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Development of the SPARGE™ FEA Computational Fluid Dynamics Design & Analysis Program

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1. GENESIS

Having authored a bit more than my anticipated life's assignment of technical texts, including a seemingly unlimited number of engineering papers, technical opinions, guidance documents, and a similar endless number of installation procedures, operating manuals, critiques, class lectures, presentations and speeches, I've since come to the self-evident conclusion that I've put in my dues as technical works are involved, enough so to permit myself a modicum of "literary latitude". If you've ever fallen asleep during your fourth attempt to remain conscious understanding the very first paragraph of a technical work, or wished you had chosen triple root canal rather than suffer through a parched technical dissertation, I can relate, and commiserate. This being stated, I've also since accepted the enduring but seemingly embarrassing self-evident industry fact that the vast majority of engineering papers are in need of 'personalization' in addition to their technical content. What this means is that a little snippet of reality, a short history into the technical development being presented and some human 'personality' greatly add to the work, so much so that an otherwise mundane, boring and/or tedious piece of writing just might be converted into a work with some liveliness embedded within. What is interesting to the reader 'sticks', what isn't is usually quickly forgotten, and in the technical realm, this potentially means the death knell to someone's life's work, possibly an effort with unfathomably important and impactful relevance being

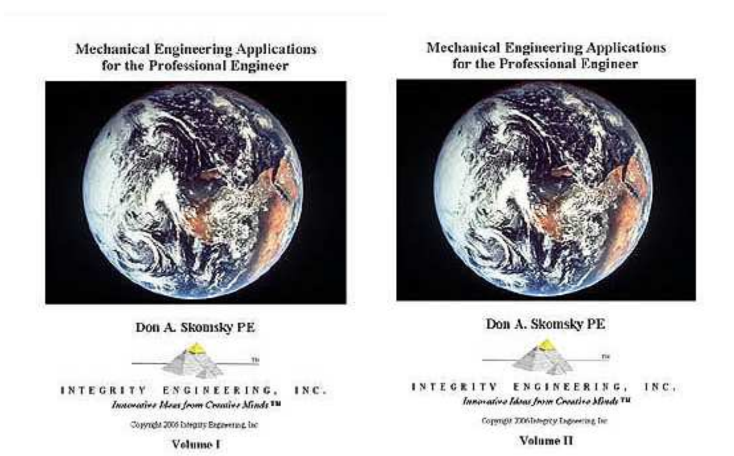

Fig. 1 A 2-volume 19 chapter lecture text developed by the Author employed as the basis for a 9-month college course for graduate Mechanical/Nuclear Engineers seeking Professional Licensure

completely ignored. What a shame for all involved, not merely the reader, but for the entire industry and our society as a whole. And, with this preface, I'll accept my self-ingratiating permission to add some 'personality' to the forthcoming story, hopefully bringing to you the reader not just a paper of technical interest, but one of humanistic interest as well. With this said, let's begin.

The genesis for the SPARGE™ environmental remediation horizontal well FEA gas injection design and analysis computer program (whew!) has its roots *over* 35 years ago, yet at the time I had no inkling that I would *ever* become involved with such an effort. During this period I was the Department Head of Mechanical and Nuclear Engineering at a dual-unit commercial nuclear generating facility in northeast Pennsylvania. For those not knowledgeable or accustomed to such sites, they are, in a word, *huge* by anyone's standards. Each reactor was designed to produce 1.2+ gigawatts of power, and being of immense need to supply our country's power grid, the entire project was one of concurrent 'design-build'. That means, for this one square mile project, the entirety of both units were being constructed as they were being designed. Quite literally, a complex set of drawings and preliminary start-up and operating procedures were finalized by the home office (located on the west coast), sent overnight to the plant, and the very next day what was designed was immediately scheduled, cost estimated, manned and construction begun. The challenges for such projects are immense – in fact in my department we coined the phrase that our work required "*An Invention Per Day*", and this moniker was *not* far from reality. Employing some 6,000 craft workers and 600± engineers of all disciplines, constructing what you are concurrently designing is an effort of immense complexity and difficulty; worker stress was always at 'an all time high', and for us engineers, you either loved or hated the work. For myself, I loved it – I wouldn't have given up this opportunity for any other career, that is, other than working on NASA's Man to the Moon project. But that's another story well outside the scope of this current paper.

