stimulation treatment

- Placement of material does not require a drilling rig, reducing cost and risk during stimulation operations
- Effectiveness of the diverter can be readily detected though the use of fiber optic temperature monitoring, a pressure monitoring tool located in the well or possibly at the surface, and/or the use of a conventional temperature logging tool
- If insufficient sealing is seen by pumping a given amount of diverter
- Degradable material can be used so no mechanical intervention requiring a rig is required after the stimulation

The focus of this paper will be on the testing and development of Temporary Particulate Diverter Systems (TPDS).

Temporary Particulate Diverter Systems (TPDS)

Two characteristics of a TPDS that were needed to make it effective were the degradation characteristics of the material and the particle size distribution of the material needed to affect a seal. The degradation characteristics had to be such that the material would remain sufficiently intact to maintain a seal in the wellbore during the length of the subsequent stimulation treatment(s) at the temperature at the sealed fracture. The Particle Size Distribution (PSD) had to be designed so that there would be sufficient large sized particles that would bridge off and not flow into the fracture. Further, the PSD of the material had to be such that a particle pack with sufficiently low permeability would form to allow for additional pressure buildup in the wellbore to initiate fracture stimulation in other fractures in the wellbore. The focus of this paper will be on the degradation characteristics.

Degradation Testing

To screen various material candidates for potential use as a diverter one of the first tests that would be carried out would be a simple degradation test. A sample of material would be weighed and put into a water filled crucible/container. These containers would be loaded into an autoclave and exposed to a set temperature with pressure for a period typically of one or two weeks. The containers would then be removed and the remaining material would be dried and weighed. The amount of degradation would be recorded and samples would be put back down for additional curing and further measurement until the material was completely gone or a decision was made to terminate the testing on that material.

Results for Material A (See Figure 3) indicate that this may work as a TPDS at a temperature below 148 °C but that degradation occurs too quickly at 148 °C and above.

Test results for Material B (see Figure 4) indicate that it should work well as a TPDS at temperatures up to 260 °C and will degrade rapidly at 315 °C. This appears to make it an ideal TPDS for very high temperatures.

Test results for Material C (See Figure 5) indicate that it could work well as a TPDS at temperatures up to 204 °C, and that it will degrade rapidly at 260 °C and above.

Test results for Material D (See Figure 6) indicate that it could work well as a TPDS at temperatures up to 88 °C, and that it will degrade rapidly at 148 °C and above. This appears to make it a good candidate for a TPDS for lower temperatures.

Test results for Material E (See Figure 7) indicate that it could work well as a TPDS at temperatures up to 88 °C, and that it will degrade rapidly at 148 °C and above. This appears to make it a good candidate for a TPDS for lower temperatures. The delay in degradation at 88 °C seems to be a little longer than for Material 4.

Test results for Material F (See Figure 8) indicate that it could work well as a TPDS at temperatures up to 260 °C, and that it will degrade rapidly at 315 °C and above. This appears to make it a good candidate for a TPDS for high temperatures.

PSD Slot Testing

PSD slot testing was conducted by blending various sizes of particles of a given material (or materials) and then mixing them in water. The mixture was put on top of a slot and then a differential pressure was applied. Measurements were made to determine the length of time it took to flow all the water through the slot and cause pressure build-up in the chamber below the slot. The longer that time was the lower the permeability of the particle pack of diverter material that formed on top of the slot. Extensive testing was conducted using sized sand to evaluate the optimum particle size distribution for providing a low permeability pack. General conclusions have been reached but results are considered proprietary trade secret. It is expected that the optimum PSD for a given material may vary some depending on the ductility of the material; i.e. a relatively non-ductile material like sand verses a more ductile material like polymeric materials.

Long Term HT Slot Testing

Long Term HT Slot Tests were conducted using a similar device as the PSD Slot Testing. A particle pack was placed in the test device and deposited across a 1 mm wide slot. The temperature of the cell containing the slot and material was raised to the specified temperature. Differential pressure was applied. Flow was measured periodically throughout the test. When flow rate increased it indicated that the particle pack of diverter material had degraded and/or dissolved sufficiently to allow increased flow through the slot.

