PART 3

IV. The Realities of Distributed Compressible Fluid Flow Analysis

In the previous section it was shown that in order to *correctly* analyze an existing well screen model, the sheer magnitude of calculations and the effort necessary to perform such calculations manually becomes a very daunting task. It was shown that in performing *incremental* mass and energy computations, the sum of all respective values must equal that entering the system to start, otherwise the overall mass-energy balance will not be achieved. If the mass-energy balance is not achieved analytically, then should the well be installed as modeled, there is no possibility it will operate as desired. In fact, the chances of such an event are nil!

Further, it can be logically argued that even *attempting* to solve such complex equations is inherently fraught with the specter of making gross calculation errors. In that the computation of the first mass leaving the well (e.g., $\mathbf{m_1}$) results in the determination of the remaining mass inside the well, $\mathbf{M_1}$, this leads to our (eventually) computing what the pressure is at the second slot $\mathbf{P_2}$. $\mathbf{P_2}$ in turn will be required to determine the value of mass leaving the second slot, $\mathbf{m_2}$, leading to our calculating $\mathbf{M_2}$, and so on until we finish with $\mathbf{P_n}$, $\mathbf{m_n}$, and $\mathbf{M_n}$ (which should equal zero). Since all calculations are iterative, should we make a mathematical error *as little as 1/100 of 1%* in our first $\mathbf{m_1}$ calculation, that error will be compounded with each successive calculation resulting in a huge impact! For the example of our 200 foot long well with 20,000 slots, the error will eventually grow so that our final results will be in error by a factor of 7.39. Note that this is not to be interpreted as being in error by 7.39 percent, but rather being off by a factor of 7.39 times the correct values. If the first calculation is in error by 2/100 of 1% the "error factor" grows to 54.58!

In that the effort to compute such system dynamics is both *required* and extremely difficult, the only solution to such a dilemma is to apply a finite element analysis approach and a computer to the problem. Such a task was undertaken in the early 90's, resulting in the development of several finite element analysis programs for the expressed purpose of determining the performance of *any* horizontal or vertical well, in *any* type (or types) of soil, with *any* slot configuration or propagation, and under *any* groundwater conditions. The programs were finalized after 3 ½ years of effort.

These programs, appropriately titled SPARGE™ (for injection wells) and EXTRACT™ [1] (for extraction wells) also offer the advantage of determining *which* specific well screen design could yield *any* desired effect. With such breakthrough products not only can any existing well be computer-analyzed to

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[1] SPARGE™ and EXTRACT™ are trademarks of Integrity Engineering, Inc.

determine if it can perform to what's desired, a specific well can be *computer-designed* such that it does yield the desired effects [2].

The equations used to solve the fluid dynamics mass-energy balance in the SPARGE™ and EXTRACT™ programs are even moreso complex than the equations presented in this treatise, in that *gas compressibility* was considered. Recall that our "simplified" mass-energy equations for our example well were derived from Bernoulli's *incompressible fluid* flow Equation. In order to "simplify" matters, we "assumed" compressibility issues were non-impactful (which is untrue). The programs include compressibility effects, and although not very impactful for small wells operating at low pressures and at very low flow rates (for example a 2" ID 50 ft. long well, with 5 psig header pressure and a total flow of 25 SCFM), compressibility for larger wells at higher flow rates becomes significant.

Without delving deeply into the analytical methods used to produce the programs' algorithms (which in themselves are quite complex), it may be interesting to readers not familiar with finite element methods to learn how this is done. First, all the design parameters of the well, the soil, and well placement under groundwater is input and stored in computer memory. The computer then "creates" a 3-D logical mathematical "image" of the well's overall geometry in the soil and under water, and the geometry and propagation of well screen slots. Thereafter, the program "slices up" the well into finite length elements and places the numeric model of each element into a very precise "logical array". Since there are many variables, or more precisely *degrees of freedom*, which impact each element, this "logical array" is 33-dimensional. Recall that we live in a 4-D world of length, height, depth and time, so 33 dimensional space is rather more complex.

