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- (71) Applicant: WEATHERFORD TECHNOLOGY HOLDINGS, LLC [US/US]; 2000 St James Place, Houston, Texas 77056 (US).
- (72) Inventors: SHAHRI, Mojtaba; 6550 W. Sam Houston Pkwy. N, Suite 250, Houston, Texas 77041 (US). HUANG,

Jian; 6550 W. Sam Houston Pkwy. N, Suite 250, Houston, Texas 77041 (US). SMITH, Clayton; 6550 W. Sam Houston Pkwy. N, Suite 250, Houston, Texas 77041 (US). FRAGACHAN, Francisco; 6550 W. Sam Houston Pkwy. N, Suite 250, Houston, Texas 77041 (US).

(74) Agent: MCDERMOTT, Sean P.; Blank Rome LLP, 717 Texas Ave, Ste 1400, Houston, Texas 77002 (US).

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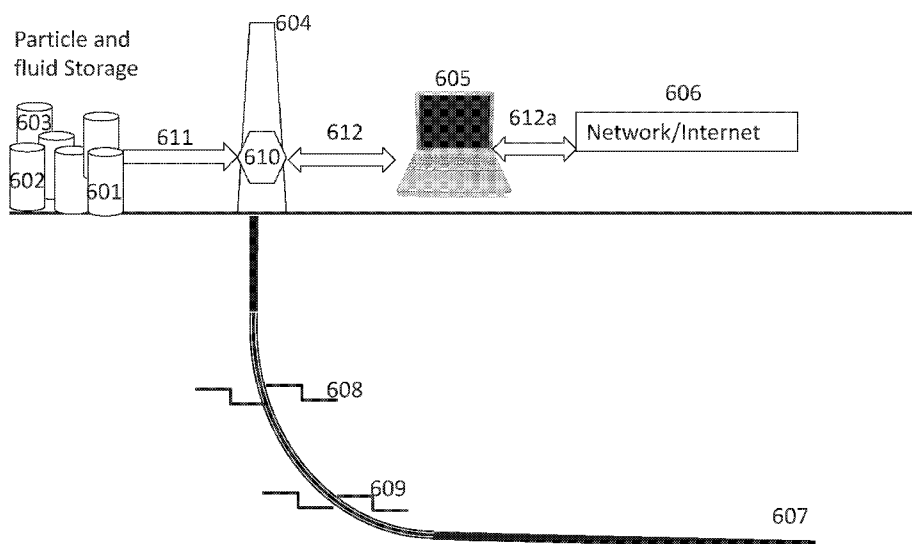


FIG. 6

(57) Abstract: The disclosure pertains to the increasing the amount of stimulated efficiency and production from a given well area by determining a number of diverter slugs and the timing for the injection of the slugs for the given well area. A number of data sets are determined using Monte Carlo analysis, each data set including a quantity of diversion slugs and the timing for the injection of the diversion slugs. A simulation is performed on a plurality of the data sets to determine the production outcome of employing the data set in a stimulation job. The results of the simulation are used to determine the optimized data set for the stimulation job.



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**SYSTEMS AND METHODS FOR OPTIMIZATION OF THE NUMBER OF
DIVERTER INJECTIONS AND THE TIMING OF THE DIVERTER INJECTIONS
RELATIVE TO STIMULANT INJECTION**

By: Mojtaba Pordel Shahri, Jian Huang, Clayton S. Smith and Francisco E. Fragachan

BACKGROUND

[0001] Inventions disclosed herein relate to stimulation of hydrocarbon wells using diverters and evaluating and optimizing the efficiency of such stimulation. Other inventions also relate to the field of fluid flow diversion by use of mechanical blocking agents, such as degradable, solid-particle diverting agents. One particular example of products in this field is Weatherford International's TBlockSure® product line. At the time of this filing, TBlockSure® is a trade name given to a suite of self-degradable, polymer-based, temporary diversion materials that are useful in a number of Oil and Gas operations, primarily to facilitate the flow of fluids into areas of the reservoir where they would not normally go based upon fluid dynamics. Fluids that are introduced into a reservoir, for purposes such as stimulation, typically take the path of least resistance and therefore will frequently go into areas where there are open flow paths. These areas of least resistance are not necessarily the areas targeted for stimulation and/or treatment (e.g., to increase production or target formation damage). To counteract this phenomenon of fluid flowing in the path of least resistance, mechanical diversion techniques may be employed. However, a variety of factors, including production need, regulatory requirements, or environmental concerns may necessitate the physical removal of the mechanical diversions. The phenomenon may also be counteracted through the use of temporary degradable diversion systems, for example blocking agents that degrade with time, heat, pressure, or other natural or augmented treatment. These temporary degradable diversions work well for zonal isolation and do not need to be removed (e.g., from a well) mechanically after the intervention since they are capable of degrading (e.g., with time) from a solid polymer state into a fluid, such as a clear non-damaging liquid monomer solution.

[0002] The chemistries used for degradable diversions, such as TBLOCKSURE® product chemistries, may be designed to exhibit a variation of jamming, sealing, and degrading properties. For example, diversion agents may be capable of degrading across a wide temperature range to monomer species that will not damage a hydrocarbon bearing formation. In addition, diversion agents may be designed to accommodate significant temperature variations (e.g., from 80°F up to 325°F) with variable degradation times (e.g., between a few hours to a few days). This may be achieved, for example, through the selection of polymer chemistry, shape, size, or other particle parameter.

[0003] However, despite the useful design of these various degradable polymers, the successful deployment and use of this technology in the field (*e.g.*, as a temporary diverter) is heavily dependent upon optimization that contemplates engineering and geo-mechanical design as it relates to the particulars of the environment. In simpler words, the potential of modern degradable diversion agents is extremely limited in the absence of timely-created workflows and processes that contemplate, in correct proportions, job-specific factors as well as historical field data, experimental data, modeling, and specifically beneficial mathematical analysis.

[0004] Furthermore, the effectiveness of diversion application may be expressed as pressure build up in the well and the effectiveness of corresponding stimulation using production data (in an area where the diversion fluids are redirected). However, the efficiency of diverters under downhole condition may not be assessed accurately using these methods in operational environments.

[0005] Moreover, when using diverter injections in the process of well stimulation, it is most common to divide stimulant injection time evenly and inject diverters between stimulant injections. For example, if stimulants will be injected for 40 minutes, a common operation is to stimulate for 20 minutes, then inject diverters, then stimulate for 20 minutes again. Of course, the 40-minute stimulation time may be divided evenly in other ways (*e.g.* 4X10).

SUMMARY

[0006] In any application where fluid paths are employed, there may be a need or desire to divert fluid around openings that might undesirably absorb fluid flow. These applications may include hydrocarbon production operations such as drilling, fracturing, or stimulating wells, but they may also include any processes where the control of fluid flow is useful. Therefore, applications of the embodiments herein may reach fluid flow in any context such as in natural formations, man-made formations, man-made facilities (*e.g.*, conduits or casings of any kind), or any combination of the foregoing.

[0007] Experimental operations have shown that, for a given well's conditions and planned stimulation time, the efficiency of hydrocarbon production from a given area of a well vary with the number of diverter injections and the timing of those injections relative to stimulant injection. For example, for a given well, the planned stimulant injection time may be 40 minutes. The most optimized production may result from stimulating a plan of the following: stimulating for 15 minutes; injecting diverters; stimulating for 7 minutes; injecting diverters; stimulating for 3 minutes; injecting diverters; and finally, stimulating for 15 minutes again. However, given the

current practices in the hydrocarbon production industry, there is very little likelihood that the optimized stimulation plan will be found or used.

[0008] Some embodiments of the disclosure provide for determining, for a given well area and associated parameters, a number of diverter injections and the timing of those injections relative to stimulant injections in the well. In particular one or more embodiments, statistical techniques such as Monte Carlo method might be used to determine multiple sets of data, where each data set includes a number of diverters slugs/injections and the timing of those diverter injections relative to stimulant injections. The data sets are tested through a simulation to determine which data set will yield the best production result. Once determined, the best data set is used in stimulating a well.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0009]** FIG. 1 shows a representative computer node that may be used, for example, as an end-user machine or a developer machine.
- [0010]** FIG. 2 shows an illustrative network environment associated with embodiments of the invention.
- [0011]** FIG. 3 shows an illustrative software layer and architecture diagram.
- [0012]** FIG. 3A show an overview of aspects of projects efficiency.
- [0013]** FIGs. 4A and 4B show illustrations of jamming.
- [0014]** FIG. 4C shows a process or workflow in accordance with one or more embodiments.
- [0015]** FIGs. 5A and 5B show illustrations of jamming and sealing.
- [0016]** FIG. 6 shows an exemplary well site arrangement.
- [0017]** FIGs. 7A, 7B, 7C, 7D, 7E, and 7F show processes or workflows in accordance with one or more embodiments.
- [0018]** FIG. 8 shows a graph related to particle sizing.
- [0019]** FIG. 9 shows a graph related to particle sizing and pressure build-up.
- [0020]** FIG. 10 shows processes or workflows in accordance with one or more embodiments.
- [0021]** FIG. 11 shows another overview of diverters application and design.
- [0022]** FIG. 12 shows the relationship between stages and clusters in an exemplary well.
- [0023]** FIG. 13 shows the figure 12 juxtaposed with a table showing an injection plan for tracer and/or fracturing fluid.
- [0024]** FIG. 14 through 16 show exemplary synthetic tracer logs.
- [0025]** FIG. 17 shows an injection plan for tracer and/or fracturing fluid.

- [0026] FIG. 18 shows an exemplary synthetic tracer log.
- [0027] FIG. 19 – 20 show exemplary processes associated with the inventions disclosed.
- [0028] FIG. 21 shows the process of FIG. 7 juxtaposed with the process of FIG 19.
- [0029] FIGS. 22a, 22b and 22c show stimulation plans or logs.
- [0030] FIG. 23a shows a production area and associated information about the production area.
- [0031] FIGS. 23b and 23c illustrate the results of a stimulation project.
- [0032] FIG. 24 illustrates a production area and associated information about the production area.
- [0033] FIGS. 24a, 24b, 24c and 24d each show stimulation plans or logs along with an illustration of a potential result of employing the stimulation plan.
- [0034] FIG. 25 shows a process associated with embodiments of the disclosure.
- [0035] FIG. 26 shows a table of test data sets.

DETAILED DESCRIPTION

[0036] This disclosure pertains to systems, tools, machinery, methods, and computer-readable media pertaining to an intelligent and staged design and application of fluid path diversion in geological structures. In particular, many embodiments of the invention relate to processes and workflows embodying stimulation engineering optimization design. Further, some embodiments relate to the use of oil field tools, including mechanical and fluid dynamic tools in conjunction with analysis and design flow that is computer aided or computer implemented. In some embodiments, there is envisioned an automated intelligent workflow or process with limited human involvement whereby oil field equipment and resources are directed by intelligent computer control, which uses dynamically gathered-on-site information along with field data and specified types of modeling and analysis to direct or control the creation and maintenance of diversion systems in fluid passageways, such as wells.

[0037] In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the disclosed concepts. As part of this description, some of this disclosure's drawings represent structures and devices in block diagram form in order to avoid obscuring the novel aspects of the disclosed concepts. In the interest of clarity, not all features of an actual implementation are described. Moreover, the language used in this disclosure has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject

matter, leaving resorting to the claims as a potential necessity to determine such inventive subject matter. Reference in this disclosure to “one embodiment” or to “an embodiment” or “embodiments” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosed subject matter, and multiple references to “one embodiment” or “an embodiment” should not be understood as necessarily all referring to the same embodiment. Furthermore, unless otherwise stated, use of the word “or” herein is intended to state options that may be applied separately or together (*i.e.*, unless otherwise stated, “or” herein does not indicate a mutually exclusive choice).

[0038] It will be appreciated that in the development of any actual implementation (as in processes, machinery, tools, or any software and/or hardware development project), numerous decisions must be made to achieve the developers’ specific goals (*e.g.*, compliance with system- and business-related constraints), and that these goals may vary from one implementation to another. It will also be appreciated that such development efforts might be complex and time-consuming, but would nonetheless be a routine undertaking for those having the benefit of this disclosure and being of ordinary skill in the design and implementation of diversion systems and related technologies.

Exemplary Hardware and Software

[0039] The inventive embodiments described herein may have implication and use in and with respect to all types of devices, including single- and multi-processor computing systems and vertical devices that incorporate single- or multi-processing computing systems. The discussion herein is made with reference to a common computing configuration that may be discussed as a server, a software development system, or an end-user system. This common computing configuration may have a CPU resource including one or more microprocessors. This discussion is only for illustration regarding sample embodiments and is not intended to confine the application of the invention to the disclosed hardware. Other systems having other known or common hardware configurations (now or in the future) are fully contemplated and expected. With that caveat, a typical hardware and software-operating environment is discussed below. The hardware configuration may be found, for example, in a server, a workstation, a laptop, a tablet, a desktop computer, a gaming platform (whether or not portable), a television, an entertainment system, a smart phone, a phone, or any other computing device, whether mobile or stationary.

[0040] Referring to FIG. 1, the disclosed embodiments may be performed by representative computer system **100**. For example, the representative computer system may act as a server, a software development platform, or an end-user device. System **100** may be embodied in any

type of device, such as a general purpose computer system, a television, a set top box, a media player, a multi-media entertainment system, an image processing workstation, a hand-held device, or any device that provides software services to users and/or other computers. Computer system **100** may include one or more processors **105**, memory **110** (**110A** and **110B**), one or more storage devices **115**, and graphics hardware **120**. Computer system **100** may also have or be connected with device sensors **125**, which may include one or more of: any known well site or oil field sensor, depth sensors (such as a depth camera), 3D depth sensor(s), imaging devices (such as a fixed and/or video-capable image capture unit), RGB sensors, proximity sensors, ambient light sensors, accelerometers, gyroscopes, any type of still or video camera, LIDAR devices, SONAR devices, microphones, CCDs (or other image sensors), infrared sensors, thermometers, *etc.* These and other sensors may work in combination with one or more GPUs, DSPs, or conventional microprocessors along with appropriate programming so the sensor outputs may be properly interpreted and/or combined and interpreted.

[0041] Returning to FIG. 1, system **100** may also include communication interface **130**, user interface adapter **135**, and display adapter **140** – all of which may be coupled via system bus or backplane **145**. Memory **110** may include one or more different types of media (*e.g.*, solid-state, DRAM, optical, magnetic, *etc.*) used by processor **105** and/or graphics hardware **120**. For example, memory **110** may include memory cache, read-only memory (ROM), and/or random access memory (RAM). Storage **115** may include one or more non-transitory storage media including, for example, magnetic disks (fixed, floppy, and removable) and tape, optical media such as CD-ROMs and digital video disks (DVDs), and semiconductor memory devices such as Electrically Programmable Read-Only Memory (EPROM) and Electrically Erasable Programmable Read-Only Memory (EEPROM). Memory **110** and storage **115** may be used to retain media (*e.g.*, audio, image, and video files), preference information, device profile information, computer program instructions organized into one or more modules and written in any desired computer programming language, and any other suitable data. When executed by processor **105** and/or graphics hardware **120**, such computer program code may implement one or more of the methods, workflows, or processes described herein. Communication interface **130** may include semiconductor-based circuits and may be used to connect computer system **100** to one or more networks. Illustrative networks include, but are not limited to: a local network, such as a USB network; a business's local area network; and a wide area network, such as the Internet; and may use any suitable technology (*e.g.*, wired or wireless). Communications technologies that may be implemented include cell-based communications (*e.g.*, LTE, CDMA, GSM, HSDPA, *etc.*) or other communications (Ethernet, Wi-Fi, Bluetooth, USB, Thunderbolt,

Firewire, *etc.*). User interface adapter **135** may be used to connect keyboard **150**, microphone **155**, pointer device **160**, speaker **165**, and other user interface devices such as a touchpad and/or a touch screen (not shown). Display adapter **140** may be used to connect one or more display units **170**. Communications interface **130** may also be used to exercise external control over outside items, such as pumps, valves, conveyances, motors, notification systems, other computers, storage containers, and anything else that may be controlled by a computer at a well site or in the oil field services industry.

[0042] Processor **105** may execute instructions necessary to carry out or control the operation of many functions performed by system **100** (*e.g.*, execution of formulas and modeling software). Processor **105** may, for instance, drive display **170** and receive user input from user interface adapter **135** or any other user interfaces embodied by a system, such as sensor interfaces or networked communication. User interface adapter **135**, for example, can take a variety of forms, such as a button, a keypad, a dial, a click wheel, a keyboard, a display screen, and/or a touch screen. Processor **105** may be any type of computing device, such as one or more microprocessors working alone or in combination with GPUs, DSPs, and/or system-on-chip devices such as those found in mobile devices. Processor **105** may include one or more dedicated GPUs or graphics subsystems that accept program instructions to create or alter display information such as pixels. In addition, processor **105** may be based on reduced instruction-set computer (RISC) or complex instruction-set computer (CISC) architectures or any other suitable architecture and may include one or more processing cores. Graphics hardware **120** may be special purpose computational hardware for processing graphics and/or assisting processor **105** in performing computational tasks. In some embodiments, graphics hardware **120** may include CPU-integrated graphics and/or one or more programmable GPUs. System **100** (implementing one or more embodiments discussed herein) can provide the means for one or more users to control the same system (*e.g.*, system **100**) or another system (*e.g.*, another computer or entertainment system) through user activity, which may include natural activity and/or predetermined gestures such as hand gestures. For example, a system may use sensors such as cameras to monitor a well site and interpret as input detected human or machine behaviors.

[0043] Various embodiments of the invention may employ sensors, such as cameras. Cameras and like sensor systems may include auto-focus systems to accurately capture video or image data ultimately used to interpret user intent or commands. Since the motion of the user may be based upon subtle activity in small regions in the captured images (*e.g.*, hands, fingers,

face, mouth, brow *etc.*) the autofocus system may be used to separately focus on multiple regions of the image in order to access better information.

[0044] Returning to FIG. 1, sensors **125** may capture contextual and/or environmental phenomena such as time; location information; the status of the device with respect to light, gravity, and the magnetic north; and even still and video images. In addition, network-accessible information, such as weather information, may also be used as part of the context. All captured contextual and environmental phenomena may be used to provide context to sensed activity or user activity or information about the sensed activity or user activity.

[0045] Output from the sensors **125** may be processed, at least in part, by processor **105** and/or graphics hardware **120** and/or a dedicated image processing unit incorporated within or without system **100**. Information so captured may be stored in memory **110** and/or storage **115** and/or any storage accessible on an attached network. Memory **110** may include one or more different types of media used by processor **105**, graphics hardware **120**, and sensors **125** to perform device functions. Storage **115** may store data such as media (*e.g.*, audio, image, and video files); sensor data; computer program instructions; and other software, including database applications (*e.g.*, a database storing field data or historical data), preference information, device profile information, and any other suitable data. Memory **110** and storage **115** may be used to retain computer program instructions or code organized into one or more modules in either compiled form or written in any desired computer programming language. When executed by, for example, processor **105**, such computer program code may implement one or more of the acts, functions, or models described herein (*e.g.*, DEM or CFD analysis).

[0046] FIG. 2 depicts illustrative network architecture **200**, within which the disclosed techniques may be implemented and the disclosed hardware may reside. This illustrative network **200** may include a plurality of networks **205**, (*i.e.*, **205A**, **205B**, and **205C**), each of which may take any form including, but not limited to, a local area network (LAN) or a wide area network (WAN), such as the Internet. Further, networks **205** may use any desired technology (wired, wireless, or a combination thereof) and protocol (*e.g.*, transmission control protocol, TCP). Coupled to networks **205** are data server computers **210** (*i.e.*, **210A** and **210B**) that are capable of operating server applications such as databases and also capable of communicating over networks **205**. One embodiment using server computers may involve the operation of one or more central systems to process models distribute the processed information to nodes on a network.

[0047] Client computers **215** (*i.e.*, **215A**, **215B**, and **215C**), which may take the form of any intelligent machine, may also be coupled to networks **205**, and/or data server computers **210**. In

some embodiments, network architecture **210** may also include network printers such as printer **220** and storage systems such as **225**, which may be used to store multi-media items or other data that are referenced herein. To facilitate communication between different network devices (*e.g.*, data servers **210**, end-user computers **215**, network printer **220**, and storage system **225**), at least one gateway or router **230** may be optionally coupled there between. Furthermore, in order to facilitate such communication, each device employing the network may comprise a network adapter circuit and related software. For example, if an Ethernet network is desired for communication, each participating device must have an Ethernet adapter or embedded Ethernet-capable ICs. Further, the devices may carry network adapters for any network in which they might participate (including, but not limited to, PANs, LANs, WANs, and cellular networks).

[0048] As noted above, embodiments of the inventions disclosed herein include software. As such, a general description of common computing software architecture is provided as expressed in the layer diagrams of FIG. **3**. Like the hardware examples, the software architecture discussed here is not intended to be exclusive in any way but rather illustrative. This is especially true for layer-type diagrams, which software developers tend to express in somewhat differing ways. In this case, the description begins with layers starting with the O/S kernel, so lower level software and firmware has been omitted from the illustration but not from the intended embodiments. The notation employed here is generally intended to imply that software elements shown in a layer use resources from the layers below and provide services to layers above. However, in practice, all components of a particular software element may not behave entirely in that manner.

[0049] With those caveats regarding software, referring to FIG. **3**, layer **31** is the O/S kernel, which provides core O/S functions in a protected environment. Above the O/S kernel is layer **32** O/S core services, which extends functional services to the layers above, such as disk and communications access. Layer **33** is inserted to show the general relative positioning of lower level services such as Open GL library and similar application and framework resources. Layer **34** is an amalgamation of functions typically expressed as multiple layers: applications frameworks and application services. For purposes of our discussion, these layers provide high-level and often functional support for application programs which reside in the highest layer shown here as item **35**. Item **C100** is intended to show the general relative positioning of the application software, including any geoscience related application software or modeling and simulation software described for some of the embodiments of the current invention. In particular, in some embodiments, a geoscience software application is used to interact with the user through user interfaces facilitated by the host device. The geoscience application software

allows the user to provide or arrange input parameters or settings and receive output assisting with diversion methodologies, materials, or techniques. The output may be implemented in any or three ways: automatically by the computer's control of tools and equipment; manually, where the user or the user's proxy is provided with instructions for implementing a diversion or one or more aspects thereof; or a combination of the former, where the computer controls some functions and/or tools or equipment and provides instructions or indications for the user that facilitate the process.

[0050] In some embodiments, application layer geoscience software may rely on frameworks and resources in one or more of the layers shown as **34** or **33**. Furthermore, in some embodiments, the invention or parts and embodiments thereof may be implemented as a resource and/or framework for use with application programs that use an API or interface provided by the invention. For example, any application offering geoscience functionality may use a framework and API to access diversion techniques, methodologies, modeling, simulations, functions, or assistance.

[0051] While the ingenuity of any particular software developer might place the functions of the software described at any place in the software stack, the software hereinafter described is generally envisioned as any of: (i) user facing, for example, to allow user operation of geoscience functionality; (ii) as a utility, or set of functions or utilities, beneath the application layer, providing geoscience or diversion resources to application programs or other programs; and (iii) as one or more server applications for providing the same functions and/or services to client devices over a network. Furthermore, on the server side, certain embodiments described herein may be implemented using a combination of server application level software and database software, with either possibly including frameworks and a variety of resource modules.

[0052] No limitation is intended by these hardware and software descriptions and the varying embodiments of the inventions herein may include any manner of computing device such as Macs, PCs, PDAs, phones, servers, or even embedded systems.

Aspects of Project Efficiency

[0053] Referring to FIG. 3A, there is shown a block diagram providing exemplary illustration of four aspects of efficiency regarding fluid diversion projects. With reference to 3A1, slurry displacement efficiency relates to optimizing the parameters controlling slurry integrity during transportation from surface to downhole. Jamming and sealing efficiency 3A2 refers to diverting (or not) the flow of fluids such as hydraulic fracturing fluids from small apertures within a well so that different parts of the well may be stimulated and produced (or not) without losing flow or pressure due to undesired fluid paths. Stimulation efficiency 3A3 relates

to the effectiveness of diversion operations in isolating portions of the well and distributing fracturing fluids towards intact portion to enhance production. Finally, production efficiency 3A4 relates to the efficiency of the project in extracting hydrocarbons from the well or portion thereof. The discussion below relates first primarily to jamming and sealing efficiency 3A2 and then transitions to stimulation efficiency 3A3. However, the primary focus on these topics is not intended to exclude or detract from thoughts or inventive concepts conveyed with respect to production efficiency 3A4, slurry displacement efficiency 3A1, or any other topic discussed herein.

Diversion

[0054] In some embodiments of the disclosure, a successful diversion can be created by understanding the jamming and sealing mechanisms that occur at the entrance of a fluid path. By understanding the physics of the fluid flow and the environment, models may be used to optimize re-work operations so as to use the minimal amount of time and material, yet create a seal that can withstand high pressure differentials even at flow path openings materially larger than the mean particle size of the largest particle. In one embodiment, the average size of the largest particle size may be 3 to 7 times smaller than the opening. There are many complex factors that all affect the efficiency of diversion and they can all either be adjusted or accommodated to achieve minimal flow into highly conductive flow paths.

[0055] The current state of the art numerical simulations for fluid path analysis are based on coupled Computational Fluid Dynamics (CFD) and Discrete Element Methods (DEMs). CFD is a branch of fluid mechanics using algorithms as well as numerical analysis to analyze (or solve) fluid flow inquiries or problems. CFD is a computer-based mechanism for making calculations to simulate interactions involving liquids, gases, surfaces, and boundary conditions. A DEM belongs to a well-known family of numerical methods used to compute particle motion and interaction. The models discussed herein may be used to better design and implement processes for controlling fluid diversion and pressure build-up. In many embodiments, coupled CFD and DEM analysis are used to understand and evaluate jamming and sealing mechanisms. For example, coupled CFD and DEMs may be used in some embodiments for probabilistic analysis regarding jamming and sealing in a particular diversion job.

[0056] Varying embodiments of the disclosure may use modeling engines, which may incorporate different scenarios so the factors affecting diversion efficiency may be optimized. By designing the application of chemistries, particle shapes, sizes, concentrations and ratios, as well as pressure, temperature, and other parameters, a diversion operation may be engineered and/or customized for the best result for each specific diversion job.

Jamming and Sealing

[0057] As discussed above, in some embodiments, significant mechanisms controlling a diversion process are jamming and sealing. Jamming refers to the formation of a stable jammed structure, which may in some embodiments form the base for an effective sealing mechanism. A jamming stage, in one or more embodiments, forms an initial “stable” structure in an opening, which may for example represent the outside or inside of a perforation, door, hole, fissure, natural fracture, hydraulic fracture mouth, *etc.* The stable structure or jammed state refers to a configuration where relatively large particles provide support for each other, remain stable, and do not pass through the existing opening.

[0058] Referring to FIG. 4A, there is shown an opening 401 having diameter D , where the opening is jammed with spherical particles 402, having diameter D' , where D' is substantially smaller than D . Of course, the shapes of the opening and the particles can vary and neither is necessarily a regular shape. For example, openings in geologic formations may embody any shape whether the openings are naturally occurring or are the result of human activity. Similarly, particles may be designed in any shape, including shapes that embody an aspect of randomness, such as a snowflake. Referring to FIG. 4B, there is shown another opening 405 with diameter D , where the opening 405 is jammed with star or pseudo-snowflake shaped particles having diameter D' . As is evident from FIGs. 4A and 4B, openings 401 and 405 appear stably jammed in that particles having diameter D' can no longer move through or about the opening (although no pressure capability is ascertainable from a drawing). Similarly, particles having sizes even somewhat smaller (*e.g.*, within an order of magnitude or more depending upon the specific configuration) similarly may not pass through the openings 401 and 405. However, fluids and substantially smaller particles (*e.g.*, multiple orders of magnitude smaller depending upon the configuration) may still pass through in small open spaces between D' -sized particles. Therefore stable jamming does not necessarily sufficiently restrict pressure communication for many embodiments of the disclosure or practical applications. For example, in some embodiments, pressure build-up required for successful practical application (such as a re-fracturing operation) may not be achieved by jamming.

[0059] With reference to FIG. 4C, an effective diversion over a given aperture or opening may be implemented in a two-phase process as shown. At phase 401, the aperture or opening is jammed and at phase 402, the aperture or opening is sealed. The process of FIG. 4C is not intended to require that the phases are performed either together, overlapping, or in mutually exclusive time periods. Any of these are possibilities contemplated by embodiments of the disclosure.

[0060] In order to create a seal over a stably jammed opening or to provide an increased pressure build-up, in some embodiments, a sealing operation may be implemented so that the fluid pathway between the jammed particles (*e.g.*, particles **402** and **406**) is either diminished or eliminated at desirable pressure levels. In one embodiment, smaller particles **510** (*e.g.*, smaller than *D'*) may be used to effectively fill the remaining fluid path as shown in FIGs. **5A** and **5B**. For example, as shown in FIGs. **5A** and **5B**, smaller particles may form a layer cake between and/or on top of larger particles and may “seal” all or most of the remaining porosity/fluid path. In this manner, pressure communication is reduced across the pressure differential shown in FIGs. **4A** and **4B**, and pressure build-up occurs. The ability to more accurately build and/or specify pressure build-up allows for more precise and efficient diversion implementation. For example, fracturing fluid may divert away from existing perforations; fissures; natural fractures; or any portion of a formation, such as geologic formations. With reference to FIGs. **5A** and **5B**, small sealing particles **510** are illustrated by way of example, while the remaining portions of FIGs. **5A** and **5B** analogize to FIGs. **4A** and **4B** respectively.