At the particular time, given my position, education and experience, I just happened to be "The Go-To Guy" who not only was responsible for the most important on-site Engineering Department - Mechanical & Nuclear Engineering - I was also the 'go-to guy' who happened to be *personally* assigned some of the most difficult and challenging projects that ever arise at such sites. These included projects whose solutions had eluded all others (both at the site and home office) to the point where time was critical and the Company and Client needed a permanent and *technically sound* solution to 'the problem' NOW! The particular *problem du jour* of relevance to this paper was to find a way to obtain and store *7.5 million gallons* of NASA Grade 2 ultra-pure de-ionized water to test the condensers, main reactor, reactor pool and the new and spent fuel pools prior to the arrival of the fuel bundles. What made this particular assignment all the more difficult was that *none* of the permanent plant equipment or systems were permitted to be used for the project, nor were any of the permanent sources of operational plant water. There was the obvious issue of where to store 7.5 million gallons of de-ionized water. But, what made the endeavor evermore difficult was how to assure that the entirety of this volume of liquid was constantly kept at its Grade 2 cleanliness level throughout a usage period of at least 3 months, and most likely far longer. I indeed *did* solve this seemingly insurmountable problem (which wasn't as difficult a challenge as most), but that's not the point of my describing this backdrop. What occurred one morning as I was making my rounds on the reactor deck, waiting each day for the reactor, spent and new fuel pools and their accoutrements to be finished, *is* the point of all of this and what eventually turned out to be the genesis for the SPARGE™ computer program.

On this one particular day, I entered the reactor deck to find that overnight the reactor dome was removed, as was the steam separator and dryer – the reactor was wide open. This was a *definite* setback to my project where the 7.5 million gallons of ultra-pure water I was storing was intended to hydraulically *test* the reactor pool with the reactor *sealed* – obviously I was 'bumped'. Around the fenced perimeter of the reactor pool, some 40 or so feet above the reactor's top flange, stood a large number of individuals, the vast majority of whom I did not recognize. This latter fact was odd in itself since for the project of this magnitude that spanned a duration in excess of a decade from concept to completion, *everyone* was deemed to be part of 'the nuclear family', that is, everyone knew and recognized everyone else. Those not recognizable meant that they were either outside industry consultants, client home office representatives or NRC officials. On this particular day, they were all three, but at least I recognized one particular individual, who happened to be a Group Lead from the site's Quality Control Department. As well as having an inordinate number of unrecognizable individuals crowding around the reactor pool, the extraordinarily deafening sound of a huge rushing waterfall of Niagara quality was clearly evident – obviously a test of the reactor internals was underway. Making way to my QC co-worker, I noted that he had an unenviable expression of dismay on his face, this begged me to approach and ask what the apparent 'situation' was. He told me to peer inside the reactor and describe to him what I saw. I did, replying that I was observing an immense volume of cooling water being sprayed onto the top core plate by both core spray headers (each formed a concentric circumferential ring along the reactor's inside perimeter). He then re-stated the question, this time a bit more 'pointedly'. I took a little more time, responded in kind as before, but added that the volume of injected water at the proximal ends of the headers was visibly *greater* than at the headers' distal ends. He concurred, adding that design documents and operating procedures <u>required</u> that the volume of injected water be uniform over the <u>entire</u> length of each header. Knowing that his work was just beginning, and that he had others to deal with at present, I thanked him for his time and added that if he required any assistance from my Department to solve this issue he was