Once all the known data is input a simple "Go!" keystroke invokes the computer to apply proprietarily developed flow equations *simultaneously and iteratively* to *all* the elements in the 33-D array, balancing the mass *and* energy of the flow from each element and what remains against all others. Energy loss due to friction is taken into account during these calculations, while concurrently the mass remaining *inside* the well ($\mathbf{M_1}$, $\mathbf{M_2}$, etc.) is computed. The program then sums all the incremental ejected mass $\mathbf{m_i}$ values, ensures that the mass $\mathbf{M_n}$ and velocity $\mathbf{V_n}$ are zero at the well's end, and if the sum of $\mathbf{m_i..m_n}$ exactly equals the $\mathbf{M_0}$ value used to begin the calculations, the program stops, since it has solved the system. If any of the balances do not occur, or key conditions are not met, the program "rethinks" the system, clears the calculation "slate" and starts again. This continues until the computer completely balances *all* of the elements (and their property values) in the array.

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[2] Such is the case where SPARGE™ was used to design the world's longest successfully-operating biosparge wells and systems at the Savannah River Site, Aiken GA in 1997. Deviation in overall performance from that computed by SPARGE™ for these 1440 ft. long wells was less than 3%.

The effort to model and predict the performance of a typical horizontal sparge well of "simple" design in a single soil type placed in uniform depth groundwater may require the solving of 10,000 to 50,000 separate equations and up to several hundred million individual calculations. Very long wells (1000 feet or so) of complex design placed through varying soil types and under non-uniform depth groundwater may require the solving of upwards of 500,000 separate equations and up to *several hundred billion* individual calculations. The approximate time to complete the computations and determine the performance of *any* well design is on the order of 2 to 5 seconds.

Suffice it to say that these types of calculations cannot be done by hand either efficiently or accurately, making the programs invaluable in performing *What if?* analyses. In that up to a hundred or more SPARGE™ or EXTRACT™ "runs" can be completed in a single day, whereas a single analysis done by hand would take weeks to complete (if indeed it could be done), these very valuable tools prove their worth with the very first use.

As added features the programs automatically compute biodegradation data, performance requirements for motive blowers and determine the *transient time* to be expected in air sparge wells (the minimum time once the blower is energized for the well to completely clear itself of groundwater and reach *steady state operation*). Transient time is most often not even considered in designing horizontal sparge wells but its impact can be significant. It is not uncommon for the time to reach steady state operation to range from 1 day to *several weeks*!

V. The Cost of Ignoring Newtonian Physics and Applying Poor Design Practice

At this point the reader may appropriately pose the question of whether not including the design complexities previously discussed would really matter to the performance of a horizontal well. After all, in reality, many horizontal wells are installed each year *with no concern for screen design* at all; how do these wells perform?

The formulation of a response to this question poses a return question, which is, "How is the performance of *any* well to be judged; what is (are) the parameter(s) that is (are) to be used as a basis to *define* performance?" After consideration of the many possible parameters that *could* be used, it may become apparent that two primary parameters are foremost in defining well and system performance. These would be:

1. For the applied header pressure or vacuum, does the well provide *the total volumetric flow desired and intended*? That is (in the nomenclature of this treatise), for the desired $\mathbf{P_0}$, is $\mathbf{M_0}$ what is desired and expected?
2. For the total volumetric flow existing, does the well distribute this flow *as desired*? That is, is the incremental mass flow $\mathbf{m_i}$ into or out of each slot or given portion of the well what's desired or expected?

