Background
The 2013 Record of Decision Amendment states, "The specific methods for Enhanced Bioremediation "EBR" will be established in consultation with EPA and ADEQ based upon biological and contaminant conditions after SEE implementation." This implies that the baseline biological and contaminant conditions will first be characterized and the baseline information will be used to inform the development of the work plan for EBR implementation in consultation with the regulatory agencies. A unilateral approach to implementation before characterization is complete would violate the agreement documented in the 2013 RODA. The May 2014 RD/RA Work Plan approved by the regulatory agencies included an outline of how EBR would be implemented, which included 61 injection and extraction wells to distribute the terminal electron acceptor (TEA) during 1.5 to 3 years of recirculation, which would also provide containment of the contaminant plume. Modeling had been used by Amec to determine that the well spacing should be no greater than 75 feet and that the pumping rate should be 160 gallons per minute (gpm). The TEA to be used had not been determined, but comparisons were provided between the use of aerobic biodegradation by supplying oxygen as peroxide, or the use of anaerobic biodegradation using sulfate.

July 2014 Field Test
Amec in July 2014 (before Steam Enhanced Extraction (SEE) implementation) conducted a field test of anaerobic biodegradation to support the anaerobic EBR modeling that was performed as part of the ST012 RD/RA WP due to the fact that significant assumptions were made in the analysis (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 1-1, Lines 156-158; "Modeling results for both processes indicated that the remediation goals could be met; however, there were **significant assumptions made for the anaerobic approach.**" (emphasis added)). This field test was comprised of two push-pull tests performed at existing wells W-11 and W-30, both of which are completed in the lower saturated zone (LSZ), and both of which were known to be impacted by LNAPL. The purpose of the field test was to determine sulfate utilization rates. While microbial data collected during the field test showed increased populations of sulfate reducing bacteria, the data collected during the extraction phase could not be used to determine sulfate utilization rates. Pumping rates during the extraction phase from W-30 could not be sustained due to well fouling, and the limited amount of groundwater extracted from W-30 'did not provide a sufficient data set to estimate sulfate utilization' (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 3-4, lines 475-476). At W-11, sulfate concentrations increased during the pull portion of the test, which 'indicate that background groundwater sulfate concentrations were being pulled into the well and prevent the accurate estimation of sulfate utilization' (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 3-4, lines 477-478).

Instead, sulfate utilization was estimated from the shut-in portion of the test. Data presented from W-11 show that the TPH and benzene concentrations remained essentially constant during the shut in period (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 2-3, Table 2-1), while normalized sulfate concentrations were greater than the normalized tracer concentrations during most of the shut in phase of the test (Addendum #2, Remedial Design and Remedial Action

Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 3-5, Graph 3-4). Thus, very little sulfate utilization was demonstrated from the results at this well.

Data from W-30 show that the DRO and TPH concentrations increased substantially during the shut-in period of the test and benzene concentrations approximately doubled (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 2-4, Table 2-2), while the sulfate concentration decreased exponentially with time (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page2-7, Table 2-6). While the results at this well showed sulfate utilization during the shut in period (Addendum #2, Remedial Design and Remedial Action Work Plan – Site ST012, Appendix C, Enhanced Bioremediation Field Test Report, page 3-6, Graph 3-5), the results did not demonstrate that TPH or benzene were consumed by the sulfate that was utilized. After review of the field test report, EPA commented: "The results of the EBR Pilot Test are equivocal, difficult to interpret for practical use, and result in high uncertainty when used to model and plan full-scale EBR, and MNA." (CSS: *Review of Documents for Operable Unit 2, Site ST012, at the Former Williams Air Force Base, Mesa, AZ* May 17, 2016).