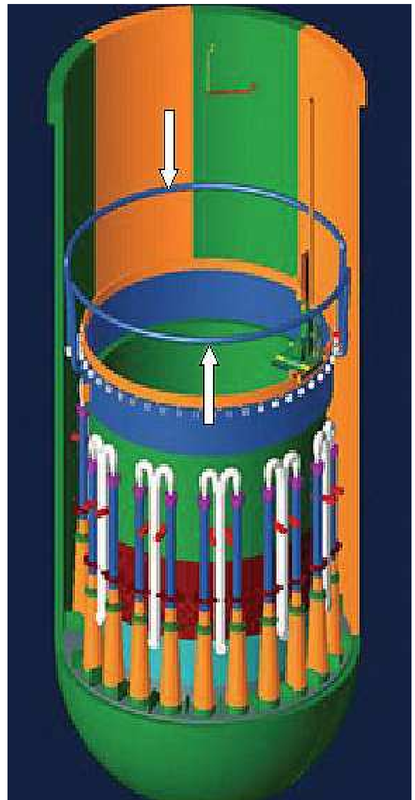

Fig. 2 Arrows illustrate the location of Top Core Plate Core Spray Headers. This diagram is of an older model BWR with only one Spray Header. The second header that I observed in a newer model Mark 5 BWR would be just above the one depicted in this diagram.

welcome to make the request and we would do what we could to solve it. I then left the scene, placing the event in the back of my mind to mull over later when I had a spare moment, which eventually I did. I now had to return to my Department Scheduler, have him assess the impact of the Core Spray Header issue on my project and recast the hydrotest of the reactor pool to a later date.

Late in the day, as I reviewed what I recalled from the supposedly 'failed' spray header test, it occurred to me that both circumferential headers were *uniformly* perforated *by design* with consistently located and sized sparge holes, which is from where the injection water exited. Running a few fluid dynamics equations through my mind, considering the inside diameter of the headers, the uniform size and propagation of the sparge holes and the overall quantity of water being injected, I quickly concluded that it was literally *impossible* for water to be injected uniformly over each header's length. Knowing that the degradation of in-pipe pressure would be extremely great (due to the enormous volume of fluid being ejected through each sparge hole), I knew that the in-pipe pressure at the distal end of each header would *have to be far less* than at the proximal end, meaning that with uniformly positioned sparge holes, there was no possibility for fluid injection to be consistent or uniform over the entire length of each header. It literally violated the laws of Physics and Fluid Dynamics for this to be so – the test *had to fail, it was inevitable!*

In time, the individuals involved with the test and header designs solved their spray uniformity issue to everyone's satisfaction, this without my involvement or that of my Department. However, without my knowing it at the time, this singular event became the initial 'spark', the genesis, for the creation of the SPARGE™ FEA compressible fluid injection computer program – some 30+ years *before* work on developing the program even started!

2. IMPETUS

Time marched on, and with the accidents at TMI and Chernobyl, the decline and eventual implosion of the Nuclear Industry was all but a certainty. Thousands of incredibly talented engineers were negatively affected, and I'd say that I wasn't but if I did, it wouldn't be true. I *was* affected, but I *moved on* to different experiences, different 'adventures', even to a different industry – the Environmental Industry. A decade or so after the Core Spray Injection Header test and the subsequent completion of five extremely successful commercial 'nukes', I was now the Operations Manager of one of the Country's top-ten environmental remediation firms. As well as managing the operations of the company's Government Projects Division across our entire country, I also ran corporate Engineering. Being permitted full rein to construct the Division as I chose, I elected to use the successful operational model of which I was familiar in the nuclear industry, and in this respect, I also chose to employ the most skilled and experienced engineers, scientists, chemists, estimators, schedulers and administrators that I could locate as subordinates. This pleased our client immensely, as it did our 'bottom line'. As I mandated, and contrary to past practice, every environmental remediation project was run as a *business* – as an actual *remediation project*, not a run-on seemingly endless experimental 'excursion' of continual groundwater and soil sampling that did nothing to clean up any contamination but merely ran up client costs while driving corporate profits down. Through a constant cultural evolution focusing everyone on what our projects' goals were, especially that of *cleaning up our country's environmental ills*, in time the Division became a model of what to do, shunning the Industry's pervasive practice of creating go-nowhere, financially wasteful research projects out of each pseudo-cleanup effort. I refused to accept the 'status quo, business as usual' culture that pervaded the Industry, opting for actionable engineering innovation that produced clearly evident, technically sound, scientifically defensible results. As far as I was concerned, the days of 20-plus-year long run-on, do nothing, no result groundwater pump-and-treat projects were over!