Sample Field Configuration

[0061] With reference to FIG. **6**, there is shown an embodiment of a field configuration for implementation in the hydrocarbon production industries. Drilling rig **604** is associated with equipment modules **610**, which may include common oil field equipment used to manually or automatically prepare material for introduction to the well and to introduce material to the well. Equipment **610** may include pumps, valves, blenders, and any other equipment or machinery known in the art for use at a well site or other location of a diversion job. Equipment **610** may also include items to facilitate removal of fluids and other materials from the well, which may include flow back lines, separators, plug catchers, chokes, tank batteries, production facilities and other equipment or machinery known in the art. Well **607** is shown as a directional well, but the embodiments herein may be applied to vertical, horizontal, or any well or opening in a formation where degradable polymers may be introduced. Well **607** has perpendicular apertures (*e.g.*, fissures) **608** and **609**, which are illustrated to represent areas of fluid porosity directed outside of the well bore. At the surface, containers **601**, **602**, and **603** respectively represent storage for diversion particulates, fluids (such as fracking fluids and mediums for the diversion particulates), and any other materials that may be desirable for use at the well site. The use of only three containers **601** – **603** is merely illustrative, as many embodiments of the disclosure contemplate as many containers as may be necessary to store any number of different materials, including multiple particulates (*e.g.*, various sizes, shapes, hardness, and degrading characteristics), multiple fluids (*e.g.*, various types of fluids and various viscosities), and many

other materials. Conveyance **611** provides a path from the stored material to the equipment module **610** so that materials may be automatically or manually conveyed for entry in the well. Conveyance **611** may include any number of pipes, pumps, valves, or other items to facilitate material movement. Computing device **605** is intended to represent computational capacity at the well site and may be in any known form, including the computing embodiments discussed above. Computing device **605** may include the software architecture described with respect to FIG. **3**, which may work in combination with the computer hardware to implement the computing tasks discussed herein, such as analysis, modeling, and sensing. Network **606** represents the ability to communicate offsite and access computing power (*e.g.*, servers) as well as network-based information (*e.g.*, over the Internet or a proprietary network). Network **606** may also take any known form and may also be a permutation of the networks discussed above. Conveyance **612** and **612a** may be electric or radio communication mediums, such as wires or wireless networking systems, such as PANs or WANs; including cell networks, such as LTE, 3G, Edge, or GPRS; but may take any form known or any form as discussed above for communications. Conveyance **612** and **612a** may be used to convey control from computer **605** or network resources to control equipment module **610** or any other equipment on site. In addition, or as an alternative, mere instructional information may be conveyed. Furthermore conveyance **612** and **612a** may be used to communicate information from the well or equipment to computer **605** or a network-based resource, which may include for example well logging information, any sensor information (such as pressures), equipment status, production data, and any other information available from the well or its attendant personnel and/or machinery.

Parameters Considered and/or Controlled For Diversions Involving Jamming and Sealing

[0062] Many embodiments of the disclosure envision accessing and manipulating all possible parameters related to creating and sustaining one or more diversions in a fluid passage system, such as a well. In one or more embodiments the following parameters are considered and/or manipulated as follows:

[0063] Particle size. Particle may be assessed by any known manner, such as diameter or circumference or averages of these and other measures across a population of particles. In some embodiments, particle size is evaluated as a ratio of the opening sought to be jammed or sealed. For example, FIG. **8** shows the probability of jamming as the ratio of particle size to opening size increases, as shown in FIG. **8**, as particle size increases relative to opening size, the probability of stable jamming also increases. Thus, some embodiments of the disclosure bias toward larger particles to increase the probability of jamming. In addition, some implementations of an

embodiment use only two particle sizes, a large particle size for jamming and a small particle size for sealing. In one particular embodiment, the small size is 100 mesh and the large size is 7 mesh.

[0064] Opening size. Opening size represents the size of the opening to be jammed and/or sealed. This may apply to openings in any context where diversion is desirable and is not confined to the hydrocarbon industry. However, in many embodiments of the disclosure, openings may refer to perforations, fissures, natural formations, or any aperture to be sealed. As discussed above, when the ratio of particle size to opening size increases, jamming probability also increases. Thus, for some embodiments of the invention, there is recognition of a decreased probability of stable jamming as opening size rises.

[0065] Particle shape. Particles may take any geometric shape or non-geometric shape, such as a snowflake. Many embodiments of the disclosure provide for optimizing the use of different particle shapes based on a combination of numeric, analytic, field, and experimental data. In addition, some embodiments of the disclosure may be based upon empirical data collected from limited testing. Using a spherical shape as a reference, the limited testing may provide an indication regarding jamming and sealing properties of different shapes. For example, in comparing the jamming related behavior of three particles, the inventors have found that spherical particles provided the lowest jamming probability, while quasi-spherical particles performed better, and non-spherical flakes performed best. Furthermore, the limited test indicated that the less spherical the particle, the larger the stable bridge that may be constructed with the particle. Similarly, the less spherical the particle, the lower the probability that no bridging will be possible. Some embodiments of the disclosure contemplate that less spherical shapes may lead to higher-pressure build-up. Therefore, in some embodiments, less spherical shapes are correlated with both more stable jamming probability and more effective sealing. Of course, while the results from this limited test and any future testing may bear on any particular embodiment, no testing detracts from the embodiments that rely on shape optimization based upon a combination of numeric, analytic, field, and experimental data. Using these techniques, any type of specific shape may be tested and modeled to determine specifically beneficial shapes for a given formation or diversion job. Finally, in some embodiments, a particle may be measured or judged as large based upon either its aspect ratio or its largest single dimension.

[0066] Particle friction coefficient: Particle friction coefficient refers to the friction coefficient between particles. The inventors have demonstrated that higher friction coefficients correlate with higher stable jamming probability and higher sealing probability. Thus, some

embodiments herein apply higher friction particles for increasing either or both of stable jamming probability or sealing efficiency and pressure build-up.

[0067] Particle density. In relevant part, particle density refers to the density of a particle relative to the carrier fluid. If the particle is denser than the carrier fluid, it tends to deviate from the flow of the fluid and is less likely to reach the opening absorbing fluid flow as desired for jamming. Therefore, in some embodiments of the disclosure, lower particle density (ratio to carrier fluid, *e.g.* approaching 1) is correlated with higher probability of stable jamming.

[0068] Particle concentration. Particle concentration refers to the mass or weight content of particles in a volume of fluid (*e.g.*, pounds per gallon or Kilograms per liter). In many embodiments, particle concentration levels may be optimized by determining the minimum concentration required to seal a specified opening. In other embodiments, particle concentration levels may be optimized by determining the minimum concentration required to seal a specified opening, given one or more other variable constraints such as time. In one or more embodiments of the disclosure, higher particle concentration is correlated with higher stable jamming probability.

[0069] Particle ratio. Particle ratio refers to the weight or volume percent ratio between different particles held in the same carrier fluid. Thus, for example, in a two-particle mix, having one large particle (approx. 7 mesh) type and a small particle (approx. 100 mesh) type, particle ratio refers to the weight or volume percent ratio between small and large particles. The inventors have found that a greater presence of small particles reduces probability of stable jamming, but increases the efficiency of sealing and pressure build-up. Therefore in some embodiments, higher ratios of smaller particles are correlated with lower stable jamming probability, and higher probabilities of sealing. In addition, in one or more embodiments, numerically weighted size average is correlated with stable jamming probability and inversely correlated with sealing, so that the numerically weighted size average of all particle types in the carrier fluid is associated with stable jamming probability (*i.e.*, higher average = higher stable jamming probability) and inversely correlated with sealing (*i.e.*, higher average = lower probability of sealing). Furthermore, the inventors have determined that a band of small particle ratios may facilitate using the same mixture for sealing and jamming (*e.g.*, where the small particle is 100 mesh and the large particle is 7 mesh). For example, ratios in the band from X% small particles to (X + Y)% small particles may best facilitate jamming and sealing with the same mixture. In some embodiments, the values of X and Y may be found by experimentation and simulations.

[0070] Flow rate. Flow rate refers to the amount or volume of material movement over a specified period of time. For example, a mass flow rate may be expressed as Kilograms per minute, while a volume flow rate may be expressed as liters per minute. Flow rate is a parameter that may be useful in designing diversion systems and particularly with respect to jamming and/or sealing analysis.

[0071] Fluid viscosity: Viscosity refers to the thickness of a fluid and in particular the fluid property that resists forces tending to cause the fluid to flow. Viscosity is a parameter that may be useful in designing diversion systems and particularly with respect to jamming and/or sealing analysis.

[0072] In addition to the foregoing parameters and embodiments, varying embodiments of the disclosure seek to measure, contemplate and/or manipulate one or more of the following diversion-related parameters:

- a) particle size (either for jamming or sealing);
- b) perforation size of the openings to be sealed;
- c) size of the fluid path on the proximal side of the intended work area;
- d) size of the fluid path on the distal side of the intended work area;
- e) particle shape(s) (*e.g.*, different shapes or the cylindrical aspect of a particle shape);
- f) friction coefficients between like-type particles;
- g) friction coefficients between each pairing of different types of particles available;
- h) friction coefficients between each particle type and each available carrier fluid (or the availability of tables/equations to calculate these coefficients as viscosity changes);
- i) friction coefficients between the each type of particle that may be introduced and the target formation;
- j) particle/fluid density ratio;
- k) ratio of concentration between different particle types simultaneously introduced;
- l) concentration of each particle type;
- m) overall concentration (all particle types together) or injection ratio (*e.g.*, pounds per gallon)
- n) fluid flow rate or pump rate (*e.g.*, volumetric flow rate);
- o) fluid viscosity (*i.e.*, carrier fluid);
- p) ratio of particle sizes;
- q) ratio of different particle shapes (*e.g.*, mass based);
- r) ratio of particle hardness (elastic property measured in mpa);
- s) blending rate;

- t) ratio of different particle types;
- u) perforation geometry (known or measured);
- v) particle properties (for each particle type) including without limitation, chemistry of the particle/polymer, elastic properties, tensile strength, compression strength, and friction coefficients as noted above;
- w) fluid properties, including density, viscosity, fluid type (*e.g.*, water based, oil based, emulsions), and PH;
- x) additives and properties of additives (*e.g.*, surfactants and corrosion inhibitors); and
- y) formation data, including type of formation (*e.g.*, shale, *etc.*), mechanical and reservoir properties, depth, geological factors, geo-mechanics factors, production data (*e.g.*, amount of hydrocarbon being produced), and production size.

Workflows or Processes

[0073] A workflow or process may be designed to optimize diverting agent design and the particulars of particle jamming and sealing. In some embodiments, a general proposed workflow starts with a candidate screening process to determine wells that are advisable for analysis and work-over. Once a suitable candidate well is identified, required breakdown pressure and Perf design can be determined based upon factors for the specific well. A quick-look screening analysis may be performed to check the extent of feasibility of a candidate set of initial particle types (potentially including size, shape, and chemistry) and diverting agent. A quick-look analysis saves engineering and computational resources by assessing particle size with respect to the opening diameter that needs to be jammed. If the quick-look analysis provides feasible candidate particle types, then advanced analysis may be employed deeper in the workflow. For example, look-up tables based on advanced analysis can be used to optimize design and simulate “sealing.” This involves fully coupled flow-polydisperse particle transport models to adjust particle concentration, ratio, shape, and flow rates. Using these models predicts pressure build-up (*i.e.*, capability using a candidate set of parameters) may be evaluated with respect to formation breakdown pressure. If breakdown pressure is greater than or equal to the predicted pressure build-up due to sealing, the design may be feasible. If breakdown pressure is less than the predicted pressure build-up due to sealing, model parameters may be fine-tuned and a new candidate set of parameters may be produced with more sensitivity to the pressure constraints. The workflow can be used in real-time or intermittently applied with field implementation so field design parameters can be updated accordingly.

Specific Illustrative Workflow or Processes

[0074] Referring to FIG. 7A, there is shown an illustrative process or workflow for creating a diversion in a fluid flow path by jamming and/or sealing an opening such as a perforation. At 710, jamming analysis is performed. In many embodiments, jamming analysis includes optimizing different parameters that contribute to the jammed structure stability and probability of success. In one or more embodiments, the optimized parameters include, without limitation, particle size, ratio, and concentration. In some embodiments, jamming analysis 710 may be used to narrow a selection of particle types (*e.g.*, particle size, shape, and chemistry) to be considered in later modeling/analysis during sealing analysis 730 or even later portions of the process/workflow of FIG. 7A (*e.g.*, limit further consideration to 3 to 5 particles). In other embodiments, jamming analysis 710 results in a set of selected parameters for consideration in subsequent operations such as sealing analysis 730 and portions of FIG. 7A beyond sealing analysis.

[0075] In many embodiments of the disclosure, coupled Computational Fluid Dynamics (CFD) and Discrete Element Method or Model (DEM) approaches are used to develop probabilistic curves (or tables such as LUTs) to aid with “jamming” analysis. In most embodiments, coupled CFD and DEM analysis includes extensive numerical simulations. Given, the large number of particles being modeled, coupled CFD and DEM analysis is infeasible without computers, thus embodiments herein may employ coupled CFD and DEM through software as discussed above using computing technology as discussed above. In addition, custom applications designed to provide all or part of the functionality of FIG. 7A may use service software to provide the coupled CFD and DEM functionality. The service software may be in the application layer or a framework layer as taught herein with respect to FIG. 3.

[0076] In one or more embodiments, the curve or LUTs created through coupled CFD and DEM techniques may be employed to investigate the effect of different parameters on the probability of jamming. In some embodiments, the parameters under investigation are one or more of particle size, ratio of particles, existence of small particles (*i.e.*, more than a magnitude smaller than the jamming particle size), perforation geometry of the target formation, and particle shapes. Of course, depending upon available time and computing resources, any number of parameters as identified above may be modeled and evaluated. By using the coupled CFD and DEM modeling, the selected parameters can be optimized to increase the probability of jamming under specific operational conditions. A sample probabilistic analysis derived by coupled CFD and DEM techniques may be seen in FIG. 8, where the probability of jamming (Y axis) is plotted against the ratio of particle size / slot opening (X axis). The curve, which may

easily be represented in a LUT for easier computer accessibility, aids with the selection of particle size because it shows how likely different particle sizes are to jam formation openings of proportionally indicated sizes.

[0077] In certain embodiments, jamming analysis 710 may also include deterministic/analytical models that are used to examine the stability of a jammed structure. A deterministic approach or model is one without randomness such that the same set of inputs will always produce the same output. With the aid of a deterministic model or approach, or by actual experimentation, particle properties as discussed above may be modified to achieve higher seal stability, which may be required for successful jamming in a particular modeled application. In one embodiment, one or more of the following particle properties is used for this purpose: particle size; ratio of different types of particles; friction coefficients, including particle-to-particle, particle-to-fluid, and particle-to-formation; and particle elastic properties. In one or more embodiments, a deterministic approach may be employed to determine stable seal configurations and/or geometries and to verify or calculate a pressure limit that the jammed structure can sustain. In some embodiments, the stability of a jam may be assessed based upon particle size, particle shape, opening size, and opening shape.

[0078] FIG. 9 shows an example of deterministic evaluation in a jamming analysis. With reference to FIG. 9, there is shown a graph with different jammed structures corresponding to a combination of parameters shown on the X-axis and stability index shown on the Y-axis. The graph of FIG. 9 is separated into regions indicating unstable jamming arrangements 905 and stable jamming arrangements 901. The vertical lines labeled respectively “jammed structure 1” through “jammed structure 3” show that, for a given jammed structure, different ranges of stable jamming may be achieved. For example, under a specific combination of parameters, jammed structure 1 has a high range of stability while jammed structure 3 has a relatively low range. Some embodiments of the disclosure may use an analytical engine to investigate the stability of a jammed structure. Using this modeling, different parameters affecting a given or hypothetical jammed structure stability may be investigated and optimized. For example, modeling may be employed to determine the appropriate values of parameters (*e.g.*, particle size, mechanical properties, *etc.*) that result in jams in the stable region 901. Thus, a target pressure or breakdown pressure may be achieved for more efficient jamming. The same analysis also may apply for sealing.

[0079] Referring now to FIG. 7B, there is shown a version of FIG. 7A where an embodiment's sub-operations for jamming analysis 710 are shown. At 711a, a Perf analysis may be performed. Perf analysis is a topic of Weatherford International's FracAdvisor. In general,

Perf (*i.e.*, performance) analysis provides objective and/or subjective information to determine the extent of benefits available (or not) from well stimulation, such as a fracking work-over. At **711b**, which may be performed in any order (including simultaneously) with respect to Perf analysis **711a**, required breakdown pressure is analyzed. BDP analysis is also known in the art, and relates to either: determining the pressure build-up that is desired (and should be endurable by the diversion); or determining whether an optional jamming configuration can withstand the desirable pressure build-up. The BDP may be calculated based upon techniques known in the industry. It may also be derived from one or all of pumping curves, pressure curves, or field observations. At **712**, proposed particle sizes, shapes, and properties may be optimized and, in one embodiment candidate, optimized particles may be selected. In some embodiments, these factors are derived by application of the probabilistic and deterministic techniques discussed above. In one or more embodiments, three to five options are yielded for particles, including a particle size; shape; and at least one other particle property, such as chemistry. In another embodiment, only one particle option is yielded, also including one or more of particle size, shape, and at least one other particle property, such as chemistry. Of course, the skilled artisan will recognize that any embodiment may employ any number of particle properties or parameters, such as those discussed above.

[0080] Returning now to FIG. 7A, after item **710** (potentially including items **711a**, **711b**, and **712**), control moves to decision block **720**, where a determination is made regarding whether jamming analysis has been optimized. In one or more embodiments, optimizing jamming analysis refers to whether the parameters of particle size, shape, and chemistry for jamming have been sufficiently optimized. In other embodiments, optimizing jamming analysis may refer to sufficiently optimizing one or more parameters of any nature (*e.g.*, any of those parameters discussed above). For example, and in some embodiments, in order to be considered optimized, the available jamming analysis result must meet one or more pre-determined criteria. Each criterion may have its own threshold or tipping condition and the criteria may include one or more of the following: provision of a reduced set of potential particles for jamming (*i.e.*, reduced from all possibilities); provision of 5 or fewer potential particles for jamming (or below any pre-determined threshold); provision of a ranked set of particle possibilities for jamming; provision of the ranked set wherein the ranked set is at least 5 in length or beyond a pre-determined threshold in length; or provision of a set of candidate particle types where each particle type is predicted to satisfy a minimum stability requirement, and where the stability requirement may or may not be job-specific.

[0081] Referring back to FIG. 7A, if there is a determination that optimize decision 720 has not been met, the control moves back to jamming analysis 710 for another attempt to develop candidate particles for an appropriate jamming structure. In one or more embodiments, upon return to the jamming analysis stage 710 after a negative decision from any decision block in the process of FIG. 7A, the jamming analysis is altered to account or compensate for the factors causing the negative decision. For example, if a negative decision at optimized block 720 was caused by a failure of candidate particle types to meet a minimum stability requirement or prediction, then jamming analysis 710 may heighten the stability sensitivity for the next set of candidate points.

[0082] If the optimize 720 decision has been met affirmatively, control moves to sealing analysis 730. Referring now to FIG. 7C, in one or more embodiments, there is a third option for decision block 720. For these embodiments, the optimized block 720 evaluates (at 721) one or both of field data from the job under consideration and historical data regarding other jobs and determines whether the further analysis of FIG. 7A is warranted. For example, in view of the field data and/or the historical data, the likelihood of a successful sealing may be high enough that further expense and time of analysis is not warranted or economically advisable. In this case, one or more candidate particles chosen at the jamming analysis 710 are used the process of FIG. 7A ends with that result. In these embodiments, if the field/historical data review 721 does not indicate an end to analysis 722, then control returns to decision block 720 for the determination regarding whether optimization has been reached. In yet another possible alternative, the jamming analysis 710 may lead to a decision to abandon the process altogether for lack of feasibility or for overly high cost.

[0083] Returning again to FIG. 7A, as stated above, if optimize decision 720 is answered in the affirmative, then control moves to sealing analysis 730. In one or more embodiments, sealing analysis 730, evaluates some or all of the candidate particles produced by jamming analysis 710 and attempts to optimize any one or more of the parameters relating to the wet state of the system, *e.g.*, particle concentration, ratio of particles (with respect to different types being used), and flow rate. In order to make this evaluation, sealing analysis 730 may use one or both of DEM analysis (discussed above) and computational fluid dynamics (CFD). Both techniques are known in the art and discussed elsewhere in this specification. Sealing analysis 730, in some embodiments, may be predicated by information known from jamming analysis 710. For example, by using a candidate particle resulting from jamming analysis 710, the nature of the formation requiring sealing may be narrowed, which simplifies and focuses the sealing analysis 730.

[0084] With or without DEM and CFD, many embodiments of sealing analysis 730 focus on a wet and full physics-based analysis of particle movement in the modeled system, which may include one or more modeled scenarios. This physics-intensive analysis may investigate drag forces, fluid properties, particle-to-particle interactions, particle-to-perforation interactions, and particle-to-wall interactions, all for different types (sizes, shapes, *etc.*) and different combinations of particles at different concentrations.

[0085] In one or more practically constrained embodiments, the selection of small particles (*i.e.*, sealing particles as compared to jamming particles) is limited to one or a few particle types. Thus, the analysis and modeling in those constrained embodiments may be limited to evaluating each candidate jamming particle with a single sealing particle, resulting in an analysis focused on optimization of concentration, rate, and particle ratio. The variation of rate, ratio, and concentration may be employed to facilitate or optimize sealing in any embodiment.

[0086] Referring now to FIG. 7D, there is shown an expanded view of sealing analysis 730, including sub-steps 731 and 732. In the embodiments of FIG. 7D, sealing analysis 730 may include coupling of CFD and DEM analysis 731. CFD and DEM analyses are described above. In some embodiments, the CFD and DEM analyses are employed to simulate varying particle combinations in the presence of the specific job conditions.

[0087] At block 732, it is shown that sealing analysis 730 may also include optimizing particle concentration, ratio, and flow rate. In one or more embodiments, once a successful jammed structure is in place, it may be effectively sealed for efficient pressure build-up and fluid diversion. Based on data specific to a job, engineering design parameters may be selected and optimized to reach the desired pressure build-up required to create new fractures. In many embodiments, the design parameters include, without limitation, particle concentration, ratio of particle types (*e.g.*, size or shape distribution), and flow rate. Other parameters may be mechanical properties and fluid properties. The selection of these parameters may be made by running coupled CFD-DEM simulations for real case scenarios or by using operational guidelines generated based on different approaches. These simulations can capture both particle-particle interaction and transport and also fluid diversion and pressure build-up required to design a successful diversion process. Using the best results from the simulations may optimize the parameters such as particle concentration, ratio, and flow rate. Furthermore, in some embodiments, a ranking of results may be maintained and stored in memory for later reference if, for example, there is a negative result in an optimized decision block later in the process.

[0088] Referring again to FIG. 7A, after sealing analysis, there may be a second optimized decision block 740, where a decision is made regarding whether sealing analysis has been

optimized. In some embodiments, optimizing sealing analysis refers to whether the parameters of particle concentration, ratio, and flow rate have been sufficiently optimized. In other embodiments, fewer or greater numbers of parameters may be considered. In order to be affirmative for the optimized block **740**, the available sealing analysis result must meet one or more pre-determined criteria. Each criterion may have its own threshold or tipping condition and the criteria may include one or more of the following: provision of a parameter set predicted to provide effective sealing and diversion at a specified pressure level; provision of a ranked set of parameters for sealing where at least the highest ranked parameters are predicted to provide effective sealing and diversion at a specified pressure level; or provision of one or more particle types (which may include size, shape, and or chemistry), a ratio of particle types, a flow rate, and a concentration level, where the combination is predicted to provide effective sealing and diversion at a specified pressure level.

[0089] Referring back to FIG. **7A**, if there is a determination that optimize decision **740** has not been met, the control moves back to sealing analysis **730**, for another attempt to develop at least one candidate rate, ratio, and concentration parameter set. In one or more embodiments, upon return to the sealing analysis stage **730** after a negative decision from decision block **740**, the sealing analysis **730** is altered to account or compensate for the factors causing the negative decision at **740**. For example, if a negative decision at optimized block **740** was caused by a failure of a candidate parameter set to meet a pressure limitation, then jamming analysis **730** may heighten the pressure sensitivity for the next set of candidate parameters.

[0090] If the optimize **740** decision has been met affirmatively, control moves to pressure build-up analysis **750**, where one or more candidate parameter sets are evaluated for compliance with the breakdown pressure for the specific job. The evaluation may take any form discussed herein or otherwise known in the art. With reference to FIG. **7E**, there is shown an embodiment specifying particular activities **751a**, **751b**, and **752** as sub-parts of pressure build-up analysis **750**. In particular, at **751a**, coupled DEM and CFD analysis is shown, as discussed above. Further, at structural analysis block **751b**, a complete structural analysis of the jammed and sealed structure is evaluated through modeling. Finally, at decision block **752**, there is a final check to determine if the selected parameter set for field use meets the BDP. If the answer is affirmative, then control moves to the completion of the process. If the answer is in the negative, control moves back to the pressure build-up analysis block **750**, where analysis may be repeated with a higher sensitivity regarding pressure. As with the negative decisions above, in some embodiments, the pressure build-up analysis may be altered in a specific response to the negative result at decision block **752**.

Particle Degrading Analysis

[0091] As discussed above, many embodiments of the disclosure contemplate the use of degrading particles so the jammed and sealed formations will eventually clear themselves and allow fluid flow again. This property is particularly useful in situations where an operator seeks to produce hydrocarbons from a previously sealed area. In one particular example, sometime during a drilling operation the operators may experience an undesirable loss of drilling fluid. The fluid may be lost into unplanned or unexpected openings such as weak, fractured, or vugular formation. Degradable particles may be used as described herein to seal the unplanned or unexpected openings so drilling operations may proceed normally. In some situations, the sealed well may be used to produce hydrocarbons within a short time period from the formation of the seal using the degradable particles. In these situations, as the seal degrades, the degraded particulate matter may flow to the surface with the production fluids. Thus, some embodiments of the disclosure account for any problems or irregularities that might be caused by the flow of degraded particulate in the production fluid. One example of a problem or irregularity is the presence of a sand screen that might be clogged by the degraded particulates.

[0092] In some embodiments of this disclosure, the timing of the degrading process is more critical because sand screens may be installed upstream from the seal. The escape of degradable particles that are large enough to clog the sand screen can impede hydrocarbon production. Therefore, in wells that may yield hydrocarbon (or other fluid) production within a short period of time from a sealing effort, some embodiments of the invention model the degrading properties of the particles and/or the expected problem or irregularity that may be caused by the degraded particles. For example, in wells that may use sand screens or in any other situation where the degradable particle breakdown may impede production, it may be useful to model the degrading of the seal so the size and shape of remaining particles at a given point in time may be predicted to prevent production problems, such as clogging the sand screen. In one or more embodiments, modeling may factor one or more of the following: the degrading properties of the available particles (*e.g.*, the time and conditions for the seal degrading given the chemistries of the candidate particles); the specifications of the sand screen or other up-well implements that may be hindered by the up-well flow of the degrading particles; and the expected time between the formation of a seal and the initiation of production or up-well flow from the well. In addition, by considering the foregoing factors, some of the embodiments of this disclosure may predict or specify any of the parameters, such as particle parameters discussed above. For example, some embodiments may predict particle size, particle shape, particle type distribution, and particle chemistry (for each particle type).

[0093] In some embodiments, the specifications of a sand screen may be part of the analysis so the optimization of jamming and/or sealing parameters may contemplate the degrading properties of particles such that the sand screens do not become clogged during production. In some embodiments, one specification regarding the sand screen that may be employed is in regards to the size of particles that may flow past the sand screen without clogging or otherwise impeding the performance of the screen. For example, the modeling may contemplate the maximum particle size or average particle size that may flow upstream without causing a production issue such as clogging a sand screen.

[0094] With reference to FIG. 10, there is shown an alteration of the process of FIG. 7A where a degrading particle analysis 760 is added with an optimize decision block 765 to determine if the degrading particle analysis is optimized. Since particles often degrade as a function of time, temperature, and fluid exposure, the degrading particle analysis may employ CFD and DEM analysis in many embodiments. Furthermore, in some embodiments, the modeling may predict the ratio of different size particles to be used because smaller particles may degrade more quickly. In other embodiments, the modeling may predict two or more of the following: the sizes of particles to be used; the ratio of different size particles; the chemistry for each particle; and the shape of each particle. In one or more embodiments, given a set of one or more specified particle types, the modeling may predict a minimum amount of time for degrading that must pass in order to safely employ a sand screen without clogging. In some embodiments, particle-degrading analysis 760 occurs after jamming analysis 710 and before sealing analysis 730, while in some other embodiments it occurs sequentially as shown in FIG. 10. In yet other embodiments, particle degrading analysis 760 may be performed as part of jamming analysis 710, sealing analysis 730, or both.