One Long Term HT test was conducted with Material F (See Figure 8 below) at 148 °C and then 464 °C. Test results indicated that a seal was maintained for 2 weeks at 148 °C. After that the temperature was raised to 464 °C. The diverter continued to hold for 2 more weeks and then the seal failed when tested again at 4 weeks. This material is no considered to be effective at 464 °C for at least 2 weeks.

Discussion of Results

The first test, the degradation test, was conducted on multiple materials. What was looked for to provide a good candidate was first a material that would have minimal degradation at a given application temperature; i.e. the temperature that the material would be exposed to in the well during the stimulation treatment. A typical guideline would be to see less than 20% degradation in 2 weeks' time. Next, the diverter needed to have nearly 100% degradation at or above the application temperature, specifically the final geostatic temperature that the TPDS would be exposed to after stimulation. It was deemed critical that all the material eventually degrade or dissolve so that no residual blockage would remain in the well after treatment. So, a typical application would require that the diverter had less than 20% degradation at 88 °C (potential treatment temperature) for two weeks, and then that it would have 100% degradation at 2 to 4 weeks at 260°C (typical geostatic temperature).

As it is anticipated that the application temperature will vary with different application, one of the goals of the diverter development work was to identify materials that would be effective at different temperatures. The variation in temperature could occur simply due the application being conducted in different geographical locations. However, the variation in temperature could also occur in the same well depending on the sequence in which the fractures are stimulated. For instance, if fracture order is bottom up then the sealed fracture will heat back up to geostatic temperature shortly after placement and will not benefit from cooling effect of injection of fracture fluid.

Applications

TPDS have been successfully been used in two trial field applications to date. Initial results showed positive results in both an injection well and a producing well. These results are documented in a in a paper presented last year at the Stanford Geothermal Workshop (Ref 1). In brief, results from the first test indicated that fluid injection could be diverted deeper into the injection well by pumping a suspension of TPDS into the well. This was determined by monitoring downhole temperature and pressure during the operation. The second application involved pumping multiple TPDS treatments over a 36 hour time period while injecting water. Tracer tests results provided indication that the initial flow path from the treated well to nearby wells was temporarily sealed and a new flow path was created. In addition, subsequent flowing temperature profile indicated that the well was producing from a deeper, hotter portion of the reservoir rock which had not been producing in the past and the total production had increased by as much as 68%.

Additional applications are being planned and considered in various geothermal fields. Immediate applications could include stimulation of existing producing wells that currently have marginal production. Other applications could include stimulation of injection wells which are not currently taking sufficient flow for disposal of outlet production fluid from the power plant. We are hopeful to have multiple additional applications within the next year.

Conclusions

TPDS have been developed to provide a non-mechanical means of achieving multiple zone stimulation for EGS and conventional geothermal wells. Using non-mechanical means of multiple zone stimulation provides a number of significant benefits, including greatly reduced cost, reduced operation risk, and the potential ability to readily stimulate two or more fractures without the need of a drilling rig and some type of mechanical operation and/or manipulation.

Various materials have been tested over a range of temperatures. Results indicate that specific materials can be developed into an effective TPDS for given temperature application ranges.