To enhance team morale amidst all of the cultural changes being made, I decided to do something that set the corporate high echelon on their ear – I set up a picnic table near some trees so employees could have a nice change of pace in the middle of the day and eat lunch *as a team* while enjoying the environment we were all changing for the better. I made it a point to be there each day, as an example for all. If the 'top guy' could roll up his sleeves and eat a homemade lunch outdoors, I thought that all the inquisitive minds within couldn't resist and would soon follow suit. Sure enough, after a month of this simple action, the need for additional tables grew from one to three, the majority of the office's staff looked forward to the break from the tedium indoors; some read, some set up daily chess matches, others played cards. All in all, corporate work ethic increased dramatically while overall stress dropped. The increase in camaraderie was palpable, former personal petty biases evaporated and everyone began to view everyone else as a fellow *human being*, with the same general issues of life as they had, all searching for friendships, all looking to conquer each's own problems of daily living.

During one particular lunch encounter, a visiting member of my team named Kevin from a distant satellite office happened to mention in passing that his *commercial* project involving the clean-up of an assortment of spilled petrochemicals beneath a large neighborhood appeared to be 'on track'. His statement floored me at the time as I recalled no commercial project under his purview at the time, nor any project involving spilled gasoline under homes anywhere. When he included in his discussion that the installation of the horizontal air sparge (HAS) well was proceeding on schedule, I had to interrupt and ask what the heck he was talking about, what project this was, and how the project's design had *not* been done through Central Home Office Engineering, and these were just for starters. He explained that the project was procured by himself personally through the locality months before I had come on board with the firm, and that he was well within his purview to complete this prior executed contract as he and his office deemed fit. OK, having 'won' this initial point on a technicality, I began to ask him about his remediation system design and what it involved. "What's your remediation strategy, how are you planning to execute it?" I asked. "Using bioremediation with a single horizontal air sparge well." "How large is the well?" I asked. "Two inch diameter with a well screen of

800 feet (!). The well's overall length is 1000 feet (!!)". "What's the well's wall thickness, and the screen's open area percentage?" I continued. "I don't know, they're not important." "Who did this '*design*'", I countered. "The well driller", was the reply. "Alright, what technical expertise does this well driller have in Mechanical Engineering, specifically Compressible Fluid Dynamics?" I wondered out loud. "None, he just has a high school education. But he's installed a slew of these wells all over the West Coast so I know that he knows what he's doing". "How *exactly* are you assured that he 'knows what he's doing', Kevin? How do *you* know that you'll get air to sparge in total *and* at the exact rate you'll need per-foot all the way to the end of your 800 foot long screen; after all that's over two and one-half lengths of a football field?"

Asking that last question, I was concurrently pointing my index finger out beyond the location at which everyone was sitting. Eight hundred feet of well screen put us beyond the entire border of our company's office property, across the adjacent 2-lane highway, the abutting median strip and its adjacent two-lane road going in the opposite direction, through the front parking lot of the business across the highway, under their entire building and into their back yard! And that's without considering the system's buried proximal header of *at least* 200 feet that would have to be run from the well head to the beginning of the first foot of well screen.

"Kevin, the well's *only* two inches in diameter, less than the diameter of my forearm. How do you *know* you'll get *any* air past the first 100 feet, let alone all the way to the 800-foot mark? Fluid dynamically that's all but impossible." I remarked. Kevin was speechless.

Literally having an envelope in my coat pocket from a trip to the mailroom just before lunch, I began to jot down some simple compressible gas flow equations, including several related to orifice flow and friction head loss. Asking Kevin what his design applied well head pressure was (he had no clue what it was going to be), making some assumptions for what this pressure *could be* within the limits of ASME-rated positive displacement blowers, I quickly came to the conclusion that there would be *absolutely* no possibility that his two inch diameter horizontal air sparge well would be able to inject *any* air beyond 200 feet or so at most. Listening in on our conversation happened to be a group lead from another Department, Sharon, who said not one word during our exchange. But after the *impromptu* tete-a-tete broke up, as we were walking up the stairs to our individual offices, Sharon broke the awkward silence and stated that she agreed with me 100% *technically* that the project would be (in her words) "...an unmitigated disaster..." These words I thought were profound (for a lack of a better phrase), for as capable as she was in her areas of expertise, she had no technical background of any kind – she was the Head of Accounting. Yet, with admittedly no technical background or education in engineering, fluid dynamics or designing remediation systems, she could readily foresee that the project would be a failure.