These two parameters literally *define* the resultant remediation effectiveness of any remediation system and well, horizontal or otherwise. In that subsurface remediation can only occur to the extent required and desired if and only if the *total* mass of gas delivered or withdrawn is what's required, and only if this mass is delivered or withdrawn *where it is required*, it is clear that any deviation from these two parameters must result in remediation not proceeding as required. Logically, if a 500-foot long horizontal air sparge well, *expected* to deliver 1 SCFM of sparge air *uniformly* over its entire length to *evenly* distribute it's air under a contaminant plume (thus requiring a total throughput of 500 SCFM), cannot do so that well cannot remediate the intended area as required. If the well only delivers 350 SCFM, and/or delivers the air incrementally with a large flow rate *skew*[3], then the right amount of air is neither being delivered where it is required, nor is the right total volume delivered to "do its job". As a result remediation cannot occur as originally intended and required, and either:

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[3] The term *skew* is defined as the comparative percent deviation in the unit length sparge (or extraction) mass flow rate between the first and last screen increment of the well. For example if a well intended to sparge 1 SCFM uniformly over its length is found to be sparging 2 SCFM in its first foot and .5 SCFM in its last foot, the *skew,* by definition, is 1.5 SCFM or 75% (e.g., | 2 SCFM - .5 SCFM | ÷ 2 SCFM x 100% = 75%).

1. The system will have to be modified to bring performance up to the desired level (increasing cost), if this is indeed possible or,
2. An additional system will have to be installed to supplement the existing system and "cover" for its weaknesses (increasing cost) or,
3. The existing system will be required to operate for a longer time than initially projected (increasing cost) or,
4. The existing system is abandoned in favor of a new attempt or approach (increasing cost).

The point that is being made is that the resultant outcome of a poorly designed system always results in increasing the cost of remediation, either monetarily, chronologically, or both.

A study to determine how the industry is fairing with regard to correctly engineering/designing and operating horizontal air sparge and soil vapor extraction systems was initiated in late 1996. Over a 1-year period, 62 separate horizontal AS/SVE well systems were forensically evaluated to determine their performance against that required and claimed by the remediation contractor. Twenty of these wells were SVE, the remainder, 42 were AS wells. For this evaluation, new measurement tools were used to determine actual system performance. These tools, in part, consist of a compressible gas mass flow rate measurement instrument and an associated computer program entitled VAPOR™ [4]. Contrary to common industry belief, it is not possible to accurately measure compressible gas volumetric or mass flow rates directly (such as with hot wire anemometers or common spring loaded flow indicators). In order to determine these rates accurately, characteristics of the flow, such as its absolute and dynamic pressures, temperature, humidity, etc. require measurement first, then the actual mass and standard volumetric flow rates (SCFM) are *calculated* [5]. The VAPOR™ program easily performs such calculations while also considering the effects of any condensed free-standing fluid (such as would be commonly seen in SVE headers) that obstruct or partially limit the flow. The theory of properly measuring and computing compressible gas mass flow rates is outside the scope of the current treatise and will be addressed in a future technical paper.

Because it is extremely difficult (and in some cases impossible) to readily determine the incremental flow rate into or out of any segment of an installed horizontal AS/SVE well, the study focused more on the comparison between actual v claimed *total* well/system flow. The reasoning follows that if the *total* flow of the well/system is not what is claimed or required, then the well/system cannot be performing to requirements. The presence of incremental well segment flow rate *skew* would further exacerbate any already-present performance difficulties beyond that of the discrepancy in total mass flow. In effect, the