Predicate Screening

[0095] With reference to FIG. 7A, some embodiments of the disclosure call for predicate screening prior to the beginning of jamming analysis 710. In particular, as shown in FIG. 7F, some embodiments of the disclosure contemplate the collection of formation data 705 prior to the onset of the process/workflow shown in FIG. 7A. Formation data may include any available data regarding the geologic context of the job under consideration, including generally the following information: field data; log data; core data; acoustic data, outcrop data; and offset well data. In particular embodiments, the following specific data may also be gathered: amount of hydrocarbon being produced; reserve size and production size; viability of the well for hydrocarbons; formation breakdown pressure; and performance of nearby wells.

[0096] In addition, some embodiments provide an initial screening 706, to determine if the inquiry involved in the workflow/process of FIG. 7A is advisable. For example, if a well is performing sufficiently, there may be little or no incentive to investigate a work-over. In addition, if a well has little or no potential to justify the effort of a work-over, then there may be insufficient reason to perform the analysis of FIG. 7A. This type of screening analysis may be performed by, for example, Weatherford International's FracAdvisor product. In sum, according to some embodiments of the disclosure, the best candidate wells for analysis of FIG. 7A are those that are under-performing in production, but have potential to produce materially more hydrocarbons after a work-over. As a threshold basis for this determination, the increased performance in a well may be measured against the cost of the work-over and analysis and the lost production time during the job (*e.g.*, a work-over or fracturing job).

Compensation for Dry Models

[0097] In some embodiments, the jamming analysis 710 is a "quick look" analysis, which ignores fluid and particle transport coupling. While this saves time and money, it ignores flow effects relying only on "dry models" where only particle-particle interactions under gravity are simulated. In these embodiments, this may be an intentional oversimplification of reality where polydisperse particles are transported in the system and under the influence of drag forces coupled with particle-particle interactions. For an accurate optimization of flow rate(s), concentration, and other motion-dependent parameters, more intensive analysis may be used relying on Discrete Element Modeling (DEM) coupled with Computational Fluid Dynamics (CFD) as discussed herein. The coupling of these techniques may be used to more realistically simulate sealing/sealing mechanisms. For example, as illustrated above, the coupling of these models can be used for optimizing particle ratio (percentage of small particles or of one particle type to others), particle concentration in the carrying fluid, flow rate, carrying fluid properties, and other motion related parameters. In addition, these models may be used to predict the pressure capabilities of a candidate set of parameters so their capabilities may be compared with formation breakdown pressure. Thus, as discussed above with respect to FIG. 7A (and particularly applicable to pressure build-up analysis 750), diverting agent design can be customized to reach a formation-specific breakdown pressure.

Safety Factor

[0098] The discussion herein has involved threshold-type limitations regarding jamming stability and pressure tolerance or capability with reference to safety factors. Some embodiments of the disclosure contemplate the use of safety factors, which generally involve applying a multiple to any pressure or stability requirement. For example, a 20% safety factor increases any

requirement threshold for pressure of stability by 20% from its base number. In some embodiments of the disclosure, a Monte Carlo analysis is applied to determine an appropriate safety factor for any particular parameter, such as stability or breakdown pressure. The use of Monte Carlo analysis relative to safety factors is well known in the art.

Learning Models

[0099] As referenced above, many embodiments of the disclosure contemplate that the models and algorithms may learn from field applications. Thus, some embodiments of the disclosure call for a learning module of the modeling software so that fed-back production data can be contemplated in subsequent use of the model. Furthermore, in some embodiments, the learning module may automatically receive production data, match the data to the former predictions, and vary the model. With reference to FIG. 6, conveyance 612 and network / Internet 606 may be employed to transport data to and from local computers and server-based resources to both perform modeling and implement model learning.

Iterative Mechanisms

[00100] As referenced above, many embodiments of the disclosure contemplate the ranking of predicted alternatives as output of the various embodiments of FIG. 7A. The rankings may be used in iterative fashion without the necessity of re-running the mode. Thus, if the first-ranked recommendation does not work (either in real production or in modeling downstream in the process), the next-lowest-ranked alternative may be used and so on.

Model or Algorithm Validation

[0100] In some embodiments, the analytical and numerical modeling discussed herein may be improved by validating and tuning against experimental and field data. This verification step may be used to calibrate the model parameters to enhance the prediction accuracy. Successful calibration may be measured by an accurate prediction of failures and design optimization as compared to the field data or experimental data. Results may be applied to guidelines for application in the field.

Modeling With Mixed Field Testing or Use

[0101] Many embodiments of the disclosure contemplate the use of FIG. 7A and FIG. 10 models to perform analyses that ultimately direct the use of real world mechanisms, such as particles, fluids, pumps, blenders, valves, and servicepersons. Other embodiments contemplate the intermittent use of real world implements within the modeling stream to affect the progression for the analysis. For example, with reference to FIG. 6, at the conclusion of jamming analysis 710, results from the jamming analysis may be applied to a well and the data from the jamming procedure may be fed back to the process to transform the operation of the

FIG. 7 or FIG. 10 processes moving forward. Similarly, the outputs of sealing analysis 730, pressure build-up analysis 750, or particle degrading analysis 760 may be applied in the field with results fed back in a way to affect subsequent modeling.

[0102] In addition, some applications of the current disclosure may be initiated in real world, well-site activity and then aided by the techniques discussed herein. For example, if a problem is encountered at a well site and drilling fluid is draining off through an unwanted opening, the techniques herein may be employed to fix the problem. In one embodiment of the disclosure, a problem, such as unwanted drainage, is detected at a well site. Sensors and production data are received related to the problem. The sensor and production data are used to design a diversion operation using the techniques discussed with respect to FIGs. 7A and 10. In some embodiments, a single fluid is developed for jamming and sealing the draining area. In other embodiments multiple fluids are developed, with at least one fluid being directed toward jamming and a second fluid directed toward sealing.

Automatic Model

[0103] With reference to FIG. 6, many embodiments of the disclosure contemplate implementations with no or limited automatic connections between the processes of FIGs. 7A and 10 and the operation of the well site. However, other embodiments of the disclosure may require differing levels of interaction and at least one embodiment is fully automated. For example, any computer-controllable implement at the well site may be automatically controlled by the processes of FIGs. 7A and 10. For example, a computerized process may do any one or more of the following: read field data or historical data from servers or its own memory; perform testing on a well site (*e.g.*, provide a stimulus and read sensor data) to receive test data for application to models; read or poll sensors deployed at the well site; create diversion fluids using stored fluid, particles, and water at the well site using a blender, pumps, and conveyances or other implements known in the art; and provide instructions for field technicians to cooperate with or aid the automated processes.

Single-Fluid or Multi-Fluid Applications

[0104] Many embodiments of the disclosure result in implementation of a diversion process using a single carrier fluid and particulate that is developed using the teachings hereunder. For example, a single carrier fluid and specified particles at specified parameters may be used for jamming and sealing. Many embodiments herein are particularly well suited for a single-fluid application because the analysis provided herein can optimize the fluid balancing the considerations for jamming and sealing. However, other embodiments of the disclosure use at least two fluids for implementing a diversion. One fluid is applied and optimized for jamming,

and the second fluid is applied and optimized for sealing (and even, in some embodiments, where the sealing is optimized to the prior jamming process). Finally, the analysis techniques taught herein provide flexibility to specify and predict results for the applications of 3 or more fluids in a diversion operation. This may be useful in particularly complex well situations where natural, man-made, or production factors favor a layering of particle types, rather than a more heterogeneous application of mixtures.

Design of Particle Properties

[0105] As indicated above, in some embodiments, particle properties may be customized to the particular job through the use of analytical and advanced numerical approaches. For example, models and/or algorithms may be constructed to account for input conditions such as target pressure build-up, formation information, and the range of available particle types and chemistries. Given these inputs, the models or algorithms may produce optimized custom values (per job or formation) regarding the application of a particular diversion job, *e.g.*, particle size, particle concentration, and/or particle combination. Ultimately, some embodiments may specify these parameters and predict achievable pressure build-up for the job under analysis. In one or more particular embodiments, custom particle properties (*e.g.*, size, shape, concentration, and ratio) and operational parameters (*e.g.*, flow rate, fluid viscosity, *etc.*) may be calculated for optimum and efficient jamming and/or sealing operations. Furthermore, the model/algorithm results obtained may be verified (*e.g.*, sanity checked), or recursively improved using field data (*e.g.*, collected from past jobs) and experimental data (*e.g.*, in a lab or test environment) to calibrate the model's/algorithm's parameters.

[0106] It is to be understood that the above description is intended to be illustrative, and not restrictive. The material has been presented to enable any person skilled in the art to make and use the invention as claimed and is provided in the context of particular embodiments, variations of which will be readily apparent to those skilled in the art (*e.g.*, many of the disclosed embodiments may be used in combination with each other). In addition, it will be understood that some of the operations identified herein may be performed in different orders. The scope of the invention, therefore, should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein."

Stimulation Efficiency

[0107] With reference to FIG. 11, the discussion of the aspects of efficiency now transitions to a focus on stimulation efficiency **1103**. Stimulation efficiency **1103** refers to the ability to

measure or quantify the effectiveness of stimulation occurring in the intended area of a well as a result of diversion's (e.g. jamming and sealing process) effectiveness in isolating a portion of the well. In some embodiments, as explained below, the stimulation efficiency may be quantified by comparing tracer logs of actual well formations with synthetic tracer logs generated by models that provide differing logs for differing levels of efficiency. When an actual log closely corresponds to a synthetic log, then the stimulation efficiency of the actual well stimulation may be analogized to the modeled efficiency of the synthetic log.

[0108] Referring to **12**, there is shown a visualization of well indicated by **1230** at the well surface and **1235** at a point beneath the surface and below operational areas of the well. In some embodiments, the deep portion of the well **1235** may be the bottom of the well and in some other embodiments it may simply be a point below one or more operational areas. Furthermore, in some embodiments, the deep portion of the well **1235** may represent a natural or artificial blockage in the well, such as a plug.

[0109] The well **1230** is illustrated with three stages: stage I **1203** near the bottom of the well; stage II **1202** in the middle area of the well; and, stage III on the surface side of the illustrated operational areas of the well. In some embodiments, there may be more or fewer stages in the well. For example, a well may have only one or two stages, or alternatively, a well may have several more stages. In the later embodiments, where the well has several more stages, some embodiments may have additional stages on the surface side of stage III, which other embodiments may have additional stages beneath stage I, while yet other embodiments may have additional stages in both places.

[0110] Referring again to FIG. **12** and well **1230**, each stage **1201**, **1202** or **1203**, is intended to represent a physical section of the well. In some embodiments, each stage (or at least one stage) of the well represents a physical section of the well that is subject to operational work such as stimulation or production after stimulation. Depending upon the embodiment, stimulation operations refer to operations in the well having the goal of causing the stimulation of production or greater amounts of production. One form of stimulation contemplated by many embodiments of the invention is hydraulic fracturing.

[0111] In practice, many embodiments herein contemplate that each stage of the well may be implemented in any known manner. For example, a stage may be a linear length of well bore such as a 400 foot long section or a 500 foot long section. Varying embodiments of this disclosure contemplate different size stages and some embodiments contemplate a well stage as portions of the well to be produced together (e.g. simultaneously). In one embodiment, one

stage may be a 400 foot long section of the well to be isolated for production, while other stages may be longer or short portions of the well, each to be isolated for production.

[0112] With reference again to FIG. 12, each stage of the well is illustrated as having multiple clusters 1211 through 1225. By way of example, each stage is shown with 5 clusters: stage III has clusters 1211 through 1215; stage II has clusters 1216 through 1220; and stage I has clusters 1221 through 1225. In some embodiments, any particular well a stage may have more or less than five clusters, although a well stage may be characterized as a section of the well having one or more clusters in an area such as a single operational zone of the well. Clusters within a single stage of a well may, for example, be 50 to 75 feet apart. Each cluster represents a group of perforations, so each cluster may include one or more perforations. For example, in some embodiments a cluster may have 8 or 16 perforations while in other embodiments the number of perforations may vary between clusters based upon operational goal or well characteristics. In some embodiments the number of perforations in a cluster or the number of clusters in a stage may vary, being categorized by operational or theoretical factors, or a combination thereof.

[0113] As discussed above, diversion agents may be used to jam or seal perforations so that fluids, such as stimulation agents, may be appropriately directed in a well. In some embodiments, jamming and sealing operations may be directed at one or more clusters or an entire stage. As discussed above, the goal of diversion is typically to block targeted perforations (e.g. clusters or an entire stage) so that other perforation may propagate. In some embodiments, Weatherford's TBlockSure® products are used as diverting agents to jam and/or seal perforations as discussed above, primarily with respect to diversion.

Using Tracers

[0114] During a well-based project, such as a stimulation project (e.g. a hydraulic fracturing operation), tracers may be used to monitor and evaluate the flow of fluids in the well such as fracturing fluids. Tracers are observable elements that are added to wellbore fluids so that the path or accumulation of the fluids may be objectively observed by personnel at the surface. For example, there is known in the energy industry radioactive tracers or chemical tracers that are added to hydraulic fracturing fluid or other stimulation agents and used to determine injection profiles and location of fractures created by the fluid. In some embodiments, the same well may employ multiple tracers that are differentiable when observed. The tracers may use radioactive elements have a tracing basis in other technologies to create an observable characteristic for use by the well operators in observing the fluid flow characteristics of the well. In some embodiments a variety of tracers may be used on the same well, but those tracers may be distinguished upon viewing data or imaging of the well. In this way, a well operator may be able

to observe the migration of different fluids in the well. There are multiple known technologies for tracers of this type and the embodiments herein contemplate use of any tracer technology currently known or developed in the future.

[0115] In discussing the use or visualization of tracers herein, there may be references to colors, e.g. blue, red, yellow, etc. The colors are used to refer to tracers being distinguished from one and other, and not meant to imply a specific type of tracer technology, a specific implementation, or even an actual color of the tracer. Therefore, a reference to a “red” (or any particular color) tracer is referencing any tracer technology. The use of the word, “red,” is to convey that the tracer may be distinguished from another color, e.g. “blue” tracer, which may also be implemented in any tracer technology. Similarly, the discussion herein may refer to tracers by number, e.g., “tracer 1” and “tracer 2.” As discussed with respect colors, reference to tracers by number is not intended to confine any embodiments to any particular tracer technology, but merely to suggest that the tracers are distinguishable by the well operators in observing information about the well, such as tracer logs. In other words, a tracer log may show three different colors representing tracers. The colors merely represent the fact that the tracers are different and do represent a particular technology of tracer or even that that actual tracer has any particular color.

[0116] With reference now to FIG. 13, there is shown the staged diagram of well 1230 juxtaposed to tracer (or stimulant) injection plan or log 1300. The log/plan 1300 is stated in the alternative (log or plan) because the illustration may represent either a record or activity (a log) or a plan for activity (a plan). In general, tracer injection log/plan interleaves diversion operations (steps 2 and 4) between different color tracers (step 1, step 3 and step 5), which are in most embodiments injected in the well as part of a stimulation agent, such as hydraulic fracturing fluid. In particular, log/plan 1300 shows: a first step of 15 minutes of red tracer injection into stage I of the well; followed by step 2, a diversion operation such as the application of jamming and sealing agents, in some embodiments applied to stage I; followed by step 3, which reflects 15 minutes injecting blue tracer in stage II of the well; followed by step 4, a second diversion operation, e.g. in some embodiments applying jamming and/or sealing agents to stage 2 of the well; and step 5 where a yellow tracer is injected into stage 3 of the well for 15 minutes. Log/plan 1300 is intended to be merely illustrative of voluminous possibilities for a tracer injection plan. For example, there may be any number of steps including any number of injection steps as applied to any number of well stages. In some embodiments, there may be multiple tracer injection steps in the same stage. Still in other embodiments, the time for each

stage may be varied. In sum, the operational team for the well may design any tracer injection plan per their operational needs, desires or goals.

[0117] Referring now to FIGs. **14** and **15** there are shown synthetic tracer logs **1400**, **1450**, **1500** and **1550**. A synthetic tracer log is generated by using project data and modeling to determine or predict the amount of tracer present in a well and the stratification of that tracer across the well. A synthetic tracer log may be contrasted to a real tracer log, which is a field reading of tracer levels as those levels are stratified in a well. Real tracer logs may be expressed in many varying graphical and mathematical formats. The concept behind a real tracer log is to show the volume and position of tracer in the well at the time the data is taken. With reference to FIG. **16**, there is shown an illustration that represents a real tracer log. Real tracer log **1600** shows colored tracers that are coded by the use of shapes. In particular, yellow tracer is represented as a triangle, blue tracer is represented as a square, and red tracer is represented as a circle. In this form of a real tracer log **1600**, the volume of a tracer is indicated by the amount of the color/shape shown in the log. For example, in Stage III of log **1600**, just below 9,600 feet, there is mostly yellow tracer surrounded by some blue tracer. In stage II of the well shown by log **1600**, in the area of 10,300 feet of depth, there are three patches of entirely blue tracer. Finally, in stage I of the well, just above 10,800 feet of depth, there is primarily red tracer, with a small amount of surrounding yellow tracer. Real tracer log **1600** is not intended to illustrate the very realistic graphic presentation that is given by most contemporary commercial products. For purposed of this disclosure, the conceptual core of a real tracer log is to illustrate the volume or quantity of tracer present at different portions of the well – e.g. the stratification of tracers in the well. Many times, a real tracer log may also be expressed as an array of data, such as one might find in a spreadsheet or a database, where data indicating the volume or quantity of tracer may be associated with locations in the well.

[0118] Returning now to synthetic tracer logs (e.g., **1400**, **1450**, **1500** and **1550**), depending upon the model used to generate a synthetic tracer log, varying types of data may be employed as input. In some embodiments, sealing and diversion data is used as input to the model. The sealing and diversion data may be sourced from the same well that is being modeled, for example, when the modeling is occurring after some amount drilling and/or stimulation and/or diversion and/or production. Alternatively, the sealing and diversion data may be sourced from wells that are considered similar to the well that is being modeled, for example, wells in the same field or geographic area or other wells that have been deemed similar by the operators (e.g. geologists, geophysicists, etc.).

[0119] In some embodiments, additional input data for the model may be pressure build up data or an assumed efficiency level. In one or more embodiments, this data can be obtained from the jamming and sealing modeling described above. For example, the model may receive as input the pressure build-up data for a well where the actual stratification of tracer in the well is known. The model may then be used to predict the efficiency of the well stimulation at the given level of pressure build up or predict the amount of pressure build up and the tracer stratification at differing levels of efficiency. In yet other embodiments relating to fracturing simulations, some of the input data may be completion data (such as stage spacing, cluster design, perforation design), pumping data (such as pressure data, fluid properties, proppant properties) and reservoir and geomechanical data (such as in-situ stress and rock properties). In still other embodiments relating to diversion simulations, similar data as coupled CFD-DEM modeling may be used.

[0120] The model to create the synthetic tracer log may be any suitable model that attempts to use real-world data about a well (or a similar well) to predict efficiency levels for different stratifications of tracers. For example, in some embodiments, the model may produce predicted tracer stratification for each of several efficiency levels. Thus, when a real tracer log is acquired from a well, a close correlation between the real tracer log and one of the synthetic logs may be used to determine the efficiency of the stimulation and diversion.

[0121] In some embodiments, synthetic tracer logs are a form of output from a model as discussed above. Illustrated synthetic tracer logs **1400**, **1450**, **1500** and **1550** are merely illustrative of this type of output. Some embodiments of this disclosure require that the “output” or synthetic tracer log should show the stratification of tracer predicted for a well, as well as the predicted stimulation efficiency that accompanies such specific stratification. Thus, the illustrative synthetic tracer logs shown as **1400**, **1450**, **1500** and **1550** visually demonstrate the volume of tracer (“Zero” to “Higher” on the Y axis) and the stratification (depth in feet on the X axis). In addition to graphical indications of the stratification of tracers in a well, the same data may be indicated in any known matter. For example, a spreadsheet of database may be used to show volumes or quantities of specific tracers and the position of those quantities in the well.

[0122] Returning briefly to FIG. **13**, recall that, there is shown the staged tracer injection plan/log **1300**. As discussed above, the tracer injection log/plan interleaves diversion operations (steps 2 and 4) between different color tracers (step 1, step 3 and step 5), which are in most embodiments injected in the well as part of a stimulation agent, such as hydraulic fracturing fluid. Tracer injection log/plan **1300** will now be used as a tool to help illustrate synthetic tracer logs of FIGs. **14** and **15**. In particular, for some embodiments, we can assume that a modeling process or program uses the log/plan **1300** as part of its input (e.g. along with physical

information about the well such as that shown in FIG. 12, along with operational data). In some embodiments, the model may then generate one or more synthetic tracer logs, such as **1400**, **1450**, **1500** and **1550**.

[0123] Referring to FIG. 14, synthetic tracer log **1400** shows amounts of all tracers (i.e., yellow, red and blue, shown overlapping) in the well at stage I, which is the lowest part of the well. Looking at log/plan **1300**, we see that yellow tracer was injected at step 5, but in Stage 3 of the well, which corresponds to an area of the well more toward the surface. Thus, it is evident that yellow tracer (along with any stimulation agent) propagated outside the intended area of treatment, meaning that synthetic tracer log **1400** correlates with a relatively low stimulation and diversion efficiency. A similar observation can be made for tracer blue which was injected at step 3 and in Stage 2 of the well which corresponds to the middle part of the well. However, due to low diversion and stimulation efficiency, blue tracers are observed outside of intended area and in Stage 1.

[0124] In one embodiment, the modeled stimulation efficiency of synthetic tracer log **1400** is 75%. If a real tracer log correlates with synthetic tracer log **1400**, then we can determine the stimulation efficiency of the real well stimulation with relation to the modeled stimulation efficiency corresponding to the synthetic tracer log. For example, if the stratification of tracer in a real tracer log has a high correlation with the stratification of tracer in a synthetic tracer log, some embodiments of the disclosure assume or proclaim that measurement of the stimulation efficiency of the real well is the modeled stimulation efficiency of the synthetic tracer log – i.e. 75%. In some embodiments, there is a threshold for the correlation so that equivalence of the stimulation efficiency between a real well and a synthetic log is only assumed or proclaimed if the correlation is above the threshold. In one embodiment, the threshold is 90% correlation, while in other embodiments, the threshold is 95%. In some embodiments, the adequacy of the threshold is determined based upon other factors. For example, a threshold may be more tolerant for some wells because the precision of the efficiency measurement is less critical.

[0125] Referring now to synthetic log **1450**, there is shown tracer stratification with blue and yellow tracer found on the shallower side of stage II, and red and yellow tracer throughout the area of stage 1. Referring to log/plan **1300**, while red and blue tracers are located generally in the area of their injection, the yellow tracer from stage 3 is found in areas where it was not injected, indicating a lower efficiency. In some embodiments, the modeled efficiency of log/plan **1450** may be 88%. Each stimulation (diversion) efficiency (e.g., 88%) may be corresponding to specific pressure build-up on the opening path due to diverters jamming and sealing.

[0126] Referring to FIG. 15, synthetic tracer logs **1500** and **1550** may be evaluated with respect to log/plan **1300** in a similar manner. Thus, it is evident that synthetic log **1500** is a relatively high efficiency (e.g. in some embodiments 94%) and synthetic log **1550** is yet higher efficiency (e.g. in some embodiments 98%). Furthermore, in some embodiments many synthetic logs may be modeled in order to increase the chance of finding a match with a real tracer log. For example, a synthetic log may be modeled for each percentage of efficiency or for each half percentage of efficiency. In yet other embodiments, since efficiency below a certain threshold (e.g. about 75%) is not particularly relevant, synthetic tracer logs may only be generate for efficiencies greater that threshold. This allows the generation of fewer synthetic logs with a smaller efficiency span between adjacent logs.

Modifying the Pumping Plan

[0127] In many embodiments of the disclosure, synthetic logs may be modeled for more complex applications of tracer and stimulation elements. The ability to model more complex stimulant application log/plans allows the determination of stimulation efficiency even for complexly managed and stimulated wells. By way of example, FIG. 17 shows a stimulation/tracer injection log/plan that injects stimulant/tracer for the same amount of time as log/plan **1300**, except the time is divided into 7.5 minute periods with diversion applied between stimulant/tracer injections. Thus, stage I receives a 7.5 minute injection of red tracer (and stimulant), followed by the application of a diverting agent, and then followed by another application of red tracer (and stimulant). Furthermore, the same pattern is repeated from the remainder of the project shown in the log/plan **1700**. By way of example, a synthetic tracer log **1800** in FIG. 18 may be interpreted as a modeled tracer log for a particular well having the injection log/plan **1700**. Note that the tracer colors are very well located as aligned with the injection plan (yellow in stage III, blue in stage II, and red in stage I), and the distribution of the tracer within each stage is more evenly distributed. This may be contrasted to the synthetic log **1850**, which illustrates the modeled log for the same total injection time, without the modified pumping schedule (i.e. injecting all 15 minutes at once rather that in two 7.5 minute periods with diversion interspersed). In some embodiments, the inventor has determined that modified pumping schedule and the resulting more even disbursement of the tracer (and by extension, the fractures) results in significantly higher production. For example, in some embodiments, the modeled production for synthetic log **1800** is over 30% greater than the modeled production for synthetic log **1850**. This is due to higher stimulated rock volume and also uniform fluid and proppant distribution along the wellbore (less out of zone fracture propagation).

Processes Associated With the Embodiments

[0128] With reference to FIG. 19, there is shown a process associated with many embodiments herein. In particular, process **1900** may be used to illustrate generation of synthetic tracer logs. Block **1901** shows a repository for well data such as sealing and diversion data and field tracer logs, as well as any other data that may be collected during the hydrocarbon production process and particularly the stimulation and production portions of the process. Block **1901** may represent a computer as discussed above or any memory type discussed above or envisioned. A simulator **1904** is used to simulate fluid flow in the well and the simulator **1904** draws on the sealing and diversion data **1902** as well as **1903** information regarding (i) diversion efficiency and (ii) an assumed stimulation efficiency (this is the stimulation efficiency that the generated synthetic log will represent). Once the simulator creates a prediction of the fluid flow dynamics of the well, a synthetic tracer log generator **1904** may use the results of the simulation to create a synthetic tracer log that corresponds with the input data, including notably the assumed stimulation (diversion) efficiency. The diversion simulator **1904** and the tracer generator **1905** may be embodied in hardware or as software application or a combination of both. In some embodiments, the distinction of the models provides flexibility in assembling an upgrading the system because one module or another can simply be replaced rather than re-writing a larger portion of software, for example, simply due to a minor change in the simulator.

[0129] After a synthetic log is generated at **1905**, it may be optionally stored in a memory **1906**. The memory may be any type discussed above. Thus, having passed once through the process **1900**, one synthetic tracer log will be generated and it will be associated with a single stimulation efficiency (i.e. the assumed stimulation efficiency **1903**). As discussed above, in some embodiments, it may be desirable to generate many synthetic tracer logs corresponding to many different efficiency levels. In order to do so, in some embodiments, assumptions are changed **1950**, and the process is repeated to create more synthetic logs. In many embodiments, the primary changed assumption is the assumed stimulation (diversion) efficiency, so that logs may be created for a variety of efficiencies. In some embodiments, the assumptions may be altered according to a program, where the program used a microprocessor to proceed through the process for a multiple sets of input data, each set of input data designed to generate a single synthetic tracer log.

[0130] Referring now to FIG. 20, there is shown a process **2000** that is a modified version of the process **1900**. In particular, at compare portion **1907** may perform a correlation between a generated synthetic tracer log and a real field tracer log **1912**. If the two match at decision block **1908**, then at **1910**, the stimulation efficiency of the real well (corresponding to the real tracer

log) is determined to be the same as the modeled stimulation efficiency of the synthetic log. If the two logs do not match at decision **1908**, then at **1909**, the process is repeated to create another synthetic log using different inputs, such as different assumed stimulation efficiency. As discussed with respect to the simulator **1904** and the synthetic tracer generator **1905**, the compare portion **1907**, “match?” portion **1908** and other active consideration or manipulation of data may be performed by a programmed processor as illustratively discussed above.

[0131] Combining Diversion Optimization With Stimulation Efficiency

[0132] With reference to FIG. **21**, there is shown an illustrative process or workflow for creating a diversion in a fluid flow path by jamming and/or sealing an opening such as a perforation; and for measuring the stimulation efficiency of the well. As discussed above with respect to the similar FIGs., at **710**, jamming analysis is performed. If at decision **720** it is determined that jamming has not been optimized, then control returns to block **710** as described above. However, if optimization is found at decision **720**, then control continues to sealing analysis **730**. At decision **740**, there is a determination regarding the optimization of the sealing analysis. If optimization is not found, control returns to block **730** as described above. If optimization is found, then control moves forward to **750** pressure build up analysis where the potential pressure buildup of the well is determined as described above. The pressure buildup **750** may then be used as input to the processes shown in FIGs. **19** and **20**.