Try as I could to bring sanity and intellect to bear and stop the project from progressing down its seemingly inevitable path, momentum on his side, it proceeded as Kevin had planned, and yes it *was* the disaster that I predicted. The 'horizontal well air sparge system' failed miserably, and cleanup took forever; I sincerely doubt it was a total or even near-total cleanup at that. However, the greatest 'casualty' in all of this, that all but a handful seemed to grasp or even care about, was Mother Earth and our environment, all the flora and fauna that we took an unabridged if not unspoken oath to protect and render pristine.

The purpose of this story is twofold. First, it demonstrates the utter frustration I faced on a daily basis in the Environmental Industry where individuals were given the authority to make technical and business-related decisions, who in truth most of whom had absolutely <u>no</u> expertise to be involved in *any* project in *any* way at this level. It exemplifies the fact that the Industry as a whole was in a complete shambles technically, with the wrong individuals making highly impactful engineering decisions they had no competence in making and yet corporate culture across the <u>entire</u> Industry had *evolved* to not only permit it, but *encourage* it. Second, remediation projects were *never* viewed as actual business ventures of a technical *engineering* nature, or (more importantly) with an unwavering conviction to actually clean up contaminated sites for the good of our planet and *all* of the creatures therein and thereon either <u>on time</u> and/or <u>on budget</u> – they were viewed as geologic investigative 'excursions'. Costs of doing business were never considered, technical unknowns, voids and requirements were not even on the plate to discuss, schedules were ignored, and worst of all, the absolutely wrong individuals were employed allowing 'plausible deniability' for all involved when the crap hit the fan and heads were being searched for to roll. Having a well driller design *anything* was just insane in my view, it was akin to having a delivery truck driver design the enriched nuclear fuel bundles for a nuclear reactor or the LOX tanks for the Space Shuttle – these analogies are <u>not</u> that far off.

Over time, the impact of poor decisions intertwined with incompetence and *complete* irresponsibility for the debacle yielded one of the worst remediation projects I can recall from this Company. It was an impactful learning experience for me in what <u>not</u> to do, so much so that years later I can vividly recall the discussion at that picnic table. It also did something quite positive, for this one episode in what *not* to do became the impetus for my later creating the SPARGE™ suite of horizontal well compressible fluid remediation system design and analysis programs. Within a short few years after this experience I left the Company and began my own small Engineering Consulting firm, specializing in solving the most difficult of the difficult technical problems across numerous industries, including those unsolvable problems in environmental remediation that eluded all other companies for decades before. Part of my own Corporate Ethic was solving the problem of how *exactly* to design, construct, install and run a horizontal well remediation project <u>anywhere</u> and under <u>any</u> circumstances the <u>right</u> way, whether the cleanup required injecting a gas (or combination of gases), withdrawing offgas, injecting any liquid, or withdrawing the same. When I express now that at that time, NO environmental firm had *any* clue how to design such systems, let alone *guarantee* that they would work, I am not pulling the wool over your eyes. Expending an inordinate amount of effort researching developments in Engineering System Design and Analysis, specifically involving Compressible Fluid Dynamics in the Environmental field, I discovered that major firms, including some outside the industry itself spent *years* of effort trying to solve this exceedingly difficult engineering design issue. In fact, several major top-ten Engineering firms spent *years* of time, *millions of dollars* and thousand of man-hours trying to solve the 'how do you design a horizontal distributed gas injection or extraction system', only to fail. All eventually concluding that the job was *impossible* to solve. I refused to accept this defeatist attitude – if we can send Man to the Moon, we can solve the problem of how to design *any* horizontal well remediation system on this Earth. And, if these large firms tried and failed, I'll just have to 'give it a go' and do it myself.

And, that's what I did. Reference books under my arm, degree and PE licenses on the wall, I decided to solve the horizontal well compressible fluid flow design problem. After seven and one-half years I was done; SPARGE™ was born.