Addendum #2, which was first submitted to the Agencies for review in November 2015, proposes a very different approach for implementation of EBR than was contained in the May 2014 work plan. First, based on the field test, sulfate was chosen as the TEA. Based on the fact that a very large amount of TEA will be required, which would be difficult to provide via oxygen injection, Amec proposes to use sulfate as the TEA. However, modeling performed at the conclusion of the Thermally Enhanced Extraction (TEE) pilot test indicated that while sulfate is depleted in the LSZ within the LNAPL plume, sulfate is not depleted within the LNAPL plume in the upper water bearing zone (UWBZ) (BEM, 2010, Appendix M, see Figure M.5.1.2.4). Second, the amount of TEA proposed by Amec to be used was reduced from 7600 tons of sulfate to 840 tons. A third change was to significantly reduce the number of injection and extraction wells from 61 to 18. A fourth change was that instead of 1.5 – 3 years of recirculation and plume containment at a pumping rate of 160 gpm, it was proposed to perform limited pumping with no recirculation during the injection of a very high concentration of sulfate (320,000 mg/L), and then to allow diffusion and dispersion to distribute sulfate throughout the LNAPL plume over approximately a five year period (see Addendum #2, Appendix E).

Agency Concerns about EBR

Although it was the Agencies' understanding at the time the RODA was signed that the majority of the LNAPL would be recovered by SEE, and what was understood by the Agencies to be minimal residual LNAPL and dissolved phase at the periphery of the SEE treatment area would be addressed with EBR. Thus, the Agencies believed that EBR would be implemented in the area surrounding the SEE treatment zone where moderate temperature increases might be expected to further enhance microbial growth and hydrocarbon degradation. SEE was expected to reduce the benzene concentrations within the treatment area to 100 – 500 ug/L, and then transition directly to monitored natural attenuation (MNA) (Final RD/RA Work Plan, May 2014, Table 4-2). However, the actual SEE treatment zone include only approximately half of the LNAPL at ST12 (Final RD/RA Work Plan, May 2014). Also, according to estimates provided by Amec (February 2017 BCT meeting), Amec now states that approximately 200,000 gallons of LNAPL

remain in the SEE treatment area. Thus, there is considerably more mass remaining in the subsurface than what the Agencies had understood would be treated by EBR, and approximately half of that mass is in the still-extremely hot SEE treatment area, which is likely too hot to support native sulfate reducing microbes. Amec recognizes this fact, as the first step in their implementation plan calls for stabilizing the temperature to no more than a 1°F increase per day before initiating EBR (ST012 Decision Tree "Decision Tree" and Criteria for Enhanced Bioremediation, March 2017).

The Air Force has stated that they are committed to "achieving remedial action objectives within our ROD Amendment's estimated timeframe" (March 15, 2017 letter signed by Phil Mook). However, the Agencies have very significant concerns that the approach proposed in Addendum #2 will not only fail to meet the remedial goals within the remedial timeframe, but will actually make the contamination situation at ST012 worse by reducing contaminant degradation rates and allowing the contaminant plume to spread. These concerns are based on:

1) Site conditions in terms of the remaining LNAPL mass are different from those contemplated in the RODA for EBR/MNA (i.e., there appears to be much more LNAPL remaining than was expected by the Regulatory Agencies).
2) EBR/MNA has not been tested and proven effective at a site of this size, complexity, and source mass – particularly in terms of the timeframe contemplated, so the proposed EBR application should involve more extensive data collection and field testing before implementation of EBR at full scale.
3) The extremely high sulfate injection rate proposed in Addendum #2 would be a 'shock loading' of sulfate which could have a detrimental effect on the microbial populations that Amec is trying to stimulate due to the geochemical changes this highly concentrated sulfate addition will cause. The August 2016 response to comments (RTC) on Addendum #2 acknowledges that the high injection concentrations of sulfate will likely limit microbial growth near the injection wells. The "Decision Tree" for EBR provided on March 16, 2017 seems to indicate that sulfate concentrations must be below 30,000 mg/L to not cause inhibition (Target Numerical Conditions, Decision Objective: To Establish Biological Degradation by Sulfate Reducing Bacteria (SRB) at ST012 and has been Enhanced, Time Frame: 3-9 months post injection, Criteria: Sulfate, Target Numerical Conditions: Non-Inhibiting, 30000* [*30000 ppm dissolved sulfate in the groundwater*], *Preliminary ranges for target sulfate concentrations in the formation. Values are subject to modification based on observation of SRB responses in the field to sulfate. Higher concentration may be present in the immediate vicinity of injection wells.) The conservative tracer transport model results presented in Appendix E Groundwater Model Outputs of Addendum #2 (for example, Figure E-21, Conservative Tracer Transport Model Results, Lower Saturated Zone - 220 Ft bgs, 1990 Days From Tracer Injection) indicate that significant portions of the site will remain at concentrations of this level for as long as 1990 days (approximately 5.5 years) after sulfate injection. Suthersan et al. (2011) states, **"sulfate application strategies that employ repeat injections at highly elevated concentrations may not be as effective as sulfate delivery strategies that achieve relatively steady sulfate concentrations over time in the range of 100 to 2000 mg/L. This can increase the efficiency of the process while limiting the geochemical footprint of the reactions."**