[0133] Referring to FIG. **21**, for illustration, transition element **2100** shows where stimulation efficiency (e.g. of FIG. **19** or **20**) may be incorporated adjacent to diversion efficiency. In the example of FIG. **21**, the process of FIG. **19** has been used to represent the stimulation efficiency process. With reference to FIGs. **19**, **20** and **21**, it may be observed that there are many ways to use the stimulation efficiency measurement techniques suggested by the varying embodiments of this disclosure. In one embodiment, a stimulation operation may begin, generating data from the operation. That data generated as well as other inputs (as discussed above) may be used to generate one or more synthetic tracer logs, each log representing a different modeled efficiency level. When a real tracer log from the well is matched to a synthetic tracer log, the stimulation efficiency of the well may be equated to the modeled efficiency of the synthetic tracer log. To the extent the efficiency is less than 100%, the well stimulation operation including diverter design may be changed to move toward 100%. Further, the production of synthetic logs may be interleaved with operational changes to form a learning process that may bring any well to its maximum stimulation efficiency.

[0134] Thus, many embodiments discussed herein to provide stimulation efficiency measurement may be used to improve stimulation operations through iterative measurement and

stimulation adjustment. Additionally, many embodiments discussed herein to provide stimulation efficiency measurement may be used to validate stimulation operations by confirming that stimulation efficiency is high or at 100%. Furthermore many embodiments herein to provide stimulation efficiency measurement, may be used to design modified pumping schedules (e.g. 1700), that result in more distributed stimulation of the well, higher pressures and ultimately higher production output.

Enhancing Production

[0135] In some embodiments, production efficiency 3A4 may be correlated to stimulation efficiency, as represented in a synthetic tracer log. Thus, the embodiments herein providing for determination of stimulation efficiency may also be used to predict production efficiency. For example, once a stimulation efficiency of the well is known, other input information may be used and a prediction may be made regarding the production efficiency of the well. In some embodiments, the production efficiency of the well is represented by the relative production efficiency of the well, meaning that the data may indicate more or less production, rather than an absolute amount of production for a stage or stages under study.

Optimizing the Number and Timing of Diversion Slugs

[0136] Many embodiments of the disclosure contemplate systems and processes for increasing or maximizing stimulated hydrocarbon production from a well area by optimizing the number of diversion slugs used and the timing for injecting those diversion slugs. With reference to Figs. 22a, 22b and 22c, each illustration shows a stimulation injection log/plan. The plans show the stimulation time intervals and the temporal placement of diversion slugs relative to the stimulation time intervals. A diversion slug is a volume of slurry and diversion materials, which is discussed generally above along with systems and methods for optimizing the contents of diversion slurries or materials. Each of the three plans/logs in Fig. 22b provides for 15 minutes of stimulant injection. Each table shows a variation of timing and the number of diversion slugs to be injected into the well. For example, Fig. 22a shows log/plan 2200, which provides for 7.5 minutes of stimulant injection, followed by a single injection of diverters, and ending with a 7.5-minute stimulant injection. Thus, plan/log 2200 provide for only a single interval of diverter injection. By contrast, Fig. 22b shows plan/log 2205, which provides three stimulation intervals of 5 minutes each, which are separated by two diversion slugs. Thus, both plan/logs 2200 and 2205 provide 15 minutes of stimulation, but plan/log 2200 has only two stimulant injection intervals separated by a single diversion slug, while plan/log 2205 has three stimulant injection intervals, separated by two diversion slugs. Finally, Fig. 22c shows plan/log 2210, which provides five stimulation injection intervals (of 3 minutes each) interleaved by four diversion

slugs. Thus all three injection plan/logs 2200, 2205 and 2210 provide 15 minutes of stimulation, but each provides a different number of diversion slugs and a different timing for the delivery of the diversion slugs with respect to the stimulation intervals.

[0137] Furthermore, the timing of the stimulation injection intervals in all three tables (2200, 2205 and 2210) is divided evenly. For example, plan/log 2200 divides the 15 minute total into two equal-size 7.5 minute segments, so the single diversion slug is injected after 7.5 minutes of stimulation; the plan/log 2205 divides the 15 minute total into three equal-size 5 minute stimulation injection intervals, so that each diversion slug follows 5 minutes of stimulation; and, the plan/log 2210 divides the 15 minute total into five equal-size 3 minute stimulant injection intervals, so that each diversion interval follows 3 minutes of stimulation. This uniformity of stimulant injection intervals is common in stimulation jobs because mechanisms for optimizing the number and timing of diversion slugs are uncommon, even though the hydrocarbon yields from this uniform approach are often less than desirable.

[0138] Referring to figure 23a, there is shown an operational area 2300 of a hydrocarbon well defined by a surface side 2350 of the operation area and a downhole side 2355. The operational area of the hydrocarbon well is shown as a straight line or well between 2350 and 2355, however varying embodiments employ different shaped operational areas (such as the common case of directional drilling) and different completion design. The operational area 2300 is shown with these sets of clusters 2311, 2313 and 2315. In addition, the dotted line 2375 shows the maximum desirable or allowable SRV (stimulated reservoir volume), which represents to productive potential of the operational area. In addition, stimulation beyond the SRV line might cause operational issues such as interfering with nearby wells and/or inefficient proppant transport for long fractures.

[0139] Referring now to Fig. 23b, there is shown the same operational area 2300 of Fig. 23a, except the result of a fracturing stimulation interval is shown in fractures 2360, 2361 and 2362. Generally, when fracturing fluid is used to stimulate a well, the most suitable (e.g. easiest) areas for fracturing are most affected. Thus, when applying a stimulation schedule to operational area 2300, one possibility is to over stimulate some areas (e.g. the easily fractured areas, 2360 and 2362) and under stimulate others (e.g. the difficult to fracture areas, 2061). This might happen due to several factors such as non-optimized pumping schedule, including diverters. For example, the inventors have determined that uniformly sized (in time) stimulation injection intervals (as shown in the logs/plans of Figs. 22a, 22b, and 22c) may often be less effective at reaching hard to fracture areas and may waste stimulant by over-stimulating easy to fracture areas. Thus, the result of the uniformly timed stimulation may often yield a non-efficient

stimulation, where multiple fractures (2360 and 2362) extend outside the SRV and another fracture (2361) is relatively small, leaving the operational area under-produced. Similarly, by using a non-optimized stimulation plan, operational zones may be under produced in any number of ways such as: creating fractures outside the SRV; failing to create fractures at all in some areas; not being able to transport proppant to some fractures, such as the large fractures; and/or creating fractures that are smaller than the optimal size. In order to overcome this issue, the number of diverter pills (i.e. slugs) and also the injection time can be designed and optimized. Fig. 23c shows one possible example of an optimized situation wherein out-of-zone fracture propagation is mitigated (2360 and 2362) and also more area can be stimulated near the wellbore (2361). Fig. 23c is intended to be illustrative and depict an optimized situation in that the fractures cover extend to the limits of the SRV and are evenly spaced in the production area. However, this is only one possibility of one or more embodiments of the disclosure. Some embodiments may yield results with greater or fewer fractures covering more or less of the production area, although the impact of most embodiments is to increase hydrocarbon yield over the production area without causing the problems discussed above.

Operational Areas

[0140] With reference now to Fig. 24, there is shown a three stage operational area of a well. Within Fig. 24, there is shown a visualization of a well indicated by 2430 at the surface side of the well and 2435 on the down-hole side of the well. In some embodiments, the down-hole side of the well 2435 may be the bottom of the well and in some other embodiments it may simply be a point below one or more operational areas. Furthermore, in some embodiments, the down-hole side of the well 2435 may represent a natural or artificial blockage in the well, such as a plug.

[0141] The well 2430 is illustrated with three stages: stage I 2403 near the bottom of the well; stage II 2402 in the middle area of the well; and, stage III 2401 on the surface side of the illustrated operational areas of the well. In some embodiments, there may be more or fewer stages in the well. For example, a well may have only one or two stages, or alternatively, a well may have several more stages. In the embodiments where the well has several more stages, there may be additional stages on the surface side of stage III and/or additional stages beneath stage I.

[0142] Referring again to figure 24 and well 2430, each stage 2401, 2402 or 2403, is intended to represent a physical section of the well. In some embodiments, each stage (or at least one stage) of the well represents a physical section of the well that is subject to operational work such as stimulation or production after stimulation. Depending upon the embodiment, stimulation operations refer to operations in the well having the goal of causing the stimulation

of production, or greater amounts of production. One form of stimulation contemplated by many embodiments of the invention is hydraulic fracturing.

[0143] In practice, many embodiments herein contemplate that each stage of the well may be implemented in any known manner. For example, a stage may be a linear length of wellbore such as a 500-foot long section. Varying embodiments of this disclosure contemplate different size stages and some embodiments contemplate that well stage represents portions of the well to be produced together (e.g. simultaneously). In one embodiment, one stage may be a measured section of the well to be isolated for production, while other stages may be longer or short portions of the well, each to be isolated for production.

[0144] With reference again to figure 24, each stage of the well is illustrated as having multiple clusters 2411 through 2425. By way of example, each stage is shown with 5 clusters: stage III has clusters 2411 through 2415; stage II has clusters 2416 through 2420; and stage I has clusters 2421 through 2425. In some embodiments, any particular well stage may have more or less than five clusters, although a well stage may be characterized as a section of the well having one or more clusters in an area such as a single operational zone of the well. As discussed above, each cluster represents a group of perforations, so each cluster may include one or more perforations.

[0145] Referring again to figure 24, in addition to the illustration of clusters 2411 through 2425, the dotted line 2475 is intended to indicate the maximum desirable or allowable stimulated reservoir volume (SRV), and may be used as a reference to visually understanding the efficiency of a stimulation result in terms of maximizing the propagation of hydrocarbons and avoiding out-of-zone fracture propagation. Furthermore, as mentioned above, the number and timing of diversion slugs (i.e. how many diversion slugs and temporal placement of each diversion slug within the window of stimulation time) will affect the amount of hydrocarbons produced from a given area. Thus, for a given well portion (stage or stages) and a given planned stimulation time (e.g. 20 minutes total), it is desirable to predict an optimized number of diversion slugs and the temporal placement of those diversion slugs within the overall stimulation time. The prediction of number and timing of slugs may apply to a single stage, multiple stages or any area intended for production. Moreover, in some embodiments the stimulation efficiency may be based upon one or more of mitigating out-of-zone fracture propagation, avoiding proppant carrying capacity and corresponding fracture conductivity issues by controlling fracture length and stimulating uniformly along the wellbore length.

Example Production

[0146] As discussed earlier, an optimized number and temporal placement of diversion intervals may be designed. For example, with reference to Fig. 24a, there is shown a stimulation plan 2491 and a graphical representation of the well after the planned stimulus 2492. As evident from stimulation plan 2491, each stage is stimulated for 20 minutes and there are two mechanical plugs, each used to isolate well stages during stimulation. No diverter slug is used in this stimulation schedule. One outcome for such a stimulation plan may look like the result shown in at 2492, which reveals uneven stimulation across the stages, i.e., an over stimulated section and many under-stimulated sections. In addition, fracture growth out-of-zone causes other issues such as frac-hit with nearby wells and also proppant carrying capacity issues. Thus, the result 2492 is sub-optimal.

[0147] Referring now to Fig. 24b, there is shown a stimulation plan 2493 and a graphical representation of the well after the planned stimulus 2494. As evident from stimulation plan 2493, each stage is stimulated for two 10-minute intervals. Furthermore, each well stage is separated from the others by a mechanical plug, and each stimulation interval within each stage is separated from another stimulation interval by a diversion slug. The corresponding result of the stimulation plan 2493 is shown in illustration 2494. As evident, by dividing the stimulation intervals into smaller *uniformly timed* segments and using diversion slugs as shown, another sub-optimal (e.g. less efficient) stimulation result may be obtained. As shown in illustration 2494, the well remains significantly under-produced. In this condition, by evenly distributing the diversion injection time, one might mitigate healthy fracture propagation near the wellbore, which results in under-stimulated zones. Accordingly, a schedule based upon an efficiently design diverter injection timing may be more desirable.

[0148] Referring now to Fig. 24c, an example is shown suggesting that stimulation efficiency may be increased by varying the number and temporal placement of diversion slugs. For example, plan 2593 yielded an under-stimulated result using 60 minutes of stimulation with three diversion slugs that were temporally placed uniformly within the 60 minutes. Alternatively, plan 2495 yielded a much more efficient result (as shown in illustration 2496) also using 60 total minutes of stimulation, but using only two diversion slugs that were only placed in stage 2 and 3. In particular, as shown in plan 2495, the first diversion interval comes in stages II and III each have two 10 minute stimulation intervals, wherein the stimulation intervals are divided uniformly by diversion slugs. In this example, while the stimulation efficiency is improved by eliminating the diversion injection in stage I, there still exists some out-of-zone fracture propagation and also under-stimulated zones.

[0149] The stimulation results may improve further merely by adjusting the number of diversion slugs and the temporal placement of those slugs. For example, Fig. 24d shows a stimulation plan 2497 that: starts with 20 minutes of stimulation in stage I without diversion; applies a mechanical plug; then follows with a five minute stimulation in stage II; applies diversion slug; followed by a 15 minute stimulation in stage two; and, 20 minutes of stimulation in stage III without diversion slug. As evident from the well stimulation illustration 2498, the same 60 minutes of stimulant injection (and only one diversion slug) may achieve a much better stimulation efficiency compared to the case with evenly distributed diversion slugs.

[0150] Thus, the inventors have demonstrated that, for a given well and stimulation time, a designed schedule for the number and temporal placement of diversion slugs may substantially alter and improve the production of the well. To be clear, modeling results indicate that optimizing the number of slugs and their temporal placement will improve stimulation and corresponding production. While the designs above suggest that non-uniform injection of the slugs results in better production, varying embodiments of the disclosure may optimize slug injection timing in a uniform way or non-uniform way. In a larger context, the design approach of some embodiments suggests production improvements by optimizing the number of slugs and the timing of their injection, not simply by providing non-uniformly timed slug injection.

[0151] In particular, the inventors have determined that, for a given well, the number and temporal placement of diversion slugs may be optimized by a simulation process. Thus, for example, a thoroughly stimulated production area may be achieved through the proper selection of number and temporal placement of diversion slugs. In particular, with reference to Fig. 25, there is shown a process diagram illustrating many embodiments for optimizing stimulation and corresponding production based upon selection of the number and temporal placement of diversion slugs in a stimulation job. While the process is illustrated and described in a specific order, the inventors do not intend to confine their invention to unnecessary ordering of process acts or steps.

[0152] With the foregoing background, block 2505 suggests that well properties be received or obtained. In computer related embodiments, this may refer to receipt by the computer (as generally discussed above) or software (application or framework as generally discussed above) of the desirable design parameters of the well. For example, in one embodiment, the parameters are fixed for a particular set of simulations so that the work of the simulation is to test a plurality of sets of number and temporal placement of diversion slugs. The simulations may be of any suitable type. One type of simulation used in some embodiment involves coupling wellbore scale diversion modeling to reservoir scale stimulation modeling. Furthermore, in some

embodiments, the reservoir scale stimulation modeling includes one or more of fracturing, refracturing or acidizing operations.

[0153] Referring now to Fig. 26 there are shown nine data sets, each having a number of diversion slugs and an indication of temporal placement for those slugs. The convention used in Fig. 26 is to state stimulation times, so that each comma represents a diversion slug. For example, row three in figure 25 shows 4 plugs temporally placed as follows: one slug after 20 minutes of stimulation; then a second slug after another 10 minutes of stimulation; then a third slug after another 5 minutes of stimulation; and finally, a fourth slug after another 10 minutes of stimulation. The format of the data sets in figure 26 is simply illustrative. Data sets may be expressed in any convenient manner such as: using percentages for temporal placement instead of absolute time indicators; combining number of slugs and temporal separation in an accumulated fashion (e.g. 10M stim, slug, 15M stim, slug, etc.); or including stage information in the data sets so that it is clear how the stages and stimulation/slugs align.

[0154] Returning to block 2505, in one or more embodiments, well properties may include one or more of the following: Perforation density (e.g. 6 shots per foot); Length per cluster (e.g. 2 feet); Perforation size (e.g. .5 inches); Flow rate (e.g. 60 barrels per minute); Target zone (e.g. 9700 feet); Geom properties such as Young's Modulus, Poisson's Ration, Matrix Permeability, Initial Pore pressure, and Closure Stress; and Fluid and Proppant Properties such as Fluid density, Fluid viscosity, Proppant density, and Proppant diameter.

[0155] Varying embodiments of the disclosure will employ one, some or all of these properties, as well as other properties that may be important to a particular simulation model.

[0156] Returning now to figure 25, at block 2510, test data sets are received. As discussed above, in most embodiments, a single test data set includes at least a number of diversion slugs and the temporal information to determine when the diversion slugs are injected. Sample test data sets are shown in Fig. 26 and discussed above. In some embodiments, test data sets may be derived using a brute force methodology. Brute force generally refers to including every possible combination of test data, or a large number of test sets extracted from or derived from every possible combination of test data. For example, every possible combination of test data may include 100,000 data sets. A brute force methodology will either simulate the entire 100,000 data sets or some portion of the 100,000. The portion may be determined in any number of known ways including by random selection or any mathematical distribution (e.g. every third set, or sets selected via a function). Other embodiments use a Monte Carlo method to select data sets. Monte Carlo methods are well known for use in simulation and optimization. For example, in one embodiment, a Markov Chain Monte Carlo sampler is employed. In yet other

embodiments, other methods such as statistical or mathematical methods may be used to select data sets. Varying embodiments of the disclosure contemplate selection of the data sets in any known manner.

[0157] Regarding block 2510, some embodiments receive, derive or create all the data sets before moving on to block 2520 to perform simulations. In some embodiments, this might include running calibration process to ensure the accuracy of the design and input data, and to minimize the uncertainty in the final results. In other embodiments, blocks 2510 and 2520 are iteratively interactive. For example, in an iterative embodiment, one or more data sets may be simulated before new data sets are received, derived or created. For example, the result of one simulation may be used to provide input to a process for deciding the next data set or multiple future data sets. In other words, the iterations may be employed similar to a control system, where future inputs are guided by past outputs.

[0158] Turning now to block 2520 simulations are performed on the received derived or created data sets. As discussed above, simulations may be interleaved or mixed with the reception of data sets, or all simulations may occur after all data sets are created. In some embodiments, the simulations use one or more of the well properties discussed above in addition to the data sets. Different embodiments of the disclosure allow for any known type of simulation to predict resulting stimulation and corresponding hydrocarbon production from a well. For example, small scale numerical coupled CFD-DEM simulations, as known in the art, can be coupled to a 3D reservoir scale fracturing simulators to design and evaluate the resulting stimulation efficiency under different diversion strategy.

[0159] In addition, most embodiments call for generating results data 2525, and in many embodiments the results data is created by the simulation. In one or more embodiments, results data is indicative of the well stimulation and production efficiency for the input well parameters and input data set. In some embodiments, results data may include the number of clusters activated, the amount of activation/propagation for each cluster, the amount of activation/propagation for each phase, stimulated reservoir volume or cumulative production volume under different conditions.

[0160] In most embodiments, the results data must be correlated to the input data set so that when a desirable result data is found, the corresponding test data set may be easily ascertained for use in real-world stimulation. Results data may be stored in the simulation computer or transferred over a network (included over the internet) to other computers and devices. For example, results data may be generated in a data center and transported by wired and/or wireless networks to production area where the data may be evaluated for use by a computer or human.

[0161] Referring now to block 2530, a data set is selected to employ in a well stimulation plan. Some embodiments involve a computer selection of the data set, which is a more desirable technique when many factors from the results data must be considered, potentially in complex analysis, in order to determine the most desirable data set. In other embodiments, humans may evaluate the results data and select the most desirable results data. In either case, the test data set corresponding to the most desired results data may be employed in a well stimulation plan and used to stimulate a well 2535.

Non Limitation

[0162] No limitation is intended by these hardware and software descriptions and the varying embodiments of the inventions herein may include any manner of computing device such as Macs, PCs, PDAs, phones, servers, or even embedded systems, such as a dedicated device.

[0163] It is to be understood that the above description is intended to be illustrative, and not restrictive. The material has been presented to enable any person skilled in the art to make and use the invention as claimed and is provided in the context of particular embodiments, variations of which will be readily apparent to those skilled in the art (e.g., many of the disclosed embodiments may be used in combination with each other). In addition, it will be understood that some of the operations identified herein may be performed in different orders. The scope of the invention therefore should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. As used in this disclosure, (i) the words “include” and “including” and variations thereof, will not be deemed to be terms of limitation, but rather will be deemed to be followed by the words “without limitation,” and (ii) unless the context otherwise requires, the word “or” is intended as an inclusive “or” and shall have the meaning equivalent to “and/or.” Furthermore, in the appended claims, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein.”

CLAIMS

1. A method comprising
receiving properties data regarding properties of a well area, the properties data including
an indication of a planned stimulation time;
receiving a plurality of test data sets, each test data set comprising a quantity of diversion
slugs and an indication of a timing for injecting each diversion slug relative to the
planned stimulation time;
for each of the plurality of test data sets, performing a simulation to predict a stimulation
efficiency and a production result from the well area in the event that a particular
one of the test data sets is used;
producing results data that correlates each of the plurality test data sets with the predicted
stimulation efficiency and the production result;
choosing, from the results data, a best of the test data sets based upon the corresponding
stimulation efficiency and production result; and
stimulating the well area by using the quantity of the diversion slugs and the indication of
the timing for injecting each the diversion slugs relative to the planned stimulation
time of the best test data set.
2. The method of claim 1, wherein the properties data regarding properties of the well area
comprises at least three of the following: perforation density, length per cluster, perforation size,
flow rate, fluid viscosity, target zone, pore pressure, and closure stress gradient.
3. The method of claim 1 or 2, wherein the properties data regarding properties of the well
area comprises at least two of the following fluid and proppant properties: fluid density; fluid
viscosity; proppant density; and proppant diameter.
4. The method of claim 1, 2 or 3, wherein the properties data regarding properties of the
well area comprises at least two of the following geomechanical and rock properties: Young's
Modulus; Poisson's Ration; matrix permeability; and initial pore pressure.
5. The method of any one of claims 1 to 4, wherein performing the simulation comprises
performing the simulation using a first of the test data sets prior to receiving a second of the test
data sets.
6. The method of claim 5, wherein receiving the second test data set comprises selecting the
second test data set based at least in part upon the results data corresponding to the first test data
set.

7. The method of any one of claims 1 to 6, wherein each diversion slug comprises a volume of slurry and degradable particles with specific properties.
8. The method of any one of claims 1 to 6, wherein one or more of the diversion slugs comprise degradable particles, and wherein specific properties of the degradable particles comprise one or more of: particles size, particle size ratio, particle concentration, and particle shape.
9. The method of any one of claims 1 to 8, wherein performing the simulation comprises coupling wellbore scale diversion modeling to reservoir scale stimulation modeling.
10. The method of claim 9, wherein the reservoir scale stimulation modeling comprises one or more of a fracturing operation, a refracturing operation, and an acidizing operation.
11. The method of any one of claims 1 to 10, wherein performing the simulation to predict the stimulation efficiency comprises basing the stimulation efficiency upon one or more of: mitigating out-of-zone fracture propagation, maximizing proppant coverage and corresponding fracture conductivity by controlling fracture length, and stimulating uniformly along a wellbore length.
12. The method of any one of claims 1 to 11, wherein performing the simulation to predict the stimulation efficiency and the production result comprises basing the predicted stimulation efficiency and production result upon an optimization algorithm applied to a corresponding one of the test data sets.
13. The method of any one of claims 1 to 12, wherein receiving the plurality of test data sets comprises determining the plurality of test data sets using a Monte Carlo method.
14. A non-transitory program storage device, readable by a processor and comprising instructions stored thereon to cause one or more processors to:
 - receive properties data regarding properties of a well area, the properties data including an indication of a planned stimulation time;
 - receive a plurality of test data sets, each test data set comprising a quantity of diversion slugs and an indication of a timing for injecting each diversion slug relative to the planned stimulation time;
 - for each of the plurality of test data sets, performing a simulation to predict a stimulation efficiency and a production result from the well area in the event that a particular one of the test data set is used;
 - produce results data that correlates each of the plurality test data sets with the predicted stimulation efficiency and the production result; and

choose, from the results data, a best of the test data sets based upon the corresponding stimulation efficiency and production result.

15. The device of claim 14, wherein the properties data regarding properties of the well area comprises at least three of the following: perforation density, length per cluster, perforation size, flow rate, fluid viscosity, target zone, pore pressure, and closure stress gradient.
16. The device of claim 14 or 15, wherein the properties data regarding properties of the well area comprises at least two of the following fluid and proppant properties: fluid density; fluid viscosity; proppant density; and proppant diameter
17. The device of claim 14, 15, or 16, wherein the properties data regarding properties of the well comprises at least two of the following geomechanical and rock properties: Yeung's Modulus; Poisson's Ration; matrix permeability; and initial pore pressure.
18. The device of any one of claims 14 to 17, further comprising instructions to cause the one or more processors to perform the simulation using a first of the test data sets prior to receiving a second of the test data sets.
19. The device of claim 18, wherein to receive the second test data set, the device further comprises instructions to cause the one or more processors to select the second test data set based at least in part upon the results data corresponding to the first test data set.
20. The device of any one of claims 14 to 19, wherein to receive the second test data set, the device further comprises instructions to cause the one or more processors to determine the plurality of test data sets using a Monte Carlo method.
21. The device of any one of claims 14 to 20, wherein one or more diversion slugs comprise degradable particles, and wherein specific properties of the degradable particles comprises one or more of: particles size, particle size ratio, particle concentration, and particle shape.
22. The device of any one of claims 14 to 21, wherein to perform the simulation, the device comprises instructions stored thereon to cause the one or more processors to couple wellbore scale diversion modeling to reservoir scale stimulation modeling
23. The device of claim 22, wherein the reservoir scale stimulation modeling comprises one or more of a fracturing operation, a refracturing operation, and an acidizing operation.
24. The device of any one of claims 14 to 23, wherein to perform the simulation to predict the stimulation efficiency, the device comprises instructions stored thereon to cause the one or more processors to base the stimulation efficiency upon one or more of: mitigating out-of-zone fracture propagation, maximizing proppant coverage and corresponding fracture conductivity by controlling fracture length, and stimulating uniformly along a wellbore length.

25. The device of any one of claims 14 to 24, wherein to perform the simulation to predict the stimulation efficiency and the production result, the device comprises instructions stored thereon to cause the one or more processors to base the predicted stimulation efficiency and the production result upon an optimization algorithm applied to a corresponding one of the test data sets.
26. A method comprising
determining a plurality of test data sets, each test data set comprising a quantity of diversion slugs and an indication of a timing for injecting each diversion slug relative to a planned stimulation time;
for each of the plurality of test data sets, performing a simulation to predict a production result from a well area in the event that a particular one of the test data sets is used, each simulation using as inputs at least one of the test data sets and a plurality of properties regarding the well area;
as a product of each simulation, producing results data that correlates each test data set with a predicted result regarding the stimulation efficiency and the production result from the well area;
choosing, from the results data, a best of the test data sets based upon a comparison of the predicted result corresponding to the best test data with the predicted results corresponding to a plurality of the other test data sets.
27. The method of claim 26, further comprising stimulating the well area using the best test data.
28. The method of claim 26 or 27, wherein performing the simulation comprises using a first of the test data sets prior to determining a second of the test data sets.
29. The method of claim 28, wherein determining the second test data set comprises basing the determination at least in part upon the results data corresponding to the first test data set.
30. The method of any one of claims 26 to 29, wherein each diversion slug comprises a volume of slurry and degradable particles.
31. The method of any one of claims 26 to 29, wherein the diversion slugs comprise degradable particles having specific properties, and wherein the specific properties comprise one or more of the following: particles size, particle size ratio, particle concentration, and particle shape.
32. The method of any one of claims 26 to 31, wherein performing the simulation comprises coupling wellbore scale diversion modeling to reservoir scale stimulation modeling.

33. The method of claim 32, wherein the reservoir scale stimulation modeling comprises one or more of a fracturing operation, a refracturing operation, an acidizing operation.
34. The method of any one of claims 26 to 33, wherein the best test data set includes a number of diversion slugs and their corresponding timing for injection to be used for real-field stimulation application.
35. The method of any one of claims 26 to 34, wherein performing the simulation further comprises performing the simulation to predict a stimulation efficiency measured based upon one or more of: mitigating out-of-zone fracture propagation, maximizing proppant coverage and corresponding fracture conductivity by controlling fracture length, and stimulating uniformly along a wellbore length.
36. The method of claim 35, wherein performing the simulation to predict the stimulation efficiency and the production result comprises using an optimization algorithm to determine the corresponding test data set.
37. The method of any one of claims 26 to 36, wherein determining the plurality of test data sets comprises determining the plurality of test data sets using a Monte Carlo method.