References

1. Diverter Paper presented in 2011 at Stanford

Data

Figure 3: Degradation of Material A

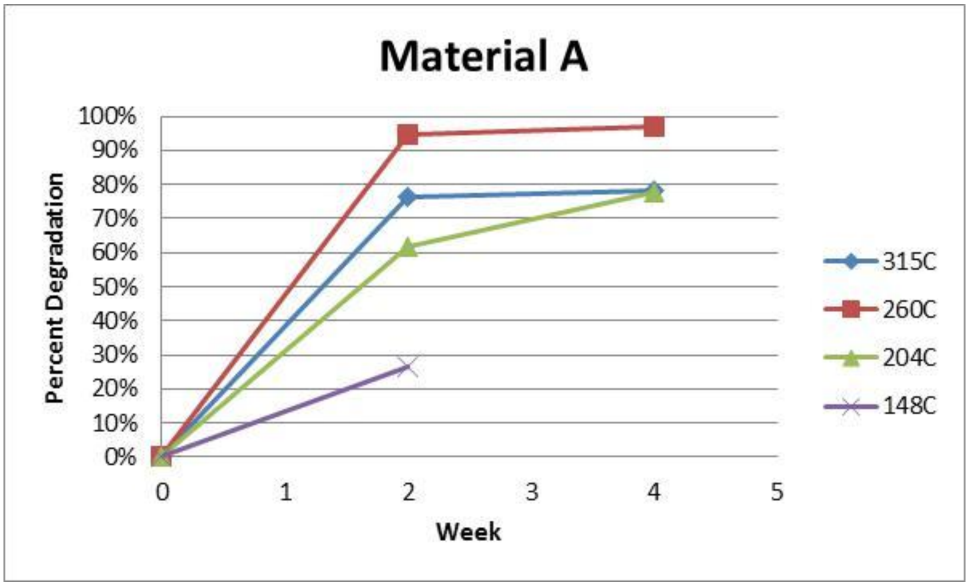


Figure 4: Degradation of Material B

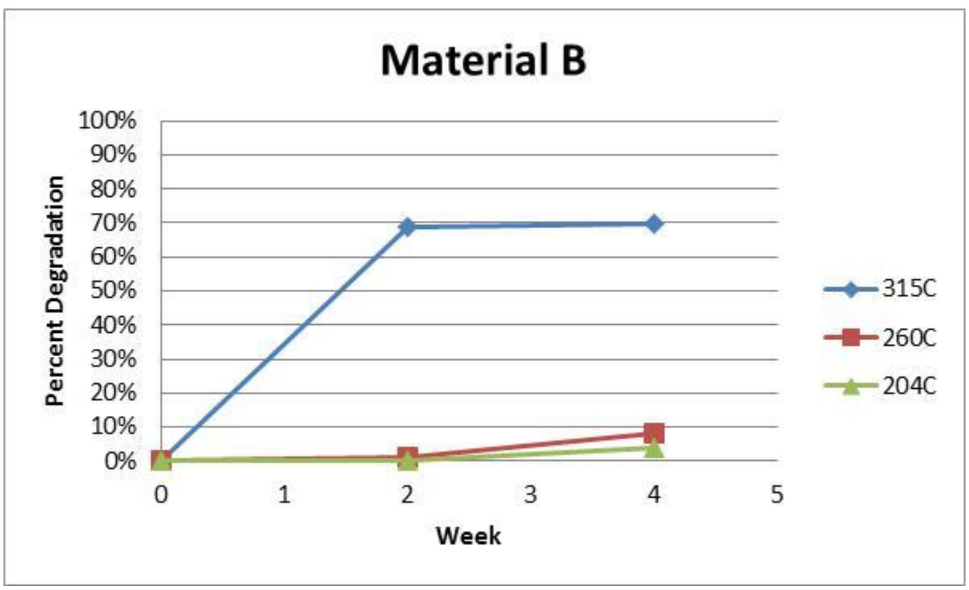


Figure 5: Degradation of Material C