4) Research has shown that even when sulfate reducing microbes that can oxidize petroleum hydrocarbons are present, benzene reduction may not occur (ESTCP, 1999). It has not been demonstrated that sulfate-reducing bacteria that can degrade benzene are present at this site. Although it appears that benzene degradation is occurring, essentially all TEA (except CO_2) are depleted at this site (BEM, 2010), and thus, benzene degradation may be occurring via a different microbial population.
5) It is not clear that the UWBZ is deficient in sulfate (BEM, 2010), in which case sulfate addition will not stimulate hydrocarbon oxidation.
6) It is not clear that the proposed mass of sulfate to be injected – as large as it is – is sufficient to degrade the LNAPL mass that remains. Addendum #2, Lines 822-827: "Initial target TEA dosage is based on treating approximately 30% of the LNAPL mass in the CZ, UWBZ, and LSZ, on treating approximately 30% of the LNAPL mass in the CZ, UWBZ, and LSZ, accounting for the likelihood that BTEX+N will be preferentially consumed during bioremediation over longer chain hydrocarbons. **Although BTEX+N are the primary COCs, other compounds will degrade and consume sulfate in the process."** (emphasis added). According to the referenced ESTCP document, "***Ground water contaminated from gasoline contains not only BTEX compounds, but many other gasoline components as well. At the Seal Beach site, much of the injected nitrate and sulfate was utilized by bacteria to degrade non-BTEX hydrocarbons. This makes it difficult to predict the amount of electron acceptor(s) that will be needed for complete BTEX removal.***" In field experiments at a gasoline spill site, Reinhard et al. (ES&T, 31(1):28-36, 1997) found that only 13 to 40% of the sulfate consumed was used to degrade BTEX.
7) Numerical modeling using MODFLOW-SURFACT was used to support the contention that 1.5 years of sulfate addition/recirculation could reduce benzene concentrations to levels that could then degrade over the next 15 years via MNA to reach the cleanup goal of MCLs (May 2014 RD/RA Work Plan, Appendix E, EBR and SEE Containment Modeling Report – Site ST012, Table E-4.15). However, as was discussed during the March 16, 2017 BCT conference call, the model likely overestimates the degradation rate due to the assumptions of equilibrium between the LNAPL and dissolved phases (i.e., no mass transfer limitations), and the use of an estimate of naturally occurring organic matter (foc) of 0.0003, which leads to too low of an estimate of contaminant sorption and retardation. Also, there was extensive discussion during this call where Amec indicated that the modeling, as performed, is not predictive. That is, the modeling results can only legitimately be used as a tool to <u>compare</u> estimated time frames under differing scenarios, and not to predict actual timeframes for reaching remedial goals. ***Thus, the modeling that was performed cannot be interpreted as support for Amec's contention that the cleanup goals can be achieved in an estimated 20 years.***
8) Approximately one year after termination of steam injection, large portions of the SEE treatment area remain at temperatures that are likely not conducive to the natively-occurring microbial populations, although some of the less-impacted areas may be experiencing increases in microbial growth. Amec's mass estimates indicate that 200,000 gallons of LNAPL remain in the SEE-treated zone, so it is particularly important that enhanced microbial degradation of BTEX+N be highly active in this high-temperature area if EBR is to be successful.