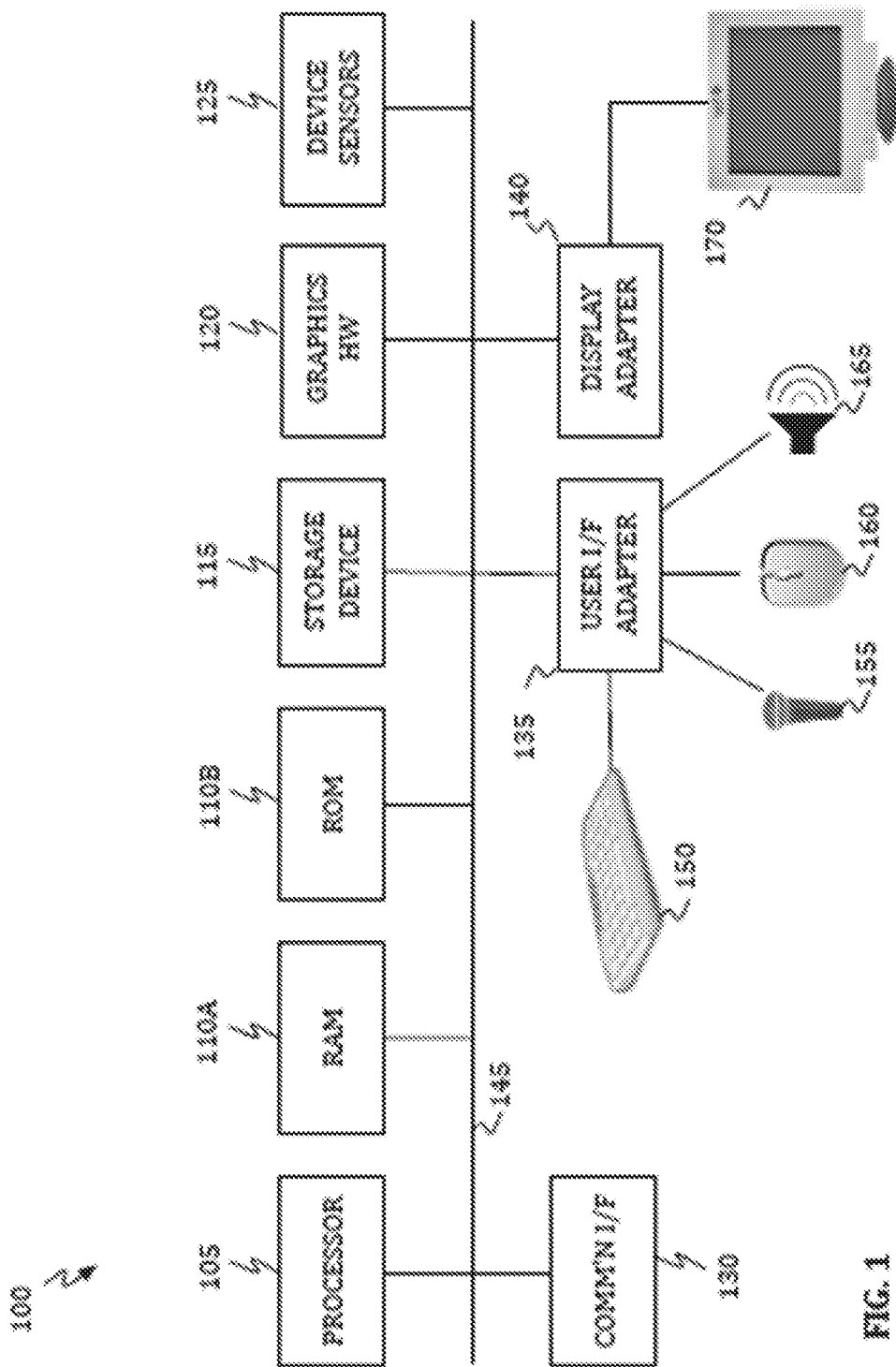


FIG. 1

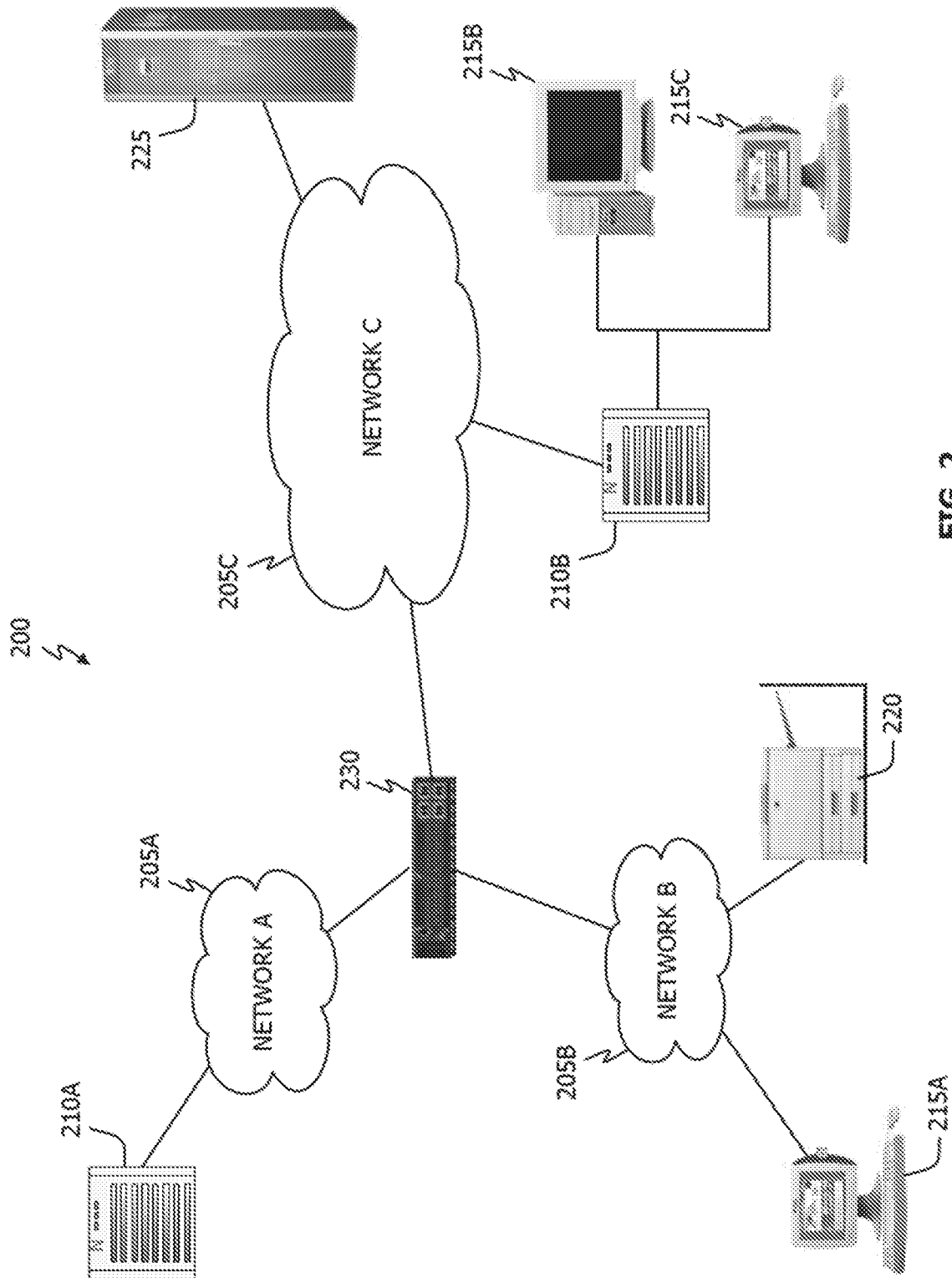


FIG. 2

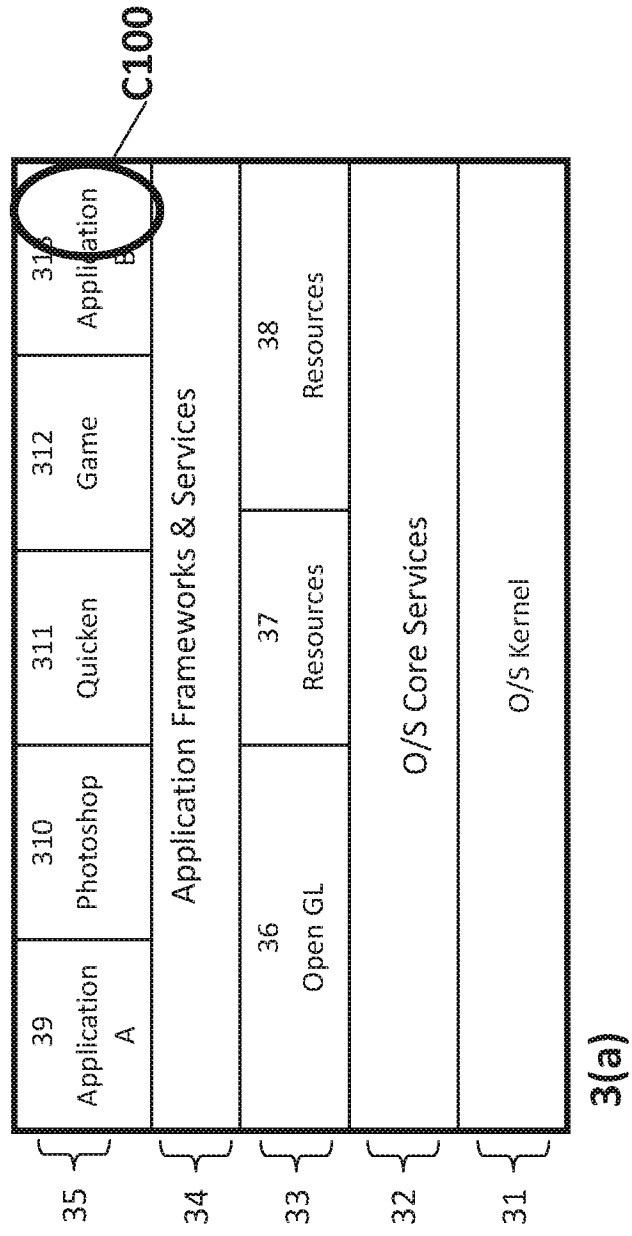


FIG. 3

Aspects of Project Efficiency

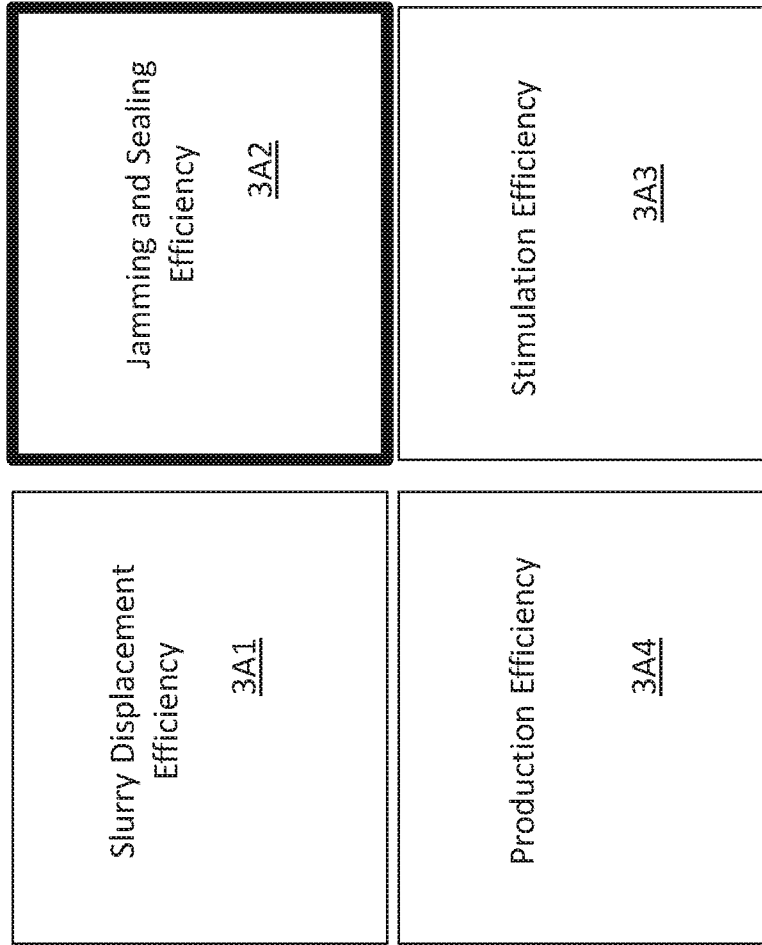


FIG. 3A

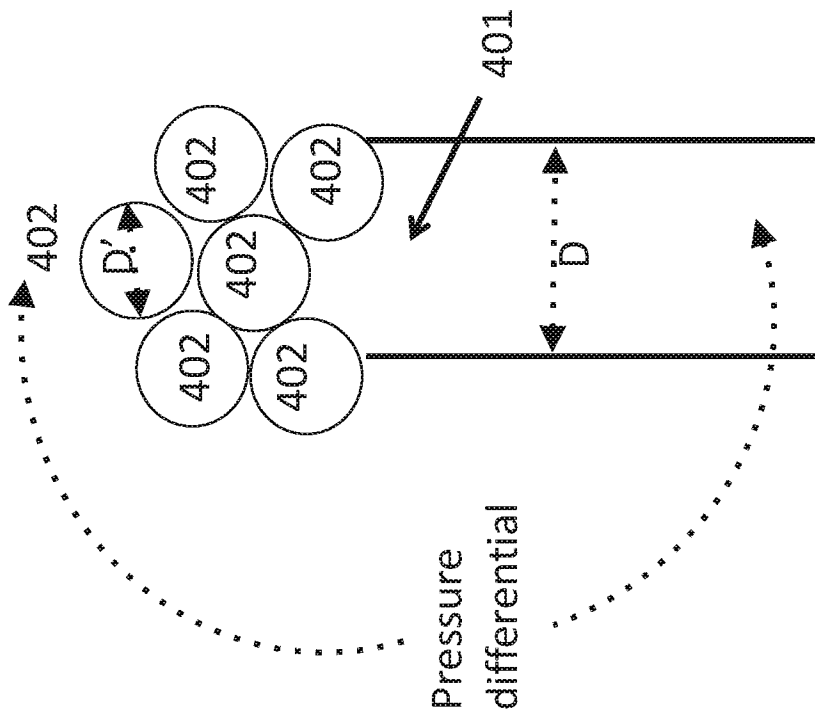


FIG. 4A

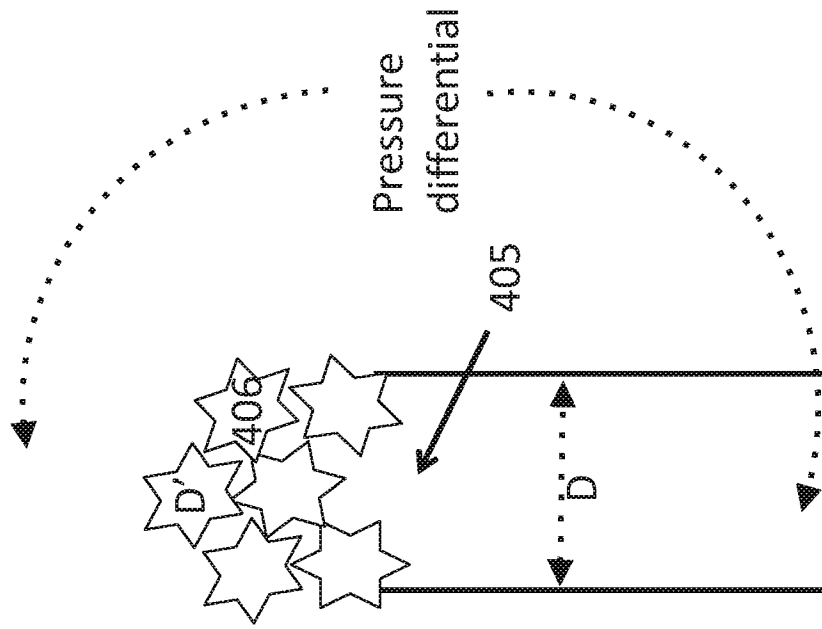


FIG. 4B

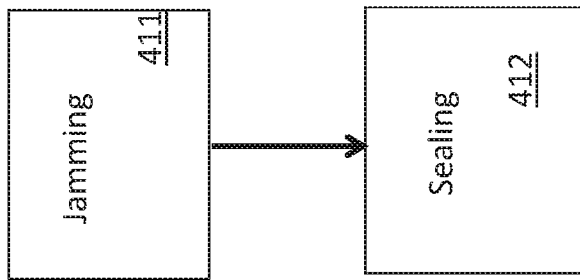


FIG. 4C

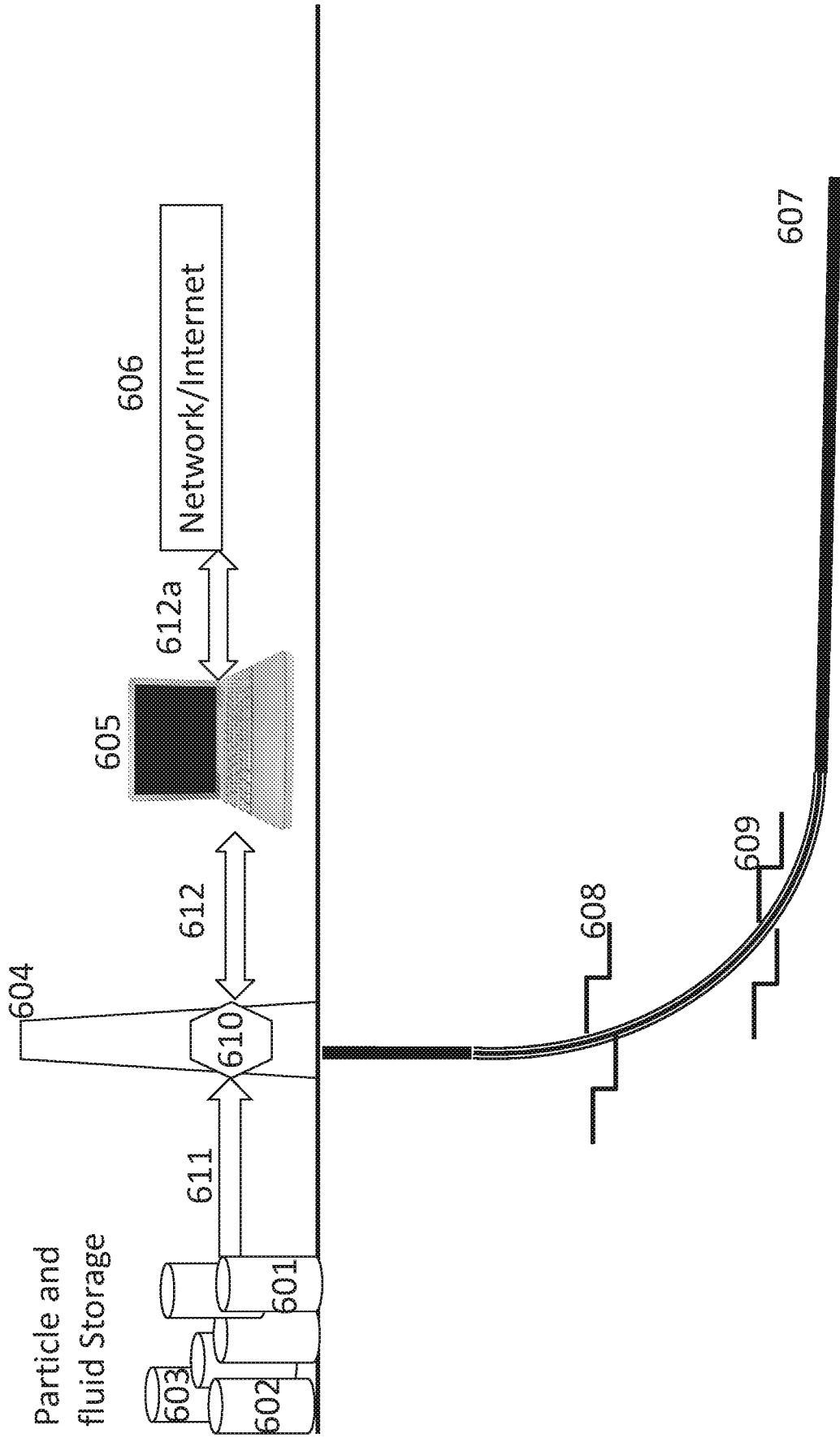


FIG. 6

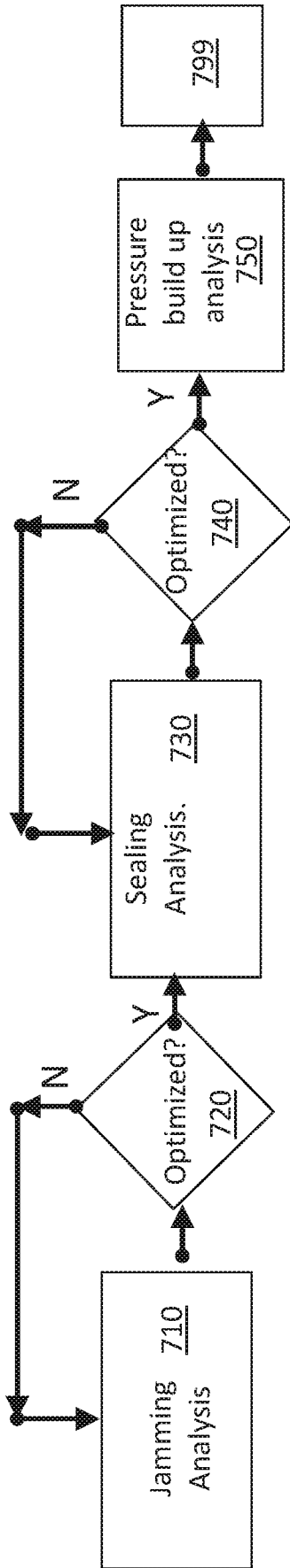


FIG. 7a

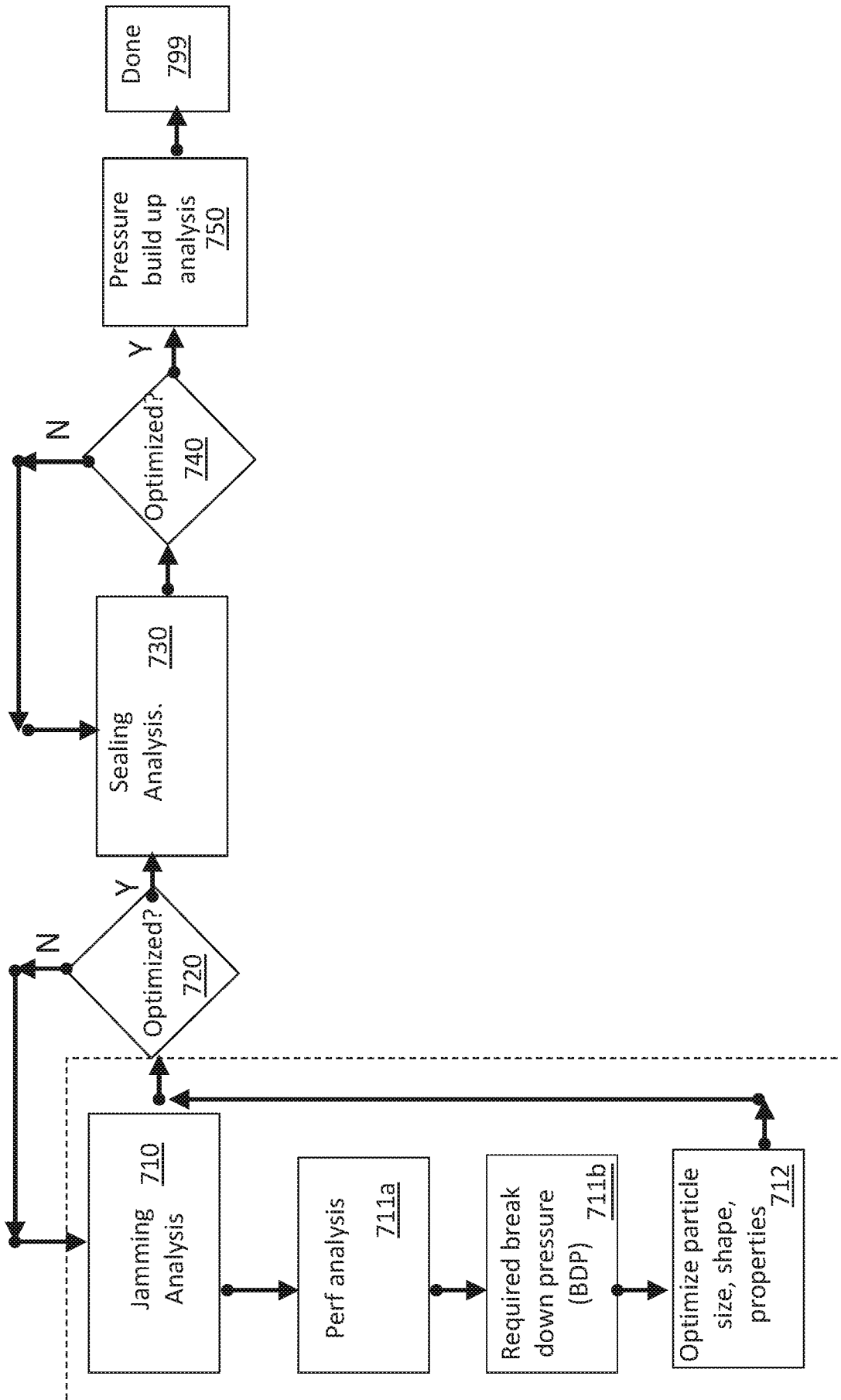


FIG. 7b

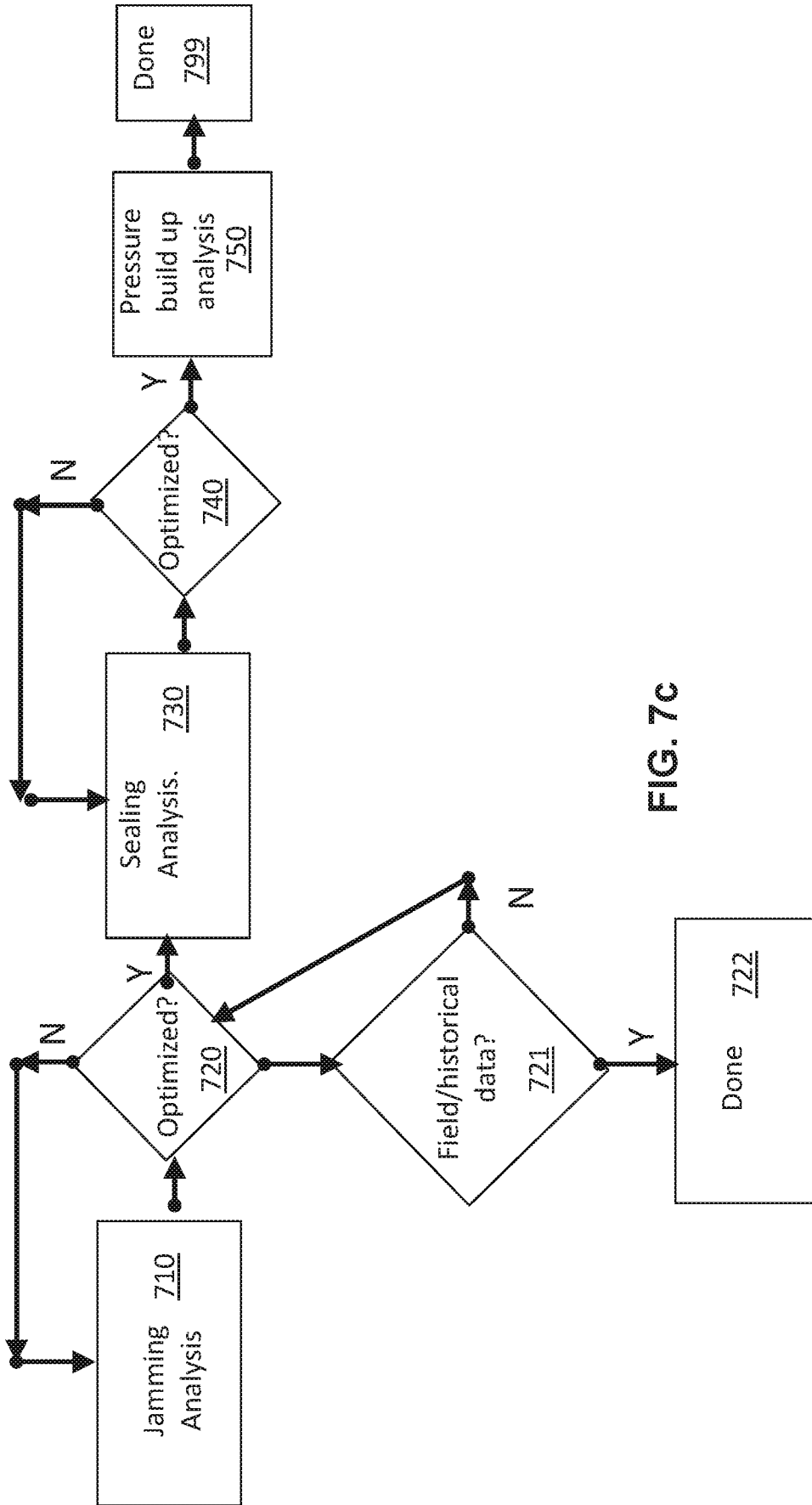


FIG. 7c

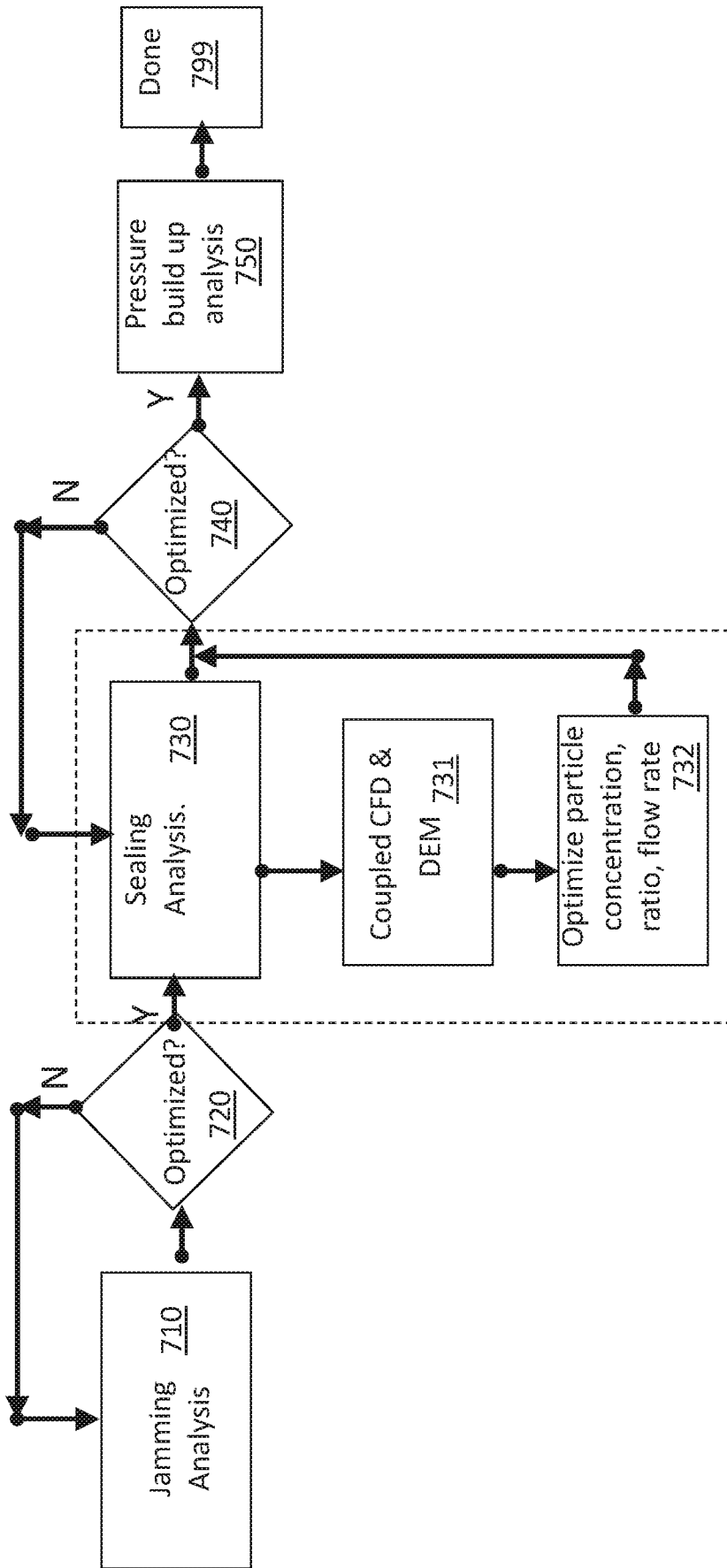