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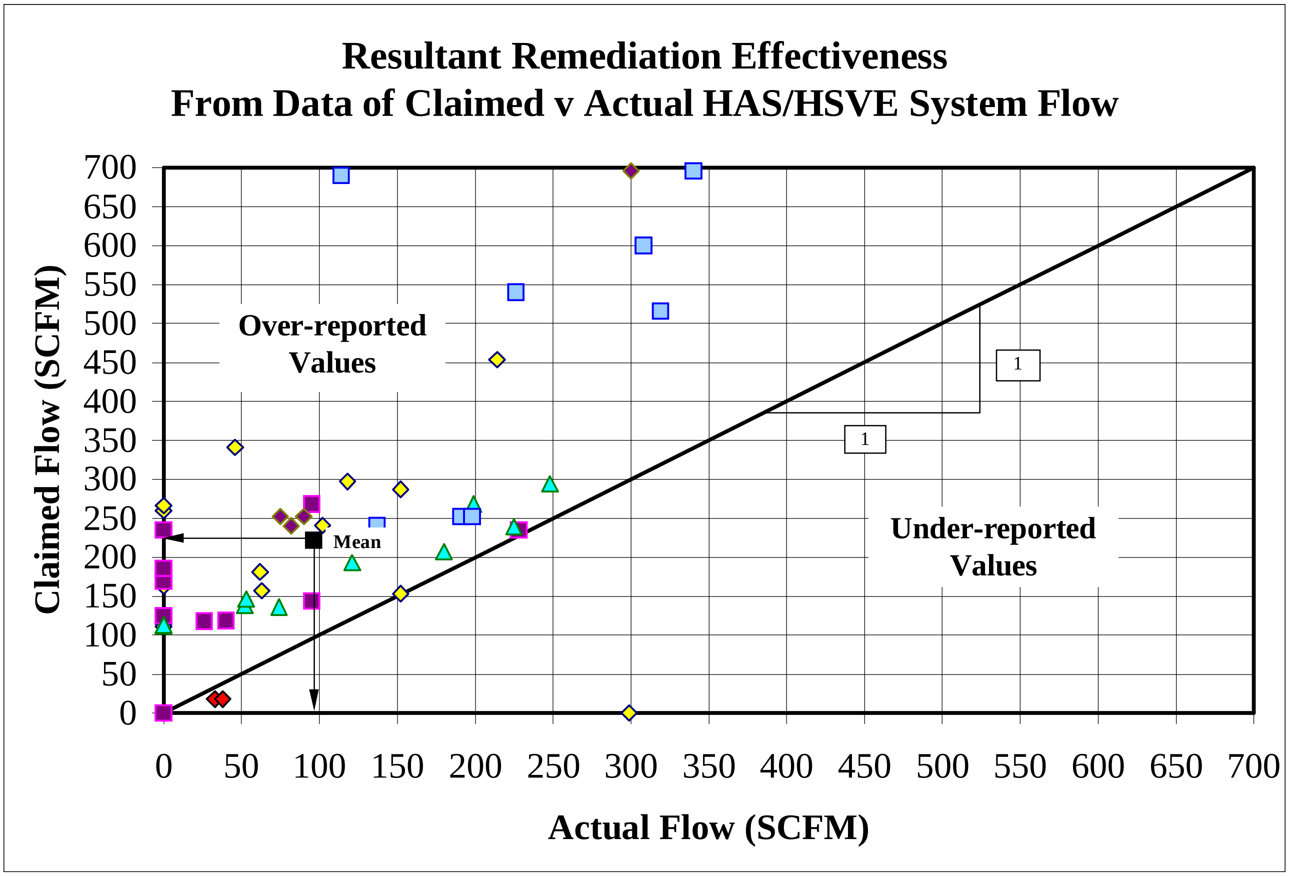
[4] VAPOR™ is a trademark of Integrity Engineering, Inc.

[5] To assure the most accuracy and precision, all instruments used in the study were digital and were calibrated to National Standards, each reading was repeated 3 times to eliminate human error, and all readings were taken in the presence of the client's site engineer.

presence of *skew* may be considered to be an additive or additional problem on top of any already existing *total* well/system flow rate problems. However, whenever possible, each horizontal AS well was further studied to establish if sparge air flow *could indeed* exist at the tail (distal end) of the well. This less-quantitative determination was done by measuring the static pressure at each well's distal end, then comparing this pressure with that needed to "break through" the local static pressure of groundwater. If the distal end pressure was at or slightly above the local static pressure of groundwater it was concluded that sparging *could not be possible* at the well's end. In this event, *skew* by definition would have to be 100% (e.g., | X SCFM – 0 SCFM | ÷ X SCFM x 100% = 100%).