9) It is not clear that sulfate can be distributed throughout the site through the reduced number of injection wells. Since the distance between the injection and extraction well varies from about 100 to nearly 250 feet, development of preferential flow pathways is likely, particularly if high pumping rates are used in the extraction wells. As a result, the sulfate is likely to be distributed primarily along the preferential flow pathways and is not likely to be distributed across all of the areas where EBR is intended to treat LNAPL and dissolved phase contamination. Modeling is useless to evaluate whether preferential flow pathways develop; only actual field data can be used to evaluate this. Section 4.1, EBR Well Field Design (May 2014 RD/RA Work Plan) states, "This 60-foot well spacing was determined to be optimal by an iterative process using the groundwater flow model to assess various configurations of the well fields within the geometry of the treatment areas. Beyond an approximate well spacing of 75 feet results from the model revealed that sufficient extraction pumping could not be achieved because of limitations associated with the permeability and storage of the aquifer and subsequent loss of Injectate to the natural gradients in these gaps between extraction well capture zones."
10) The apparent intent to treat only dissolved benzene is not likely to be successful because the LNAPL is a significant reservoir of benzene, which will continue to dissolve into groundwater for many years. Therefore, it is important to treat both LNAPL and dissolved-phase benzene. Further, encapsulation of LNAPL by microbial films (to degrade the BTEX moving from LNAPL to GW), by iron sulfide precipitates (to reduce flux of BTEX from LNAPL to GW), fouling and precipitates in and around LNAPL bodies (so that GW does not flow close to the LNAPL such that benzene is not readily be dissolved) could cause GW concentrations of BTEX to fall, while much BTEX remains in the remaining LNAPL. Even if this occurs, eventually (i.e., the timeframe cannot be predicted) benzene would likely dissolve out of the LNAPL.

Path Forward

In order to go forward with EBR, the Agencies strongly recommend that the first step in the AMEC-proposed phased implementation approach be application of EBR in limited areas of the site to gather the information necessary to ensure that EBR is applicable to all areas of the site (i.e., high LNAPL/no LNAPL, CZ, UWBZ, LSZ) and is being implemented in an optimal manner and consistent with the objectives and intent outlined in the 2013 ROD Amendment. From this information, we can establish milestones and criteria against which we can compare the full scale implementation to ensure that the remediation is proceeding in a manner and at a rate that will allow the remedial goals to be achieved in the estimated desired time frame throughout the entire site. **The Agencies have very significant concerns that if Amec proceeds with the injection of very large quantities of sulfate (320,000 mg/L; Addendum #2, Section 4.2.2, line 1044) that it will inhibit microbial growth and thus contaminant degradation over a large portion of the contaminated area, which will allow the contaminant plume to migrate downgradient, and make it impossible to achieve the cleanup goals via biodegradation in any kind of a reasonable timeframe.**

The "Decision Tree" states that the first step in implementing EBR would be "To establish location is ready for EBR injections". During this pumping/LNAPL removal and temperature

stabilization step, other actions can be taken to alleviate the Agencies' concerns about EBR implementation at this site:

a) Amec should provide well-documented case studies of specific sites where EBR, as Amec plans to do it, has actually remediated hundreds of thousands of gallons of LNAPL/BTEX so as to reach 100-500 ug/L BTEX in groundwater, with no LNAPL remaining (or, at least, no LNAPL with COCs in the LNAPL). This information has been requested by the Agencies previously. If sites comparable to this have not been treated successfully using EBR, then the Agencies believe it is prudent to thoroughly test the proposed implementation plan before actions are taken that may make the contaminant situation worse.
b) In light of the inconclusive results from the field test on benzene degradation accompanying sulfate utilization, a demonstration that the sulfate-reducing microbial consortia at this site is capable of degrading benzene is needed. If benzene can be degraded via sulfate reduction, information is required on what conditions are necessary to maximize the degradation rate. This can be demonstrated via laboratory experiments. If these laboratory experiments show that benzene degraders are not naturally present, it may be necessary to incorporate bioaugmentation into the EBR work plan. Also, if benzene degradation is found to be delayed until TEX and other compounds are degraded, the effect of this delay on remedial timeframes and plume extent must be assessed.
c) Laboratory experiments could determine if the existing microbial systems at the varying areas of the site (high LNAPL, etc) are deficient in sulfate, and if so, the amount of sulfate needed to maximize degradation rates, and the amount of sulfate required for degradation of BTEX.
d) As temperatures now vary widely across the site, lab experiments should also evaluate impact of temperature variability on microbial populations. Laboratory testing could determine the optimal temperature for EBR and evaluate degradation rates at different temperatures.