FIG. 7d

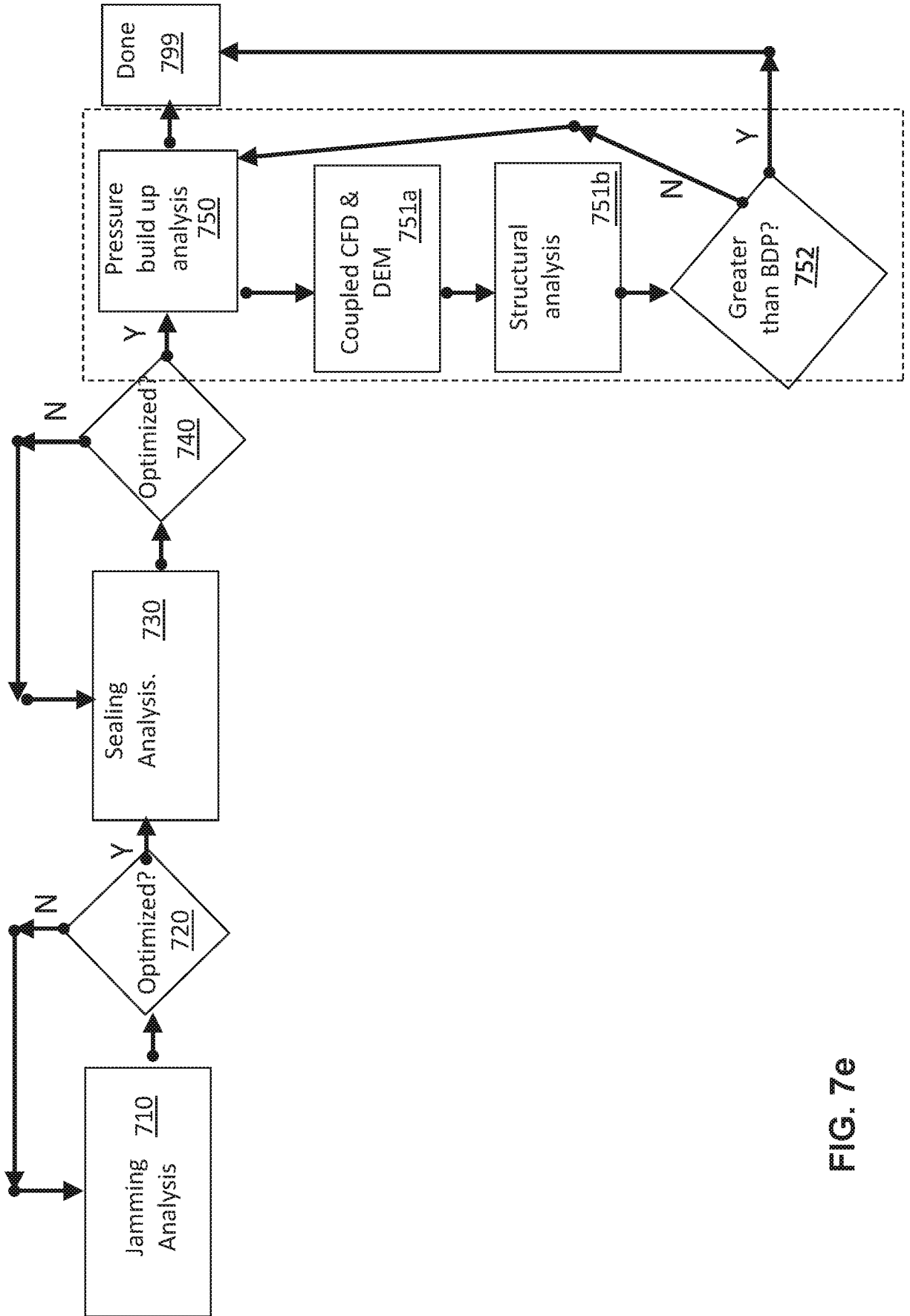


FIG. 7e

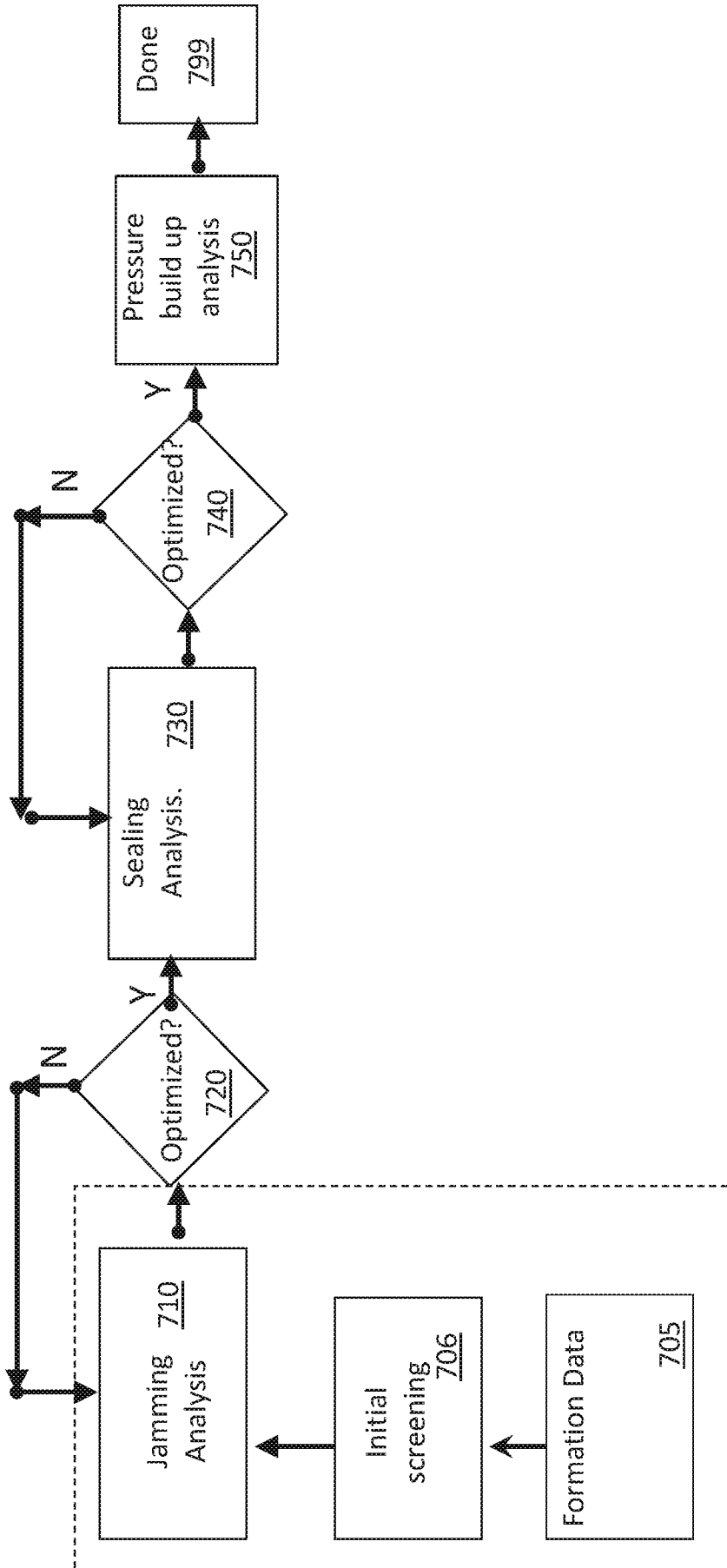


FIG. 7f

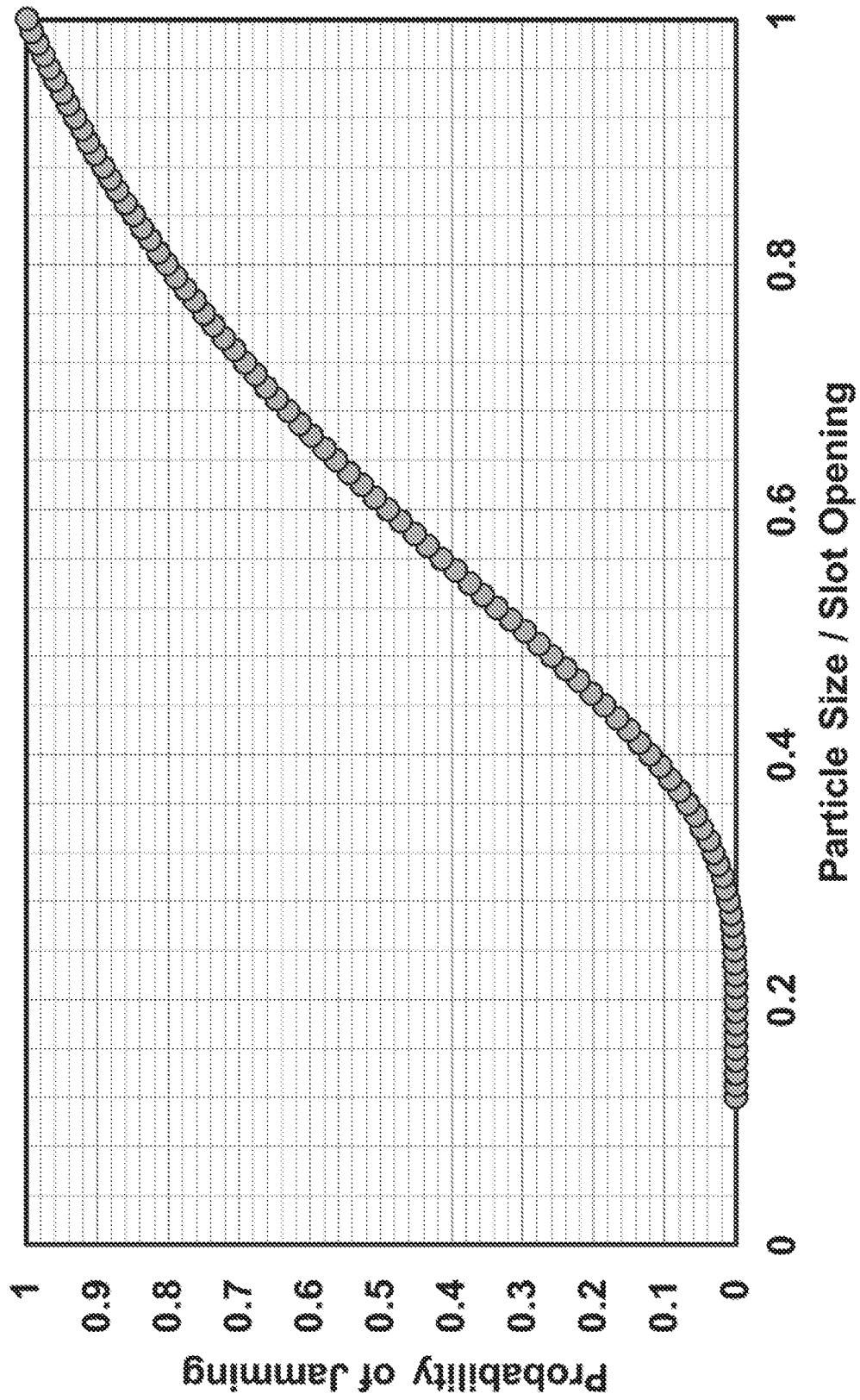


FIG. 8

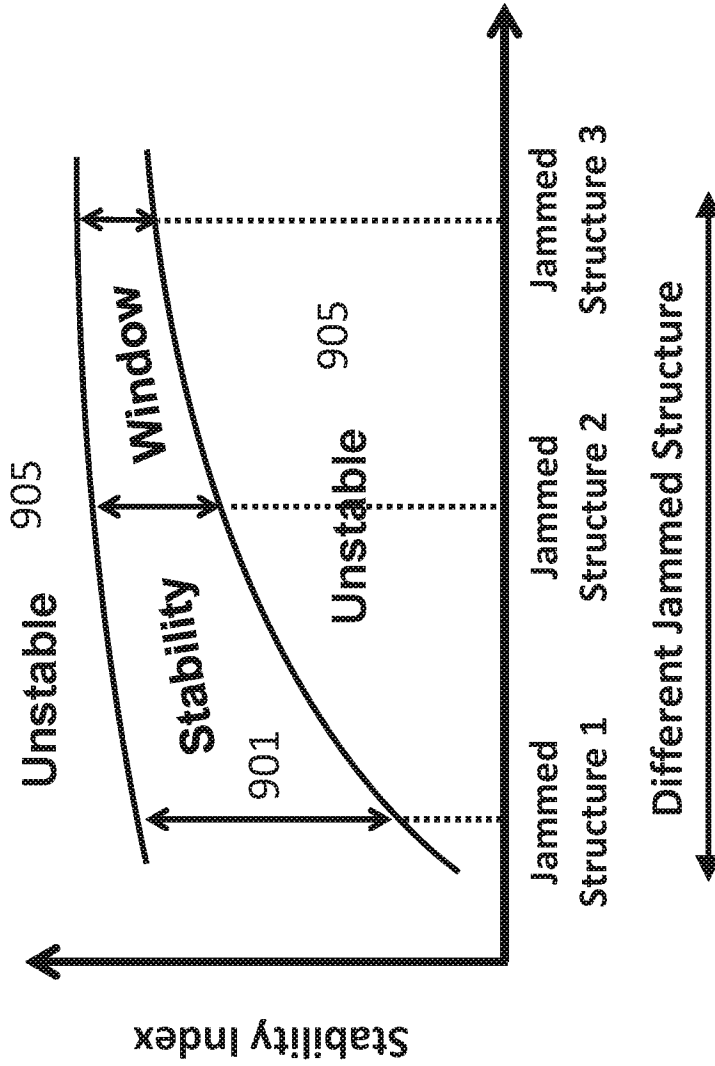


FIG. 9

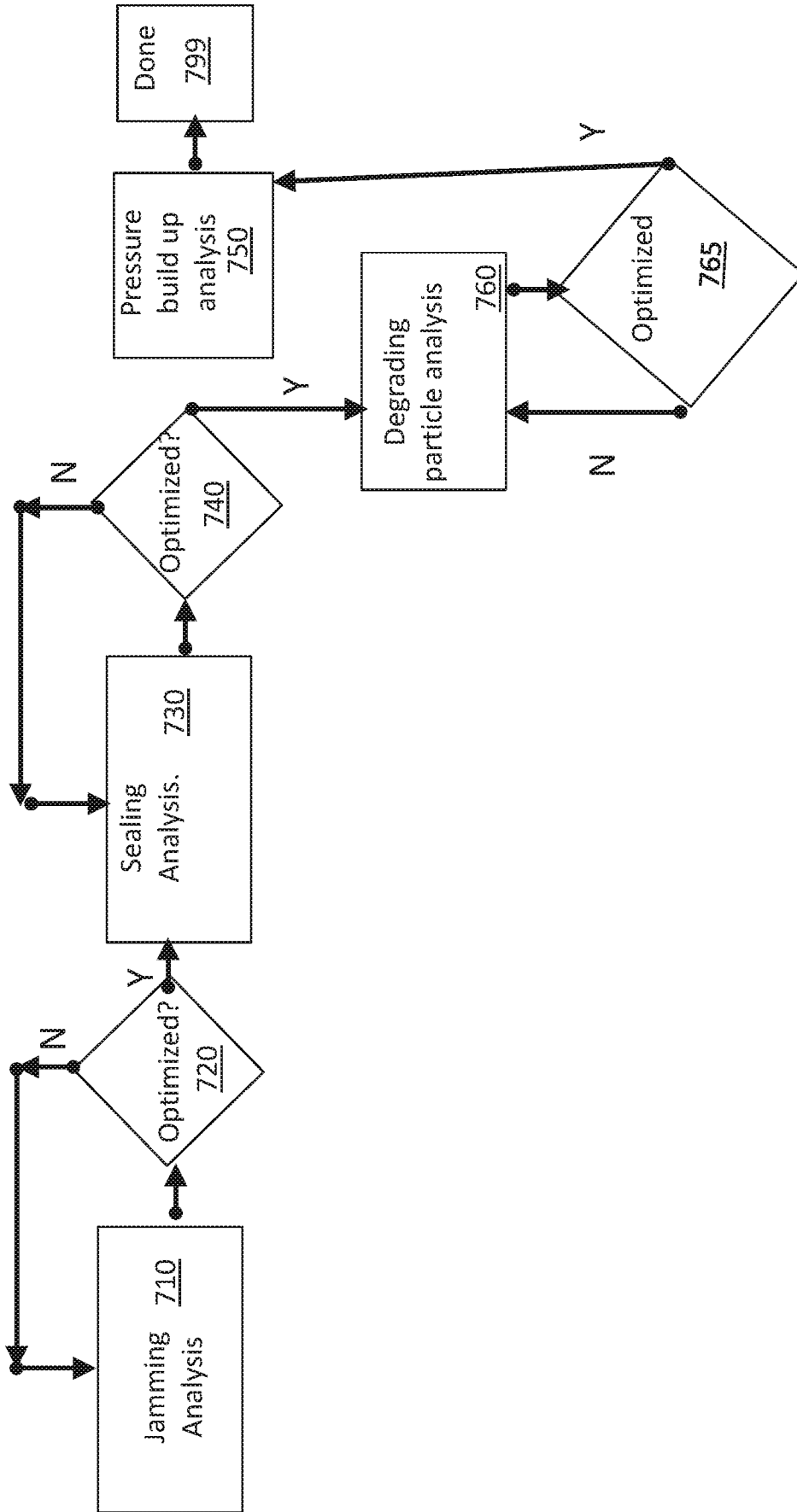


FIG. 10

Aspects of Project Efficiency

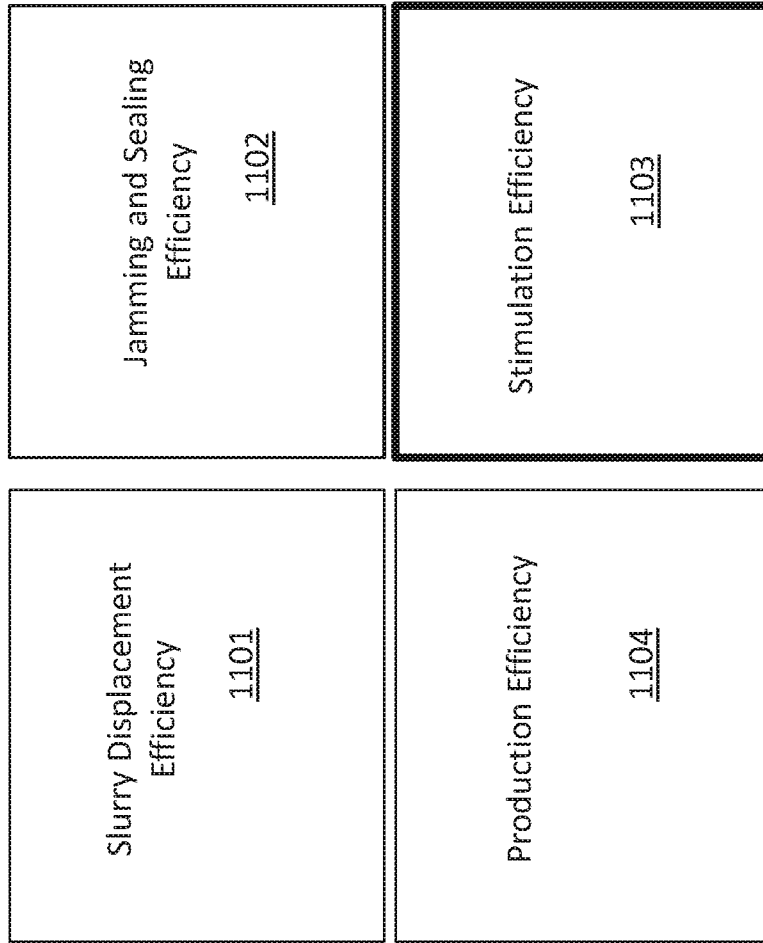


FIG.11

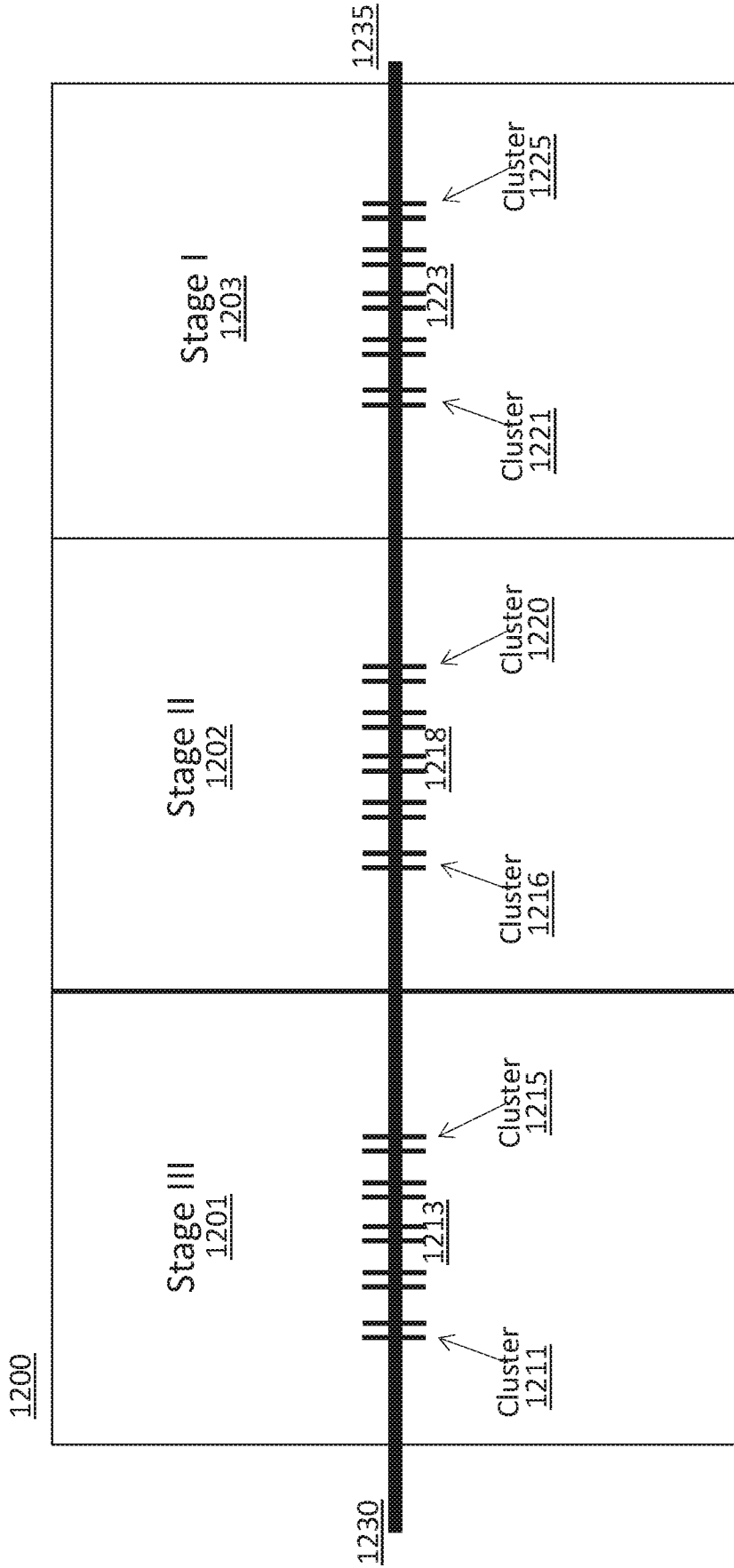
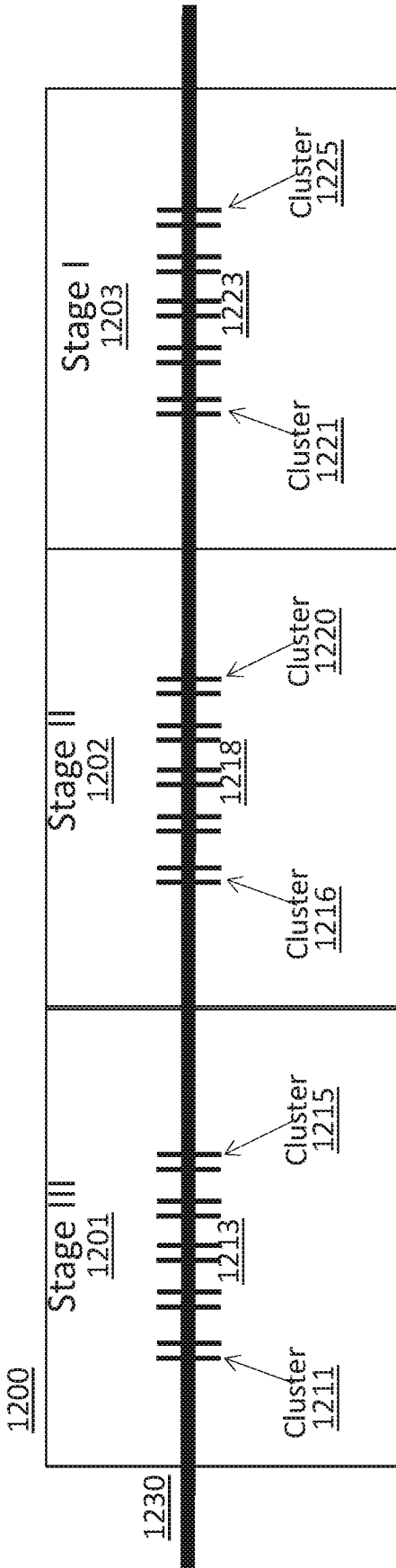


FIG.12



Step	Duration	Tracer Color
1. Stage 1 tracer injection	15 min	Red
2. Diversion		
3. Stage 2 tracer injection	15 min	Blue
4. Diversion		
5. Stage 3 tracer injection	15 minutes	Yellow