The total flow data obtained during the study is graphed on the following page. The data is graphically presented so a visual comparison could easily be made between the total well/system flow *claimed* versus the *actual flow measured* in each well. Logically, if each well/system were operating precisely at its respective design (and required) level and a graph were prepared with the X-axis representing "Actual Flow" and the Y-axis representing "Claimed Flow", all data points would fall along a single line of a 1:1 slope. Those points falling *below* this line would indicate that the remediation contractor is *understating* his well/system performance. Conversely points falling *above* this line would indicate that the remediation contractor is *overstating* his well/system performance. By the laws of chance and the minor effects of measurement error, one would also expect that *if accurately designed and truthfully reported,* all data would either fall directly on the 1:1 sloped line or hover near it, some slightly above it and some slightly below it, over its full length. Given these reasonable caveats and expectations the reader is encouraged to thoroughly review the data and graph and thereafter draw the appropriate conclusions.

The most obvious conclusion that can be drawn from the study is that *few wells/systems perform as desired or required*. Of the 62 wells in the study, only 3 were *under-reported* and 8 would be considered to be accurately reported. However, of these 8 correctly reported wells, 5 of these had zero flow (e.g., 0 SCFM claimed, 0 SCFM measured) meaning that the remediation effectiveness of these 5 wells was similarly zero.


Resultant Remediation Effectiveness
From Data of Claimed v Actual HAS/HSVE System Flow
Claimed Flow (SCFM)
Actual Flow (SCFM)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Over-reported Values
Under-reported Values
Mean
1
1

The vast majority of wells/systems, 51 in total (or alternatively 82% of the total number investigated) were *over-reported* and believed to be performing well beyond that thought. Fourteen of these 51 wells were claimed to possess total flows up to 266 SCFM when in fact they all had no flow at all.

Overall, considering all wells/systems (over, accurately and under-reported) the average effectiveness of any well/system was only 43% of that required! Thus to compensate for this lack of performance, the average system would have to be operated *2.3 times as long as required*, at a cost 2.3 times as much (in time and most likely in dollars) as originally expected.

As previously mentioned, flow distribution *skew* is as important as that of total versus required flow in any horizontal well. Though the actual incremental flow discharge from any section of any well could not be measured, the level of pressure at the distal end of a horizontal AS well is an indication if *sparging is possible* at that end. During the study it was found that the distal end pressure of only 9 of the 42 total horizontal AS wells could be taken. Of these 9 wells, 3 (or 33% of those wells that could be measured) had distal end pressures equal to that of the local groundwater static head, meaning that sparging to the ends of these wells *was not possible.*

The conclusions that can be drawn from a thorough review and analysis of the field data are rather striking:

1. Of the 62 horizontal wells in the study, (42 air sparge 20 soil vapor extraction), only 6 wells that possessed flow had their total flow rates *equal to or greater than* that expected and claimed. This represents 9.7% of the wells in the study.
2. Fifty-six wells out of 62 or 90.3% *completely failed* to meet their requirements or objectives.
3. Five wells, or 8.1% of the total, were both claimed and verified as possessing *no flow at all*.
4. Fourteen additional wells, representing 30.6% of the wells in the study had no flow at all, though *all were required and claimed to possess flow.*
5. Fifty-one of 62 wells, representing 82.3% of the wells in the study had total flow rates *well below* that required and claimed.
6. The average *actual* total flow rate for all wells (as a group) was 96 SCFM, while the average *required/claimed* total flow rate for the group was 222 SCFM. The difference between the average *actual* total flow and the average *required* total flow is 126 SCFM. The *actual* average total flow proved to be only 43% of that required.
7. Of the 9 horizontal AS wells that could be further studied to determine incremental flow *skew,* 3 wells, 33.3% of those measured, were incapable of sparging at their distal ends, representing 100% *skew.*

Through the effort of this study, it can be confidently stated that not performing a rigorous horizontal well design nor performing any such design which excludes the key engineering elements previously discussed will ultimately (and always) result in dismal well and system performance. In that 90.3% of the wells/systems studied completely failed to meet their stated (and desired) requirements, regardless of what could be studied by comparison, car seat belts, computer hard drives, or even sneaker soles, a failure rate this high is truly indicative of the presence of some very serious systemic design process problems in the environmental industry.