These laboratory experiments must be performed utilizing groundwater samples from all four of the hydrologic zones: cobble zone (CZ), UWBZ, low permeability zone (LPZ), and LSZ.

Based on what is learned from the laboratory experiments, the first phase of the field implementation can be designed that will allow determination of benzene degradation in each of the hydrologic zones. Again, all four hydrologic zones should be targeted, including areas of heavy LNAPL saturation, and areas only affected by dissolved contaminants. Benzene degradation rates can be estimated using a flow-through field setup rather than a push-pull test as was used in the field pilot test. Estimates of benzene degradation derived from the field test can be used in an appropriate predictive model to estimate treatment times, although it must be kept in mind that, "***Anaerobic bioremediation is still not thoroughly understood, especially under field conditions, making clean-up times difficult to predict***" (ESTCP, 1999). The presence of significant LNAPL at this site and low permeability zones that are known to contain LNAPL will limit the biodegradation rate (ESTCP, 1999, page 6). More details on the laboratory and first phase of the field implementation are provided below.

Laboratory Work

The following sections propose a methodical and scientific evaluation to establish baseline conditions before further actions are taken. The overall goal of acquiring and properly evaluating these baseline conditions is to ensure that an adequate microbial population exists at the site before expensive and time-consuming activities are conducted, determine the appropriate path forward, and prevent additional environmental harm to the site (i.e., prevent further contaminant migration, prevent the unintended addition of amendments that subsequently become toxic to the site, etc.).

These tests will provide a baseline against which to compare data on microbial populations during EBR implementation, as well as assessing benzene degradation and the effects of adding sulfate. This baseline data also provides the AF with the opportunity to demonstrate remedial success, by clearly documenting the starting conditions for this phase of site work.

The below describes two biological monitoring tools, and two geochemical methods, for monitoring site microbial activity. Although these tools can be used individually, when used together they can produce a thorough image of baseline biogeochemical conditions. Furthermore, they can be used to monitor ongoing site conditions (and compared to the baseline conditions) in a way that is both quantitative and scientifically accepted.

Stable Isotope Probes

A limitation of Stable Isotope Probes (SIP) samplers is that they cannot be deployed in the high-temperature core of the SEE treatment zones. Instead, they should be deployed towards the periphery, where temperatures are lower. This will still have significant benefits, however, given that bioattenuation typically works from the periphery of a plume inwards towards the core. Thus, this periphery area is where EBR would likely be most active.

SIP data can provide direct information about:

1. Size of the total microbial community;
2. Community structure (percent metal oxidizers, percent anaerobes, etc.) - in other words, what microbial groups make up the total community, and how big are these individual groups;
3. Confirmation of target compound degradation and biological uptake by indigenous site microbes;
4. Partial identification of community members responsible for compound biodegradation;
5. Biodegradation rates of target compounds under in-situ conditions;
6. An indication of how degraders are utilizing the target compound (for a carbon and/or energy source, for example);
7. An assessment of the overall health of the microbial community, and whether the community will support EBR;
8. Other environmental factors of interest– for instance, whether nutritional deficiencies are potentially present in the environment.

Quantitative Polymerase Chain Reaction Technology (qPCR)

A qPCR analysis uses a one-time grab sample. Analysis of qPCR data can:

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1. Determine target organisms, including classes of microbes, such as sulfate-reducers or hydrocarbon-degraders;
2. Determine whether a target organism or capability (such as the degradation of a particular compound) is present in a sample;
3. Identify specific microbes of interest, such as a particular genus (helpful if the target microbe is one known to perform a particular function under similar site conditions);
4. Determine If the organism/capability is present, quantify the size of the population in that sample;
5. Determine whether population sizes are different between one area of a site and another;

Stable Isotope Ratio Technology
Stable isotope ratio (SIR) technology only requires a one-time sample to determine if biological activity has occurred and to what degree. Analysis of SIR data can answer:

1. Is a compound is being degraded through biological or non-biological processes?
2. Is biological degradation continuing to occur, or have activities ceased?