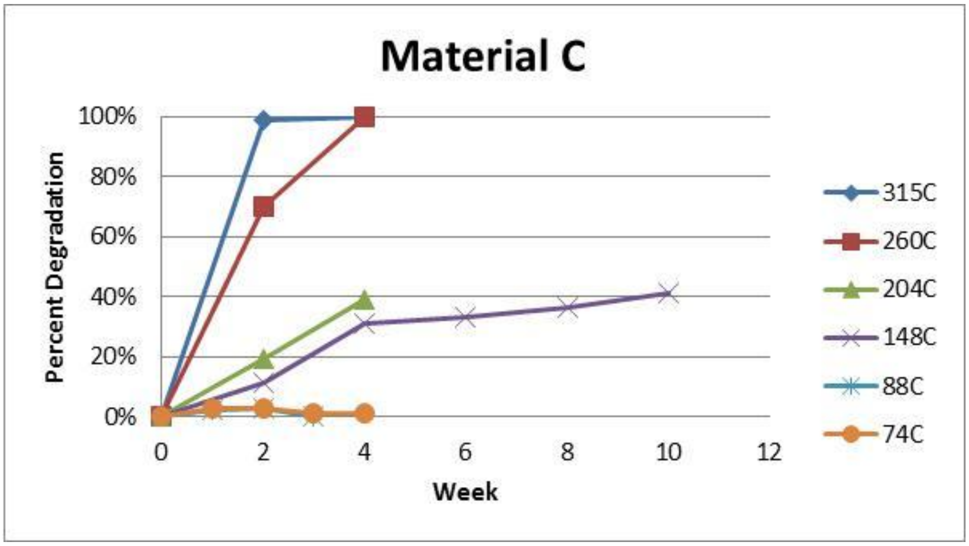


Figure 6: Degradation of Material D

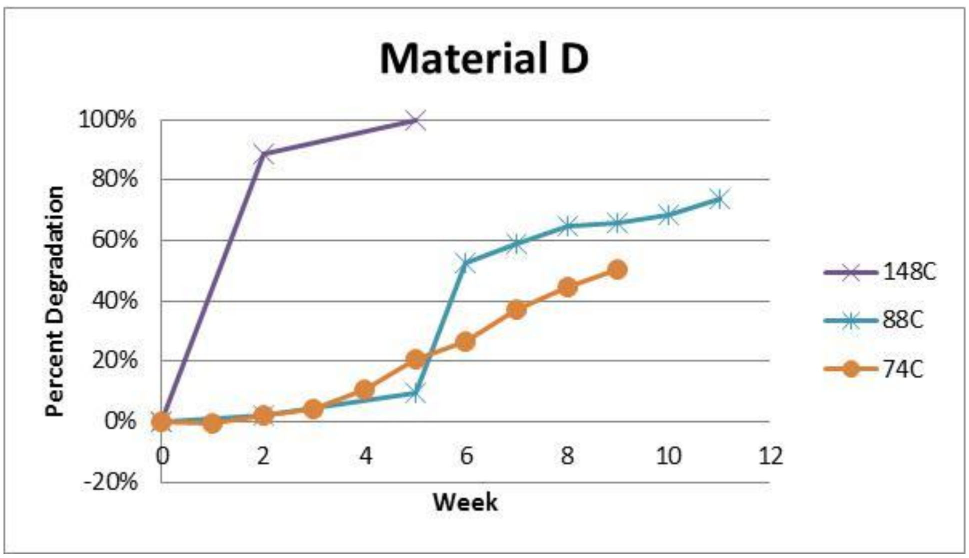


Figure 7: Degradation of Material E

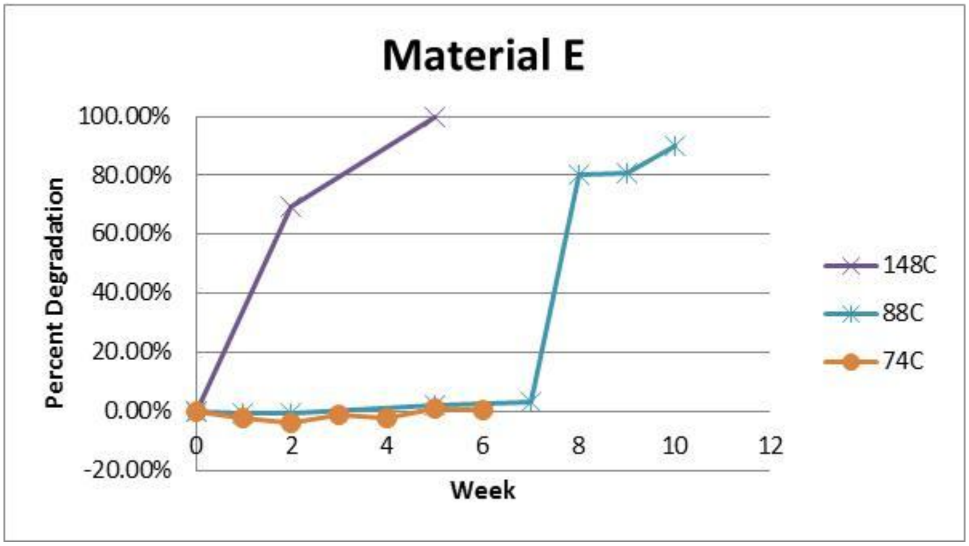


Figure 8: Degradation of Material F