1300

FIG.13

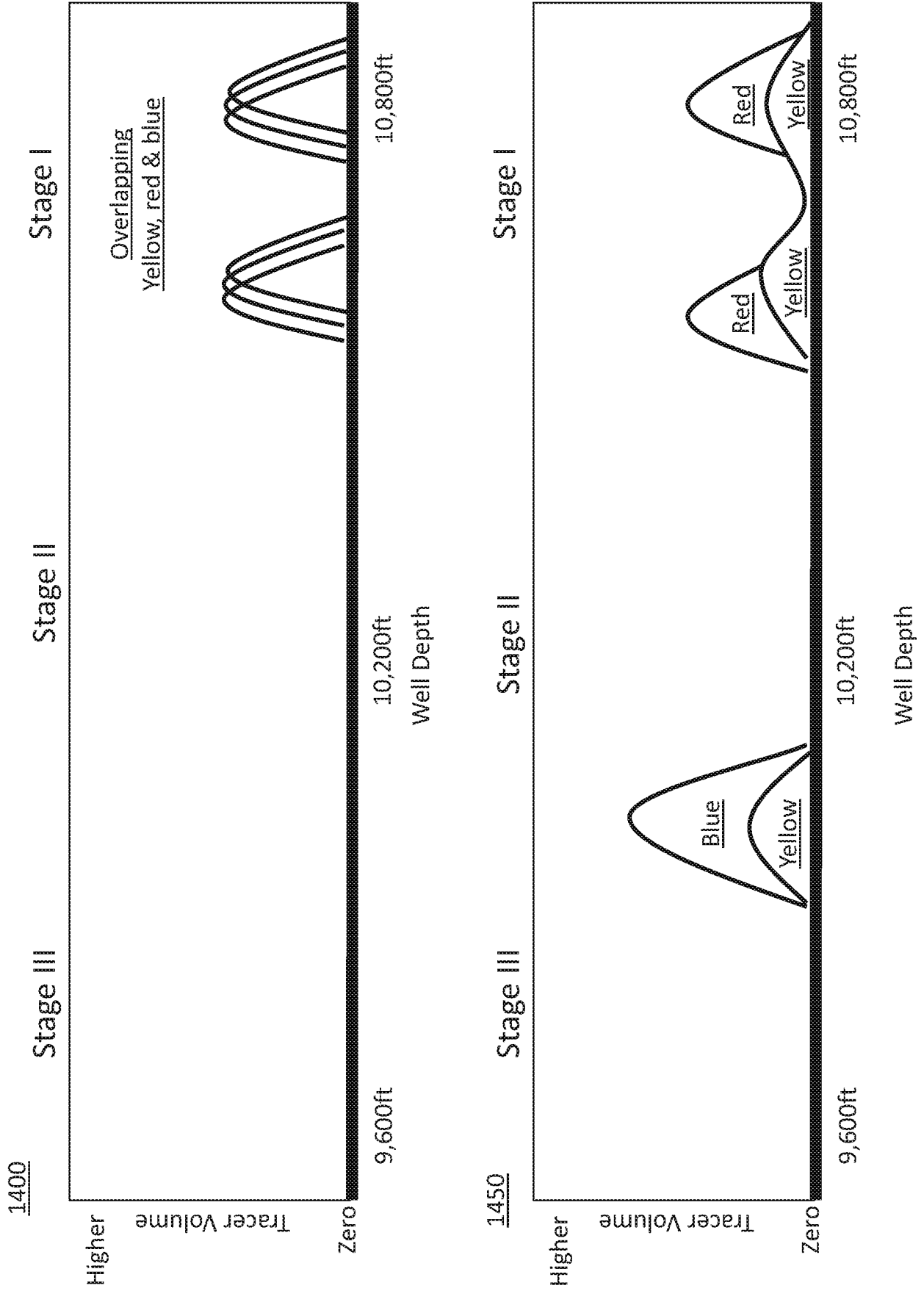


FIG.14

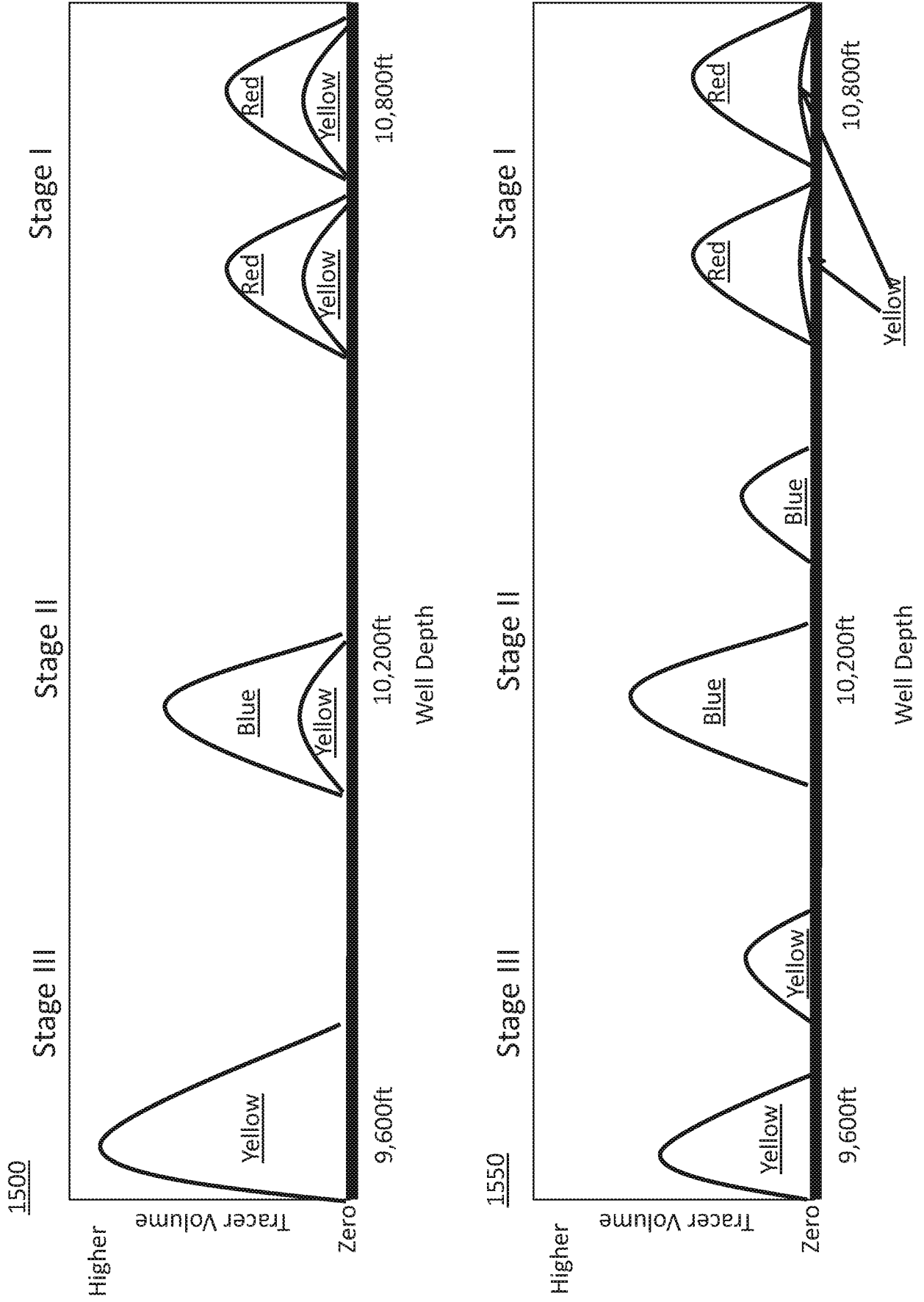


FIG.15

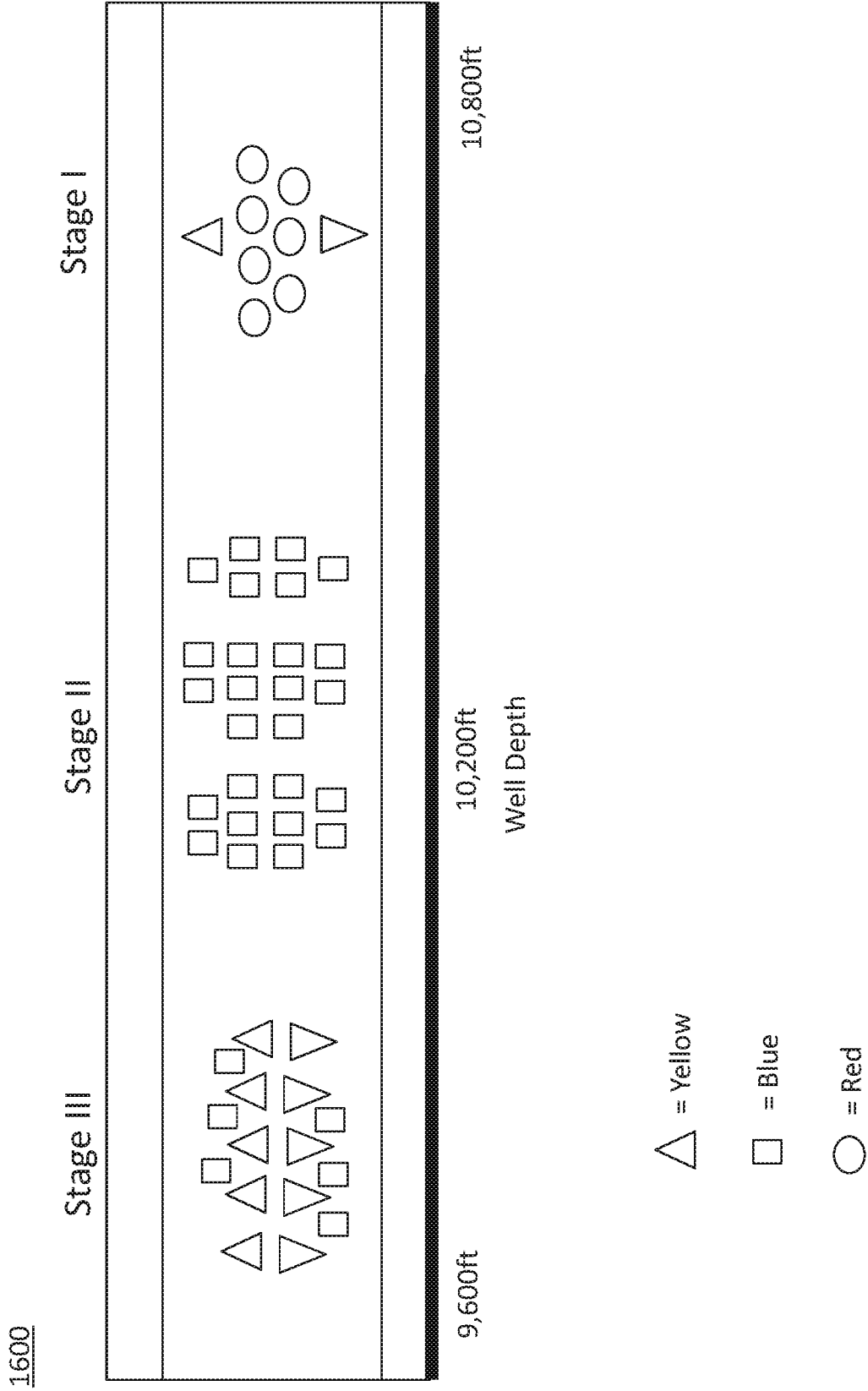


FIG. 16

1700

Step	Duration	Tracer Color
1. Stage 1 tracer injection	7.5 min	Red
2. Diversion		
3. Stage 1 tracer injection	7.5 min	Red
4. Diversion		
5. Stage 2 tracer injection	7.5 min	Blue
6. Diversion		
7. Stage 2 tracer injection	7.5 min	Blue
8. Diversion		
9. Stage 3 tracer injection	7.5 min	Yellow
10. Diversion		
11. Stage 3 tracer injection	7.5 min	Yellow

FIG.17

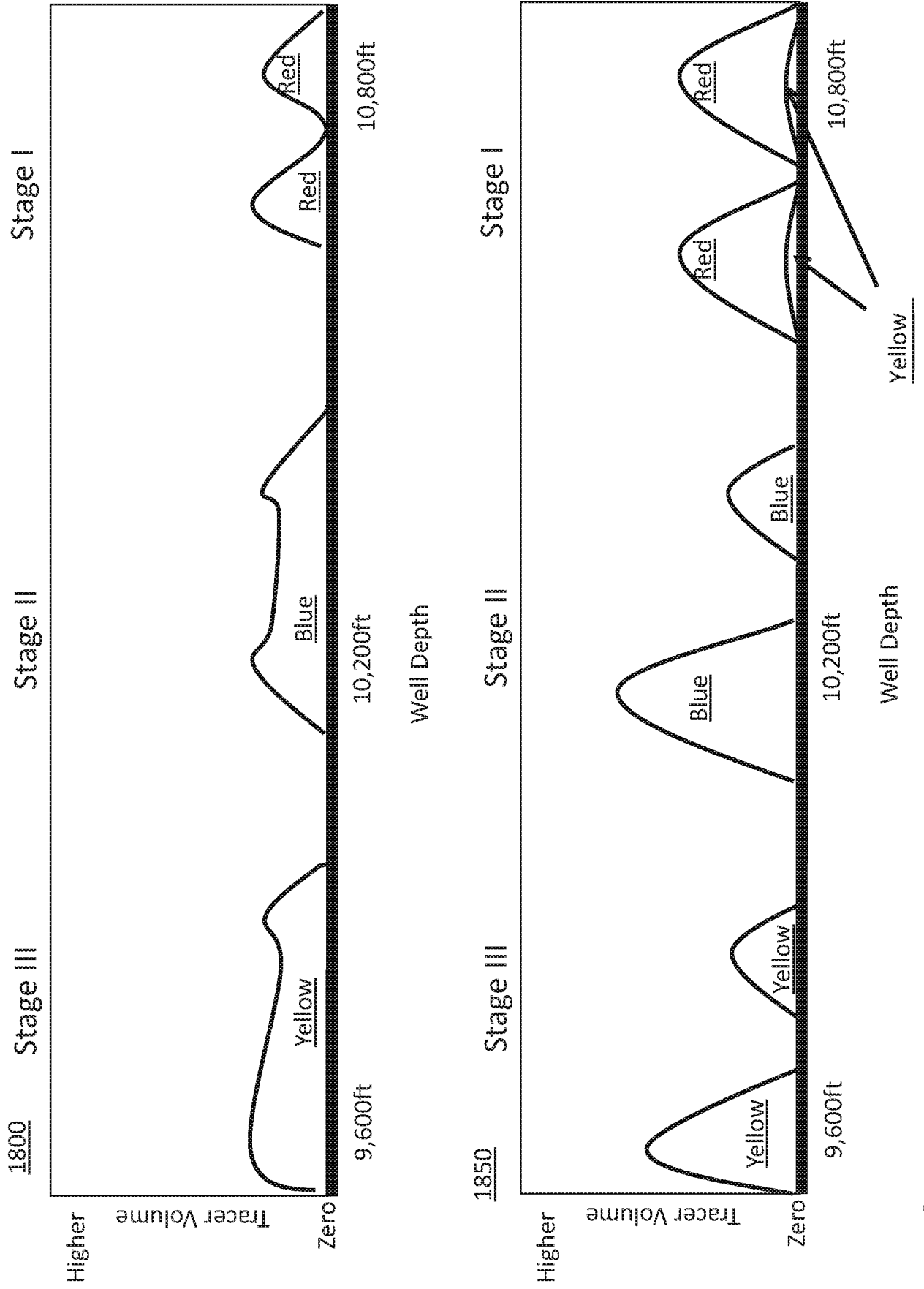


FIG.18

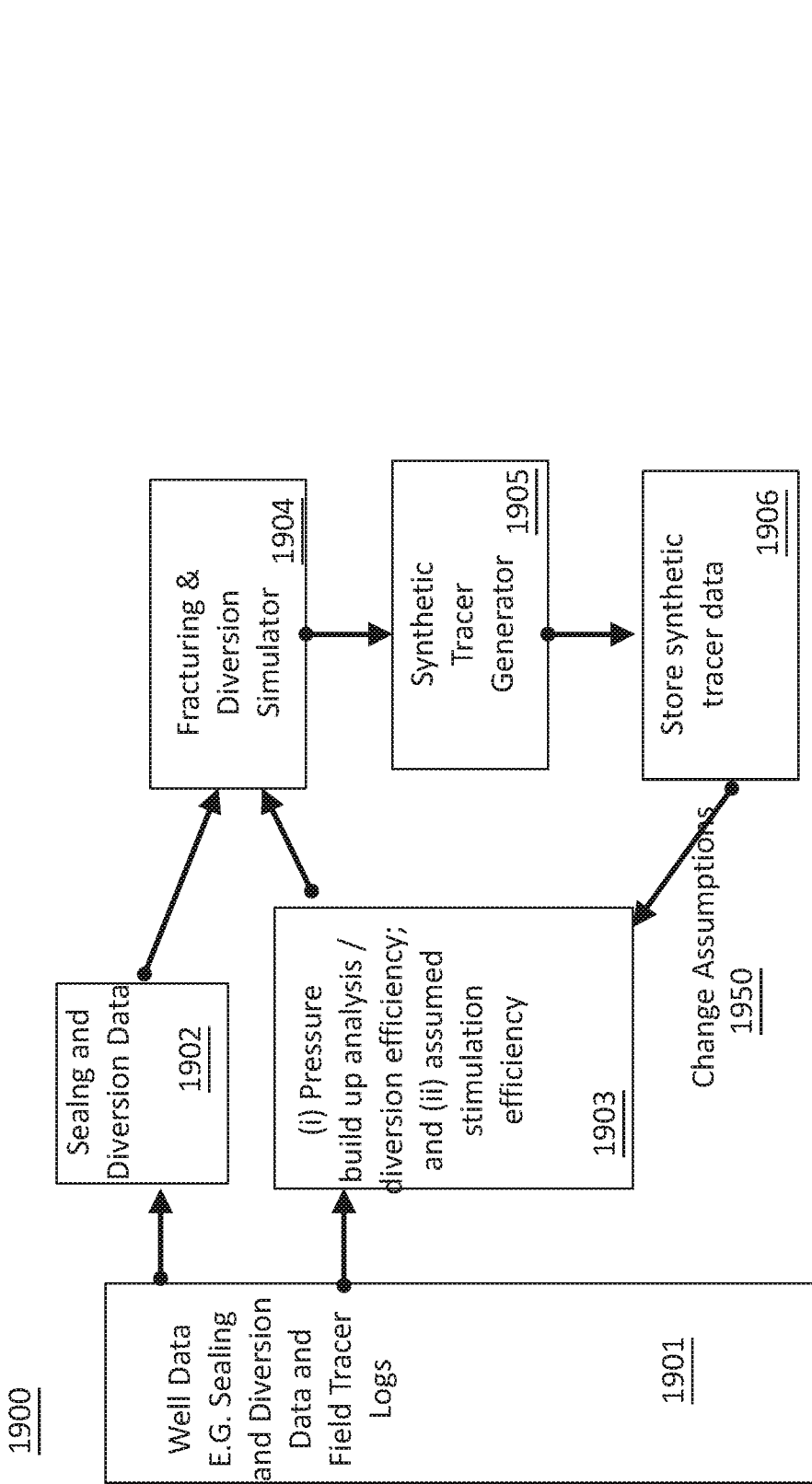


FIG. 19

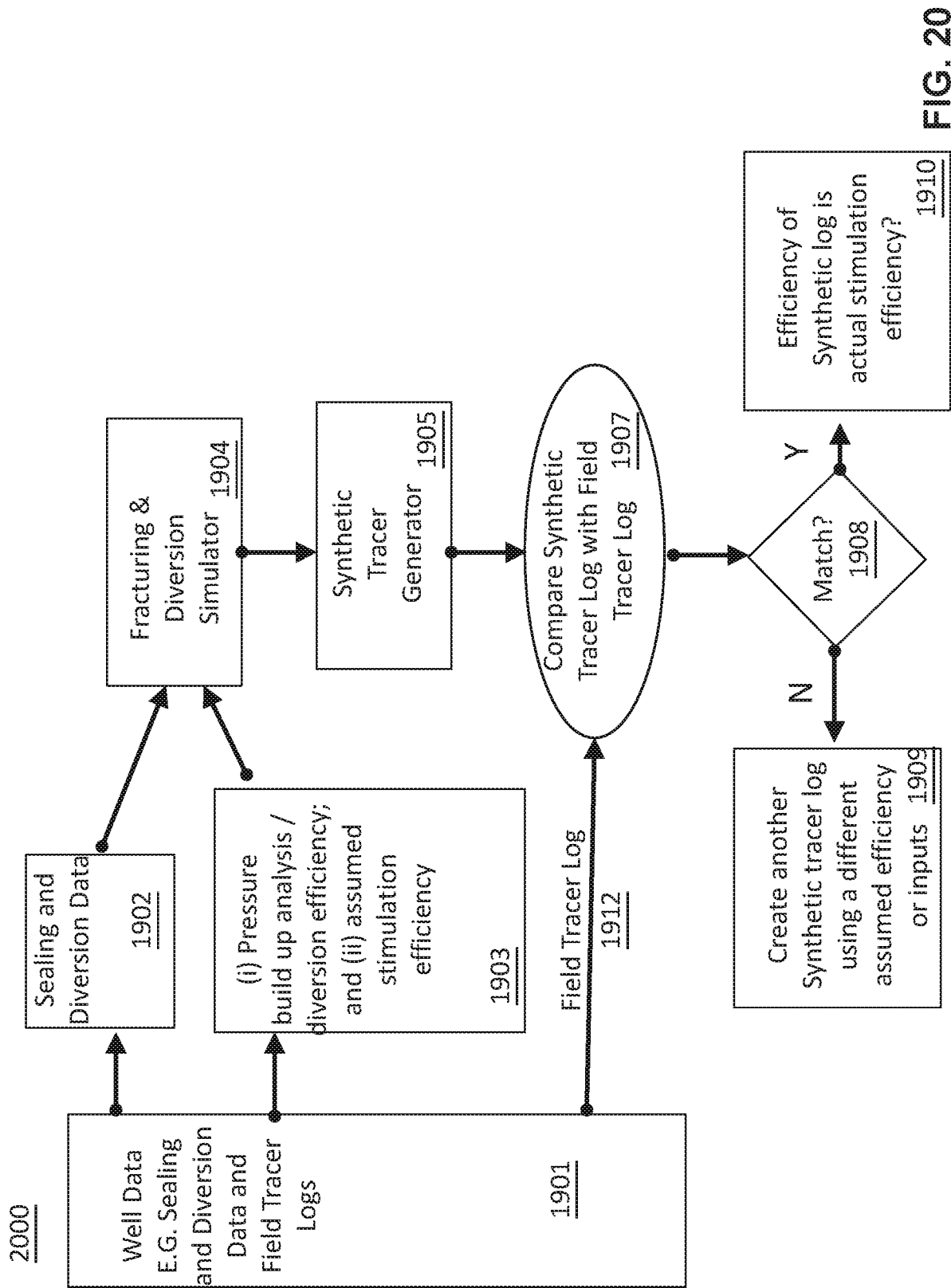


FIG. 20

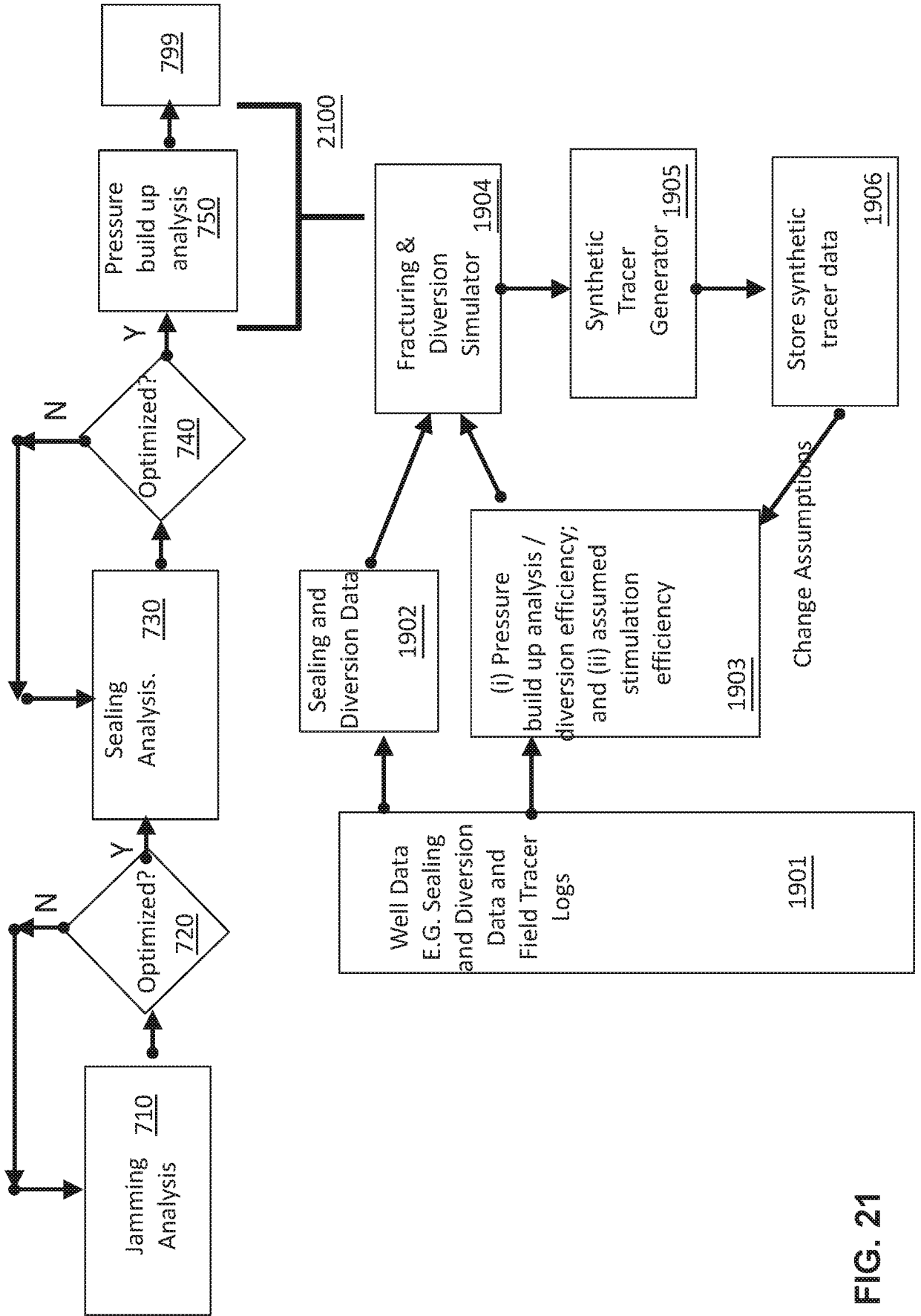


FIG. 21

2200

Step	Duration
1. Stimulation injection	7.5 min
2. Diversion slug	
3. Stimulation injection	7.5 min

FIG.22a

2205

Step	Duration
1. Stimulation injection	5 min
2. Diversion slug	
3. Stimulation injection	5 min
4. Diversion slug	
5. Stimulation injection	5 min

FIG.22b

2210

Step	Duration
1. Stimulation injection	3 min
2. Diversion slug	
3. Stimulation injection	3 min
4. Diversion slug	
5. Stimulation injection	3 min
6. Diversion slug	
7. Stimulation injection	3 min
8. Diversion slug	
9. Stimulation injection	3 min