Geochemical Parameters
Unlike the above-mentioned stable-isotope and molecular technologies, which directly monitor the site's indigenous microbial population, this sequential use of TEAs allows for indirect monitoring of the indigenous microbial population.

1. Analyze the geochemical parameters sulfate, nitrate, total iron, ferrous iron, pH, DO, and ORP in an appropriate number of wells from each hydrologic zone (CZ, UWBZ, LPZ, LSZ) in separate areas of the plume (plume core and periphery);
2. Determine the stability of established microbial communities responsible for biodegradation;
3. Determine if the hydrocarbon-degrading population requires additional site amendments;

All baseline data should be presented in a Technical Memorandum for regulatory review prior to implementing EBR. The Technical Memorandum should include the following:

1. Provide a complete review of the biological data that describes the indigenous microbial population, including, but not limited to, the portion of the total community that is made up of sulfate-reducing bacteria as well as other classifications of anaerobes;
2. Identify the potential for site microbes to degrade the contaminants of concern;
3. Refine the site monitoring program based on the baseline data, including appropriate methods to monitor changes in the microbial community and geochemical parameters as EBR progresses;
4. Present conclusions and recommendations based on the current site baseline data, considering the following:
    i. Identify whether bioaugmentation is necessary;
    ii. Identify proposed amendments.
    iii. Include milestones and endpoints with realistic and defensible timeframes.

First Phase Field Implementation

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Following a thorough analysis of the baseline data, EBR should progress to a field implementation that involves actually remediating an LNAPL mass (up to 5 feet accumulation in the well, to be consistent with the Decision Tree), and examining benzene degradation in areas of dissolved contamination only. The first phase of field implementation should allow for observation of degradation in each of the three hydrologic zones (CZ, UWBZ< and LSZ). Injection wells are needed upgradient of the implementation area, and a transect of monitoring wells approximately 3 to 6 month of of travel time downgradient of the area. Sulfate and a tracer should be injected planned for the full-scale EBR – or as found to be optimal based on lab tests? If AF can timely remediate the LNAPL well so that no LNAPL is found in the well, and the COC concentrations in that well and the downgradient monitoring transect are below standards, then that would be strong evidence that a full-scale approach could work.

Chosen areas could be at elevated temperature, as long as laboratory testing indicates the EBR is effective at those temperatures, to correspond with the general site conditions.

Assuming the first step implementation continues for at least a year, performance monitoring would be conducted to monitor the changes around the injection, LNAPL, and monitoring wells in terms of microbiology, sulfate concentrations, sulfide production, hydrogen sulfide generation, precipitation of iron sulfides, possible aquifer plugging, changes in pH, oxidation-reduction potential, etc. The resulting data should be evaluated to assess the viability of a full-scale remedy, and any likely dangers, showstoppers, etc.

Fouling should be assessed for all wells (injection, LNAPL, monitoring), to determine the likely needs for well reworking, refurbishing, eventual replacement, etc. This is particularly important for the follow-on contractor (after AMEC's contract expires) to have an idea of long-term costs, and how to bid. Also, corrosion of carbon steel wells should be assessed, as it is well known in the oil industry that sulfate reduction and the production of H2S accelerates corrosion.

The downgradient monitoring transect should be utilized to monitor COC changes, and to assess the geochemical footprint of downgradient locations, which would be pertinent to evaluating possible enlargement of a sulfate/etc. plume at full scale.

Also, the distribution and concentrations of sulfate achieved downgradient of the injection transect is of great interest. The Amec model indicates they can get a reasonable (to them) sulfate distribution, but reality in subsurface environments is often different from the models. The first phase implementation should be designed to provide suitable data to design injection well spacing, injection rates, injection concentrations, pressures, etc., so as to achieve useful sulfate concentrations across the site.