FIG.22c

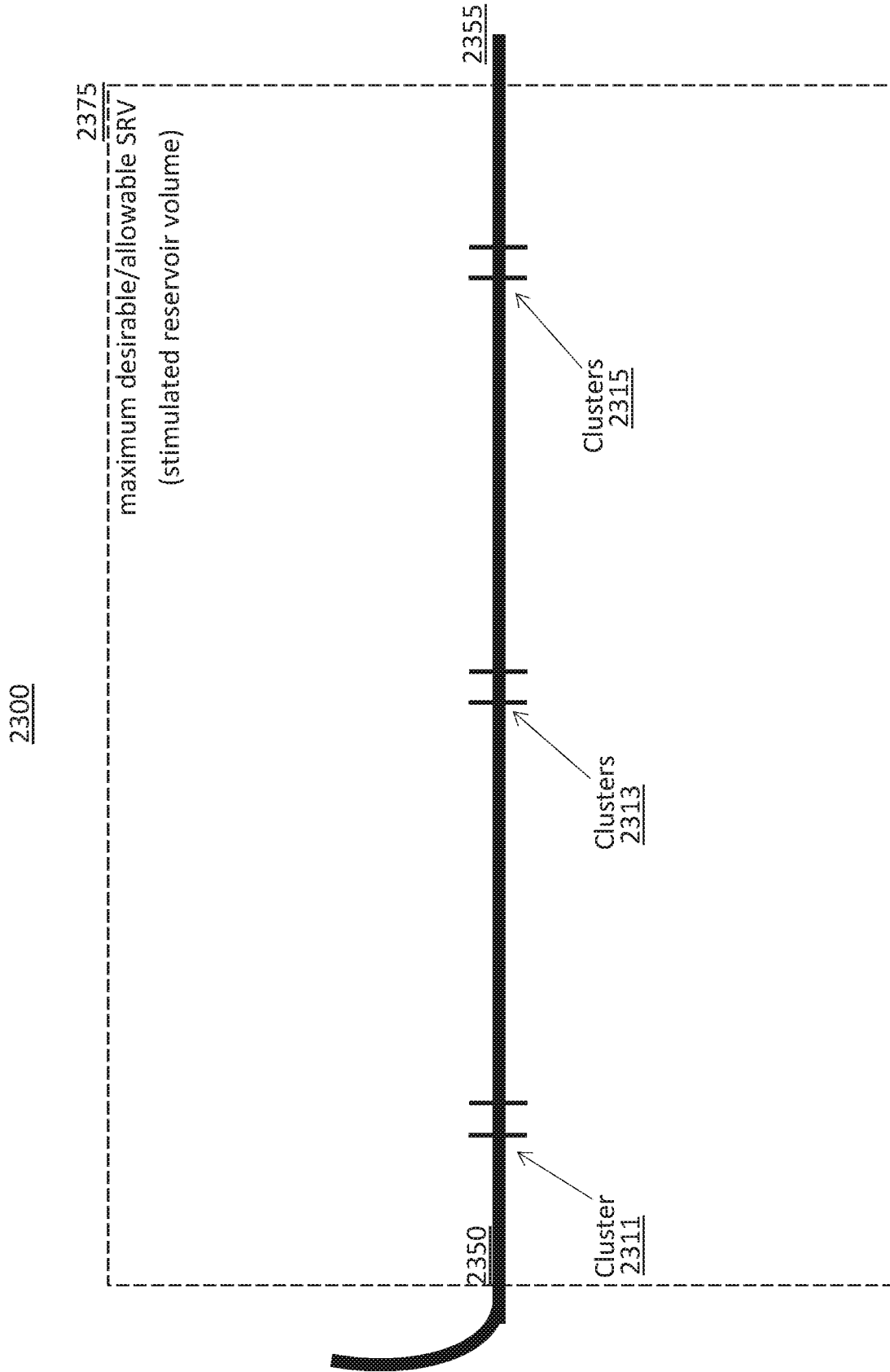


FIG.23a

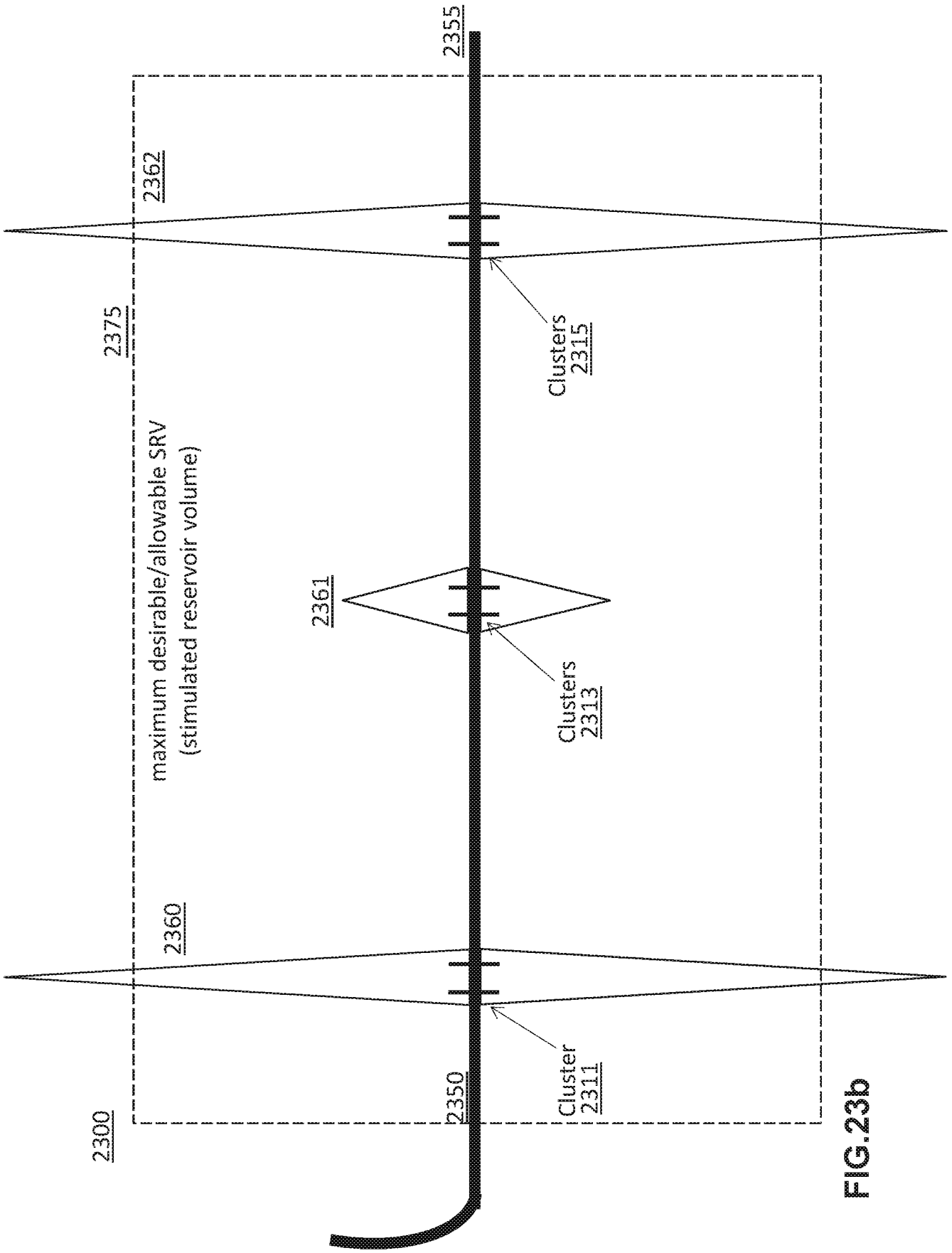


FIG.23b

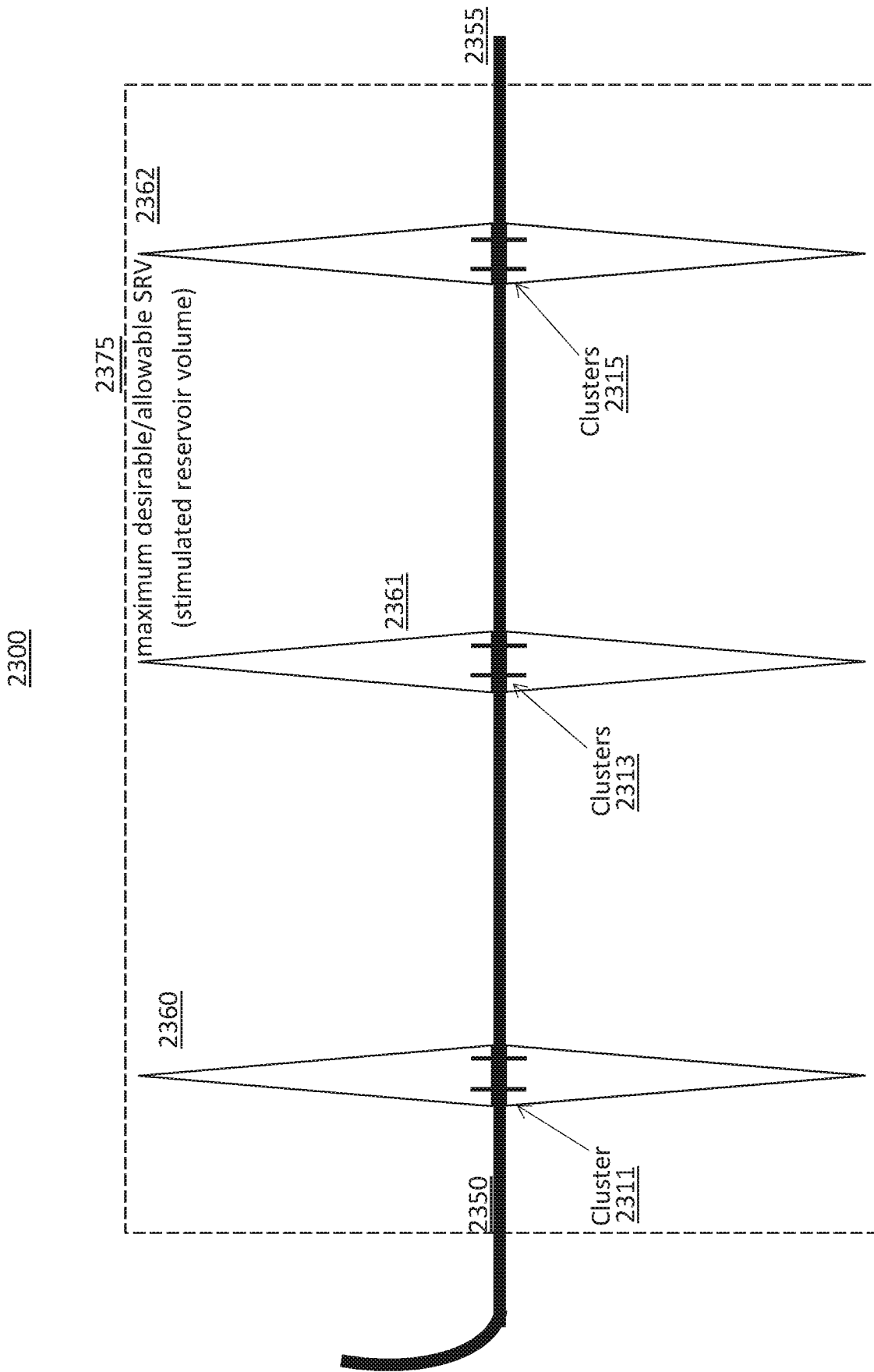


FIG.23c

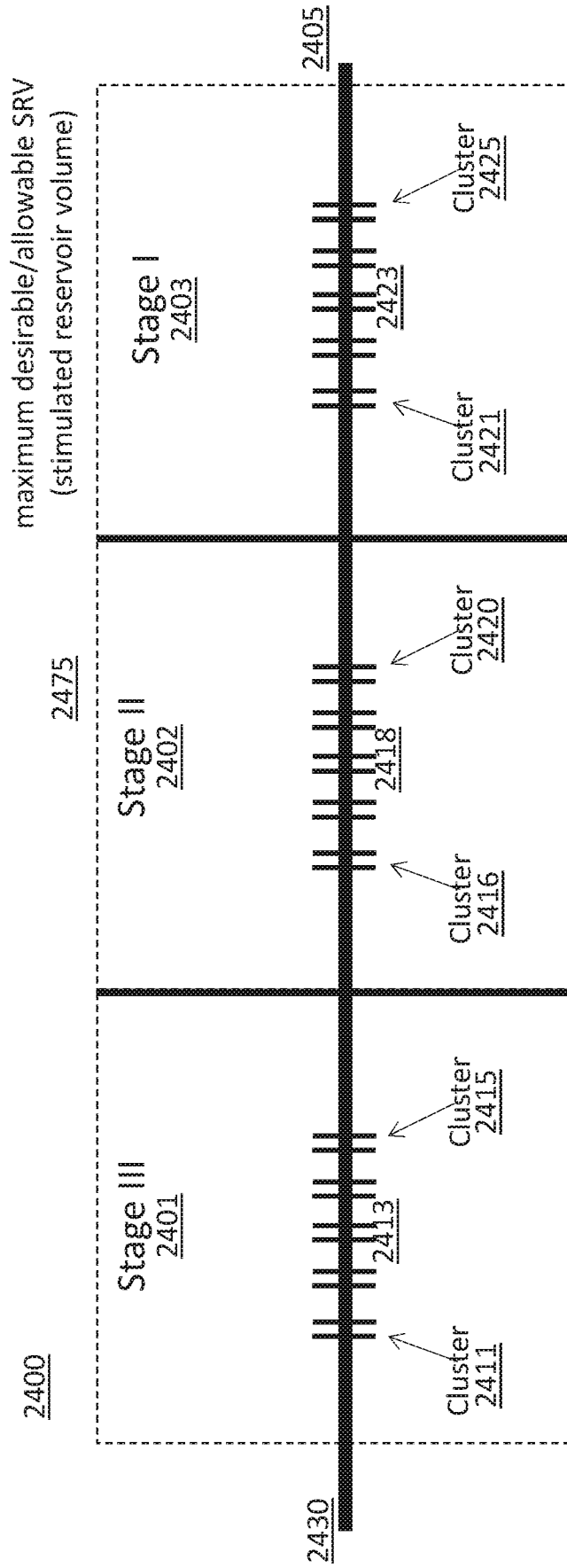


FIG.24

2491

Step	Duration	Well Stage
1. Stimulation injection	20 min	I
2. Mechanical Plug isolating stage I		
3. Stimulation injection	20 min	II
4. Mechanical Plug isolating stage II		
5. Stimulation injection	20 min	III

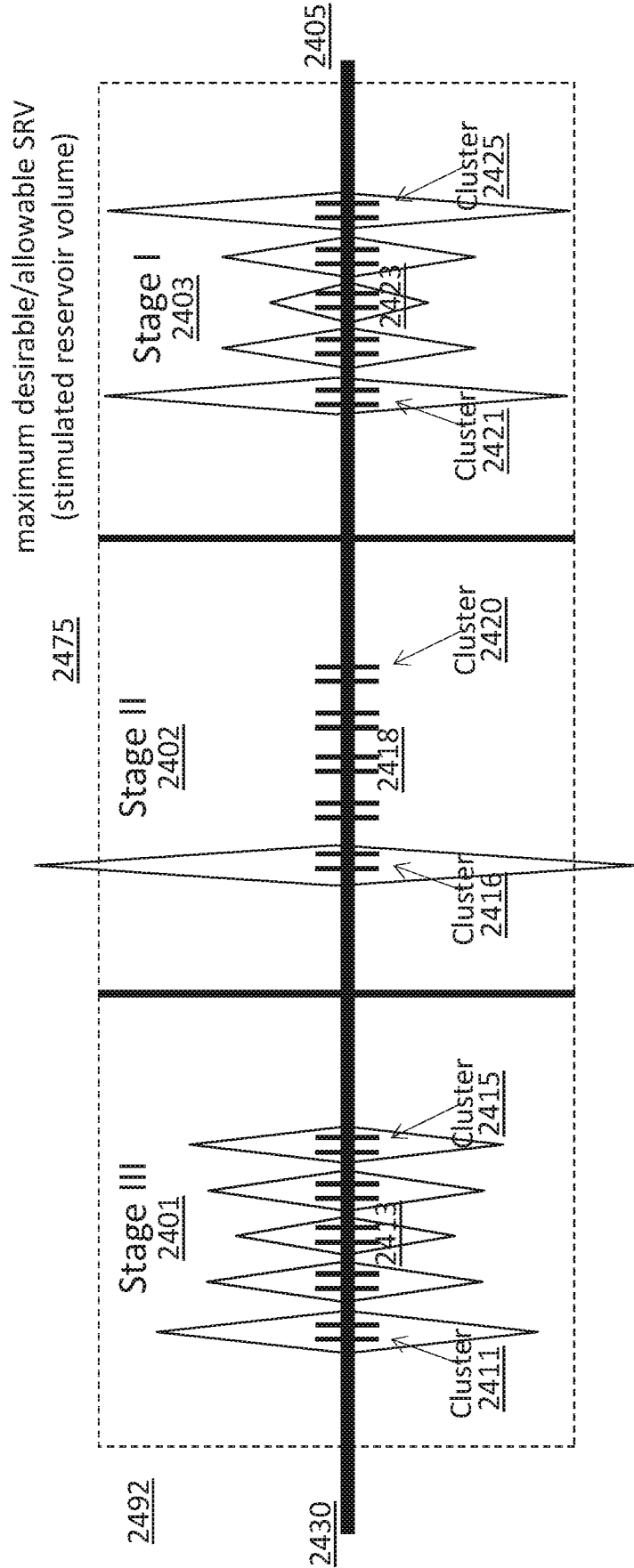


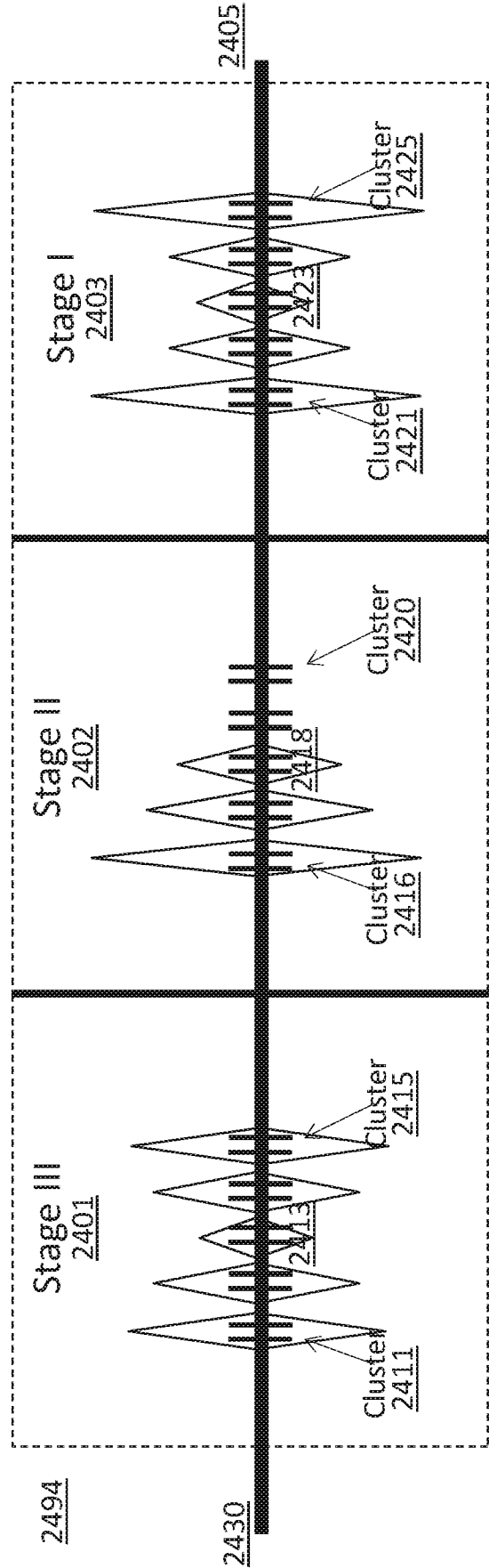
FIG.24a

2493

Step	Duration	Well Stage
1. Stimulation injection	10 min	I
2. Diversion slug		
3. Stimulation injection	10 min	I
4. Mechanical Plug isolating stage I		
5. Stimulation injection	10 min	II
6. Diversion slug		
7. Stimulation injection	10 min	II
8. Mechanical Plug isolating stage II		
9. Stimulation injection	10 min	III
10. Diversion slug		
11. Stimulation injection	10 min	III

FIG. 24b

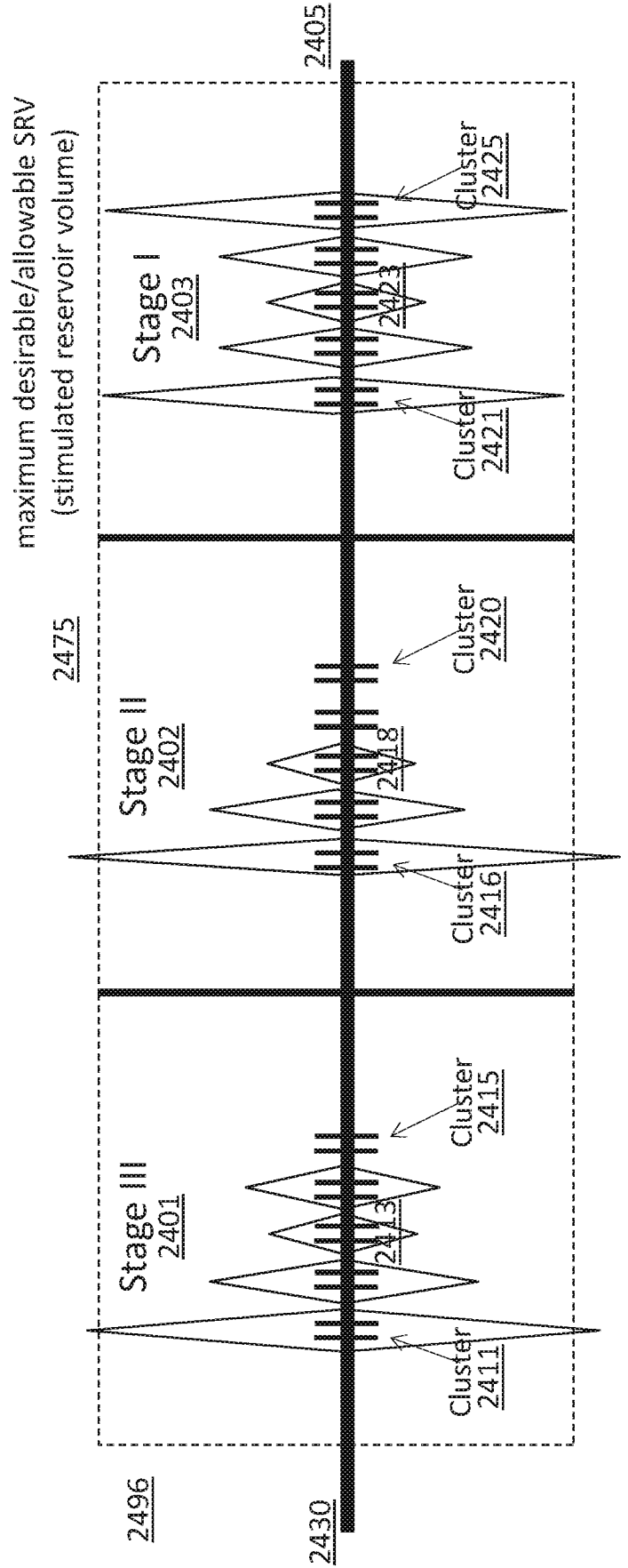
maximum desirable/allowable SRV
(stimulated reservoir volume)



Step	Duration	Well Stage
1. Stimulation injection	20 min	I
2. Mechanical Plug isolating stage I		
3. Stimulation injection	10 min	II
4. Diversion slug		
5. Stimulation injection	10 min	II
6. Mechanical Plug isolating stage II		
7. Stimulation injection	10 min	III
8. Diversion slug		
9. Stimulation injection	10 min	III

2495

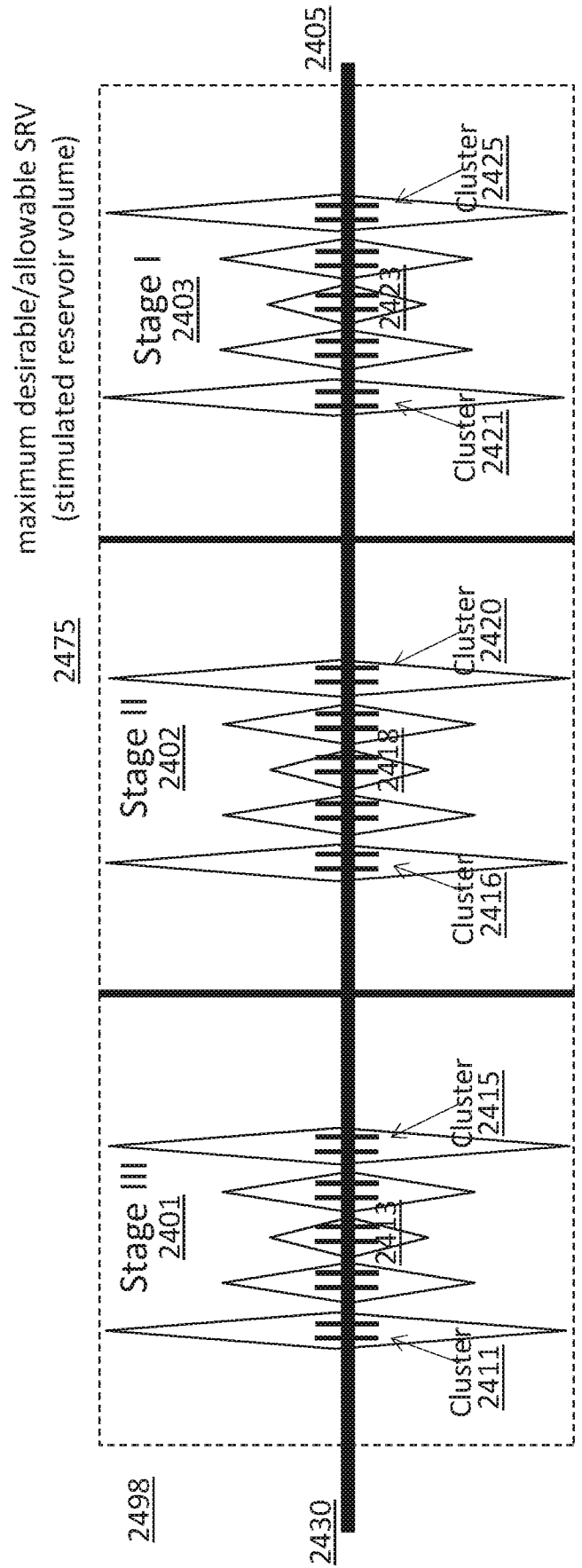
FIG.24C



Step	Duration	Well Stage
1. Stimulation injection	20 min	I
2. Mechanical Plug isolating stage I		
3. Stimulation injection	5 min	II
4. Diversion slug		
5. Stimulation injection	15 min	II
6. Mechanical Plug isolating stage II		
7. Stimulation injection	20 min	III

2497

FIG.24d



2498

2430

2475

maximum desirable/allowable SRV
(stimulated reservoir volume)

Stage III
2401

Stage II
2402

Stage I
2403

Cluster
2411

Cluster
2415

Cluster
2416

Cluster
2418

Cluster
2421

Cluster
2425

2405

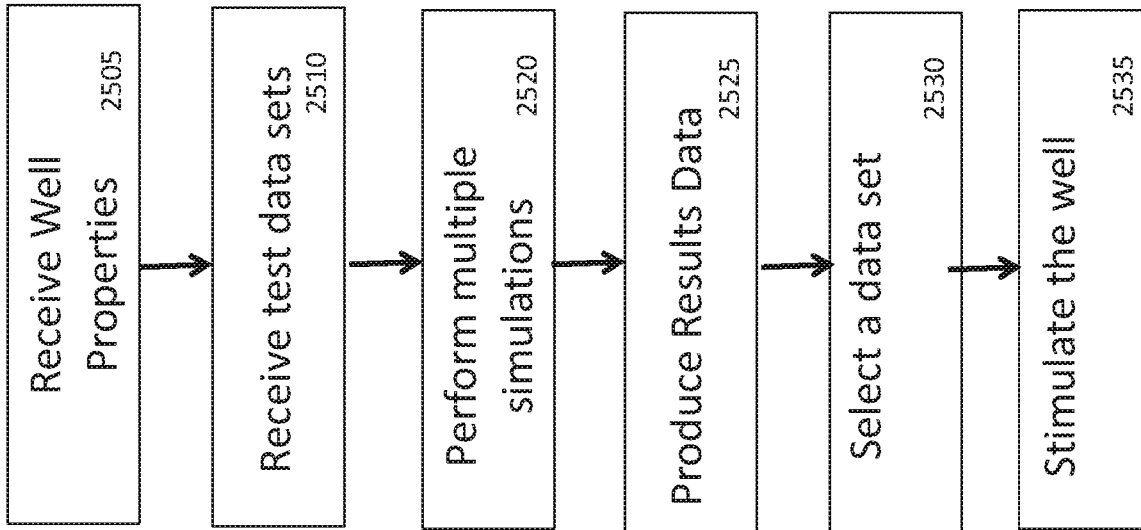


FIG.25

Number of diversion slugs	Temporal placement of diversion slugs
2	15,20,15
2	20,20,10
4	20,10,5,10,5
4	10,10,10,10,10
4	10,5,5,10,20
4	15,10,5,10,10
5	20,5,5,5,5,10
5	15,5,5,10,5,10
6	10,5,5,10,5,5,10

FIG.26

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/018133

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B43/00 E21B43/26 E21B43/267
ADD.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
E21B
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	S. MOHAGHEGH ET AL: "Intelligent Systems Can Design Optimum Fracturing Jobs", 1999 SPE EASTERN REGIONAL MEETING, CHARLESTON, WV, PAPER 57433, 1 January 1999 (1999-01-01), XP055185753, DOI: 10.2118/57433-MS the whole document	1-37
A	WO 2008/075242 A1 (SCHLUMBERGER CA LTD [CA]; SCHLUMBERGER SERVICES PETROL [FR]; SCHLUMBER) 26 June 2008 (2008-06-26) the whole document	1-37
A	WO 2014/032003 A1 (SCHLUMBERGER CA LTD [CA]; SCHLUMBERGER SERVICES PETROL [FR]; SCHLUMBER) 27 February 2014 (2014-02-27) the whole document	1-37
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Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 13 April 2018	Date of mailing of the international search report 11/05/2018
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Manolache, Iustin
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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/018133

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2014/146004 A2 (INTELLIGENT SOLUTIONS INC [US]) 18 September 2014 (2014-09-18) the whole document -----	1-37

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2018/018133

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WO 2008075242	A1	26-06-2008	AR 064451 A1 01-04-2009
			CA 2672852 A1 26-06-2008
			EA 200702563 A1 30-06-2008
			US 2008149329 A1 26-06-2008
			WO 2008075242 A1 26-06-2008

WO 2014032003	A1	27-02-2014	CA 2881718 A1 27-02-2014
			CN 104685153 A 03-06-2015
			EP 2888441 A1 01-07-2015
			US 2015204174 A1 23-07-2015
			WO 2014032003 A1 27-02-2014

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			WO 2014146004 A2 18-09-2014
