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(54) **SYSTEMS AND METHODS FOR
GENERATING PHASE DIAGRAMS FOR
METASTABLE MATERIAL STATES**

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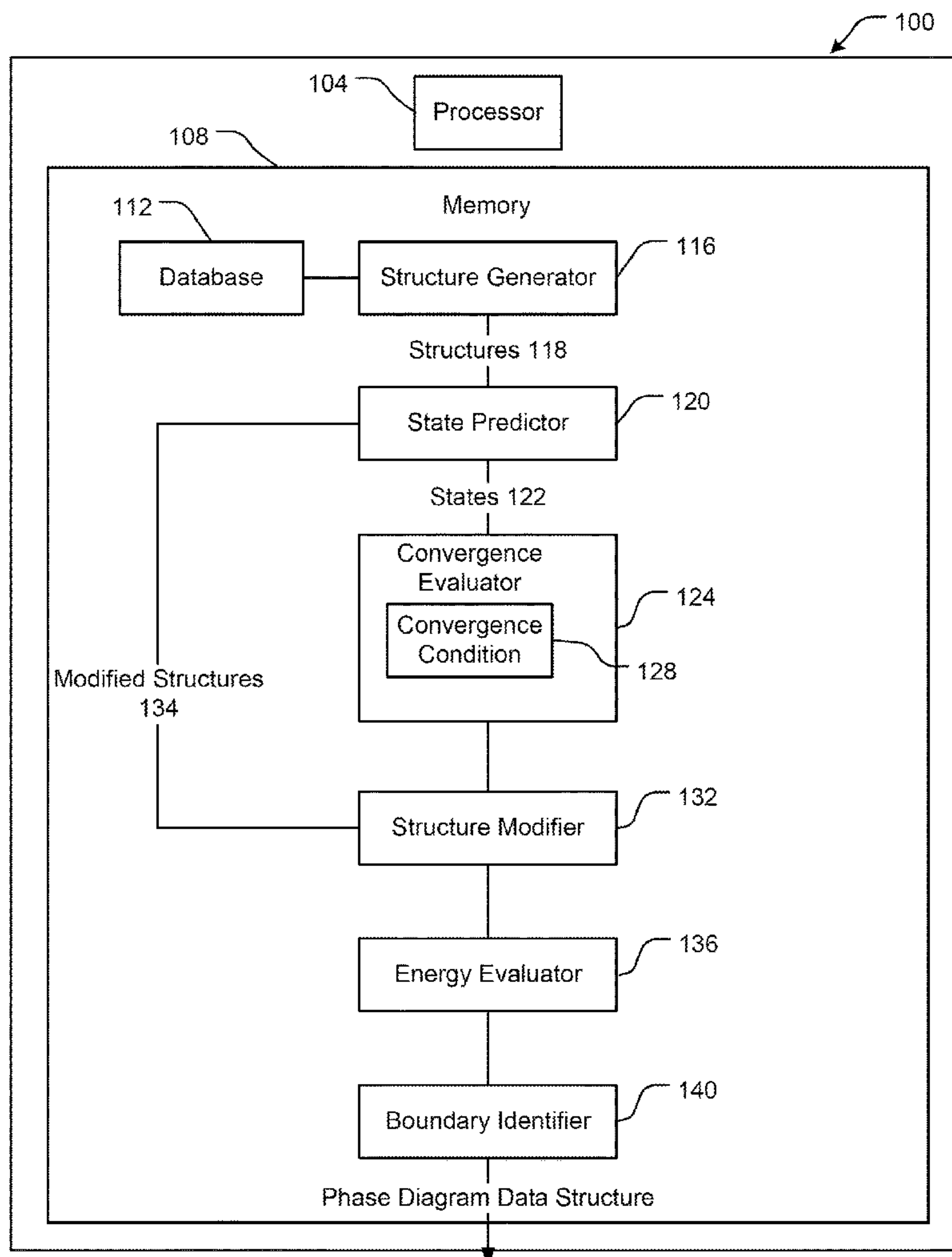
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(57) **ABSTRACT**

A system can include one or more processors configured to access at least one parameter of a material, generate a plurality of structures of the material using the at least one parameter, determine a state of each structure of the plurality of structures using the at least one parameter, determine a difference between the state of each structure of the plurality of structures and a ground state value, evaluate a convergence condition responsive to determining the difference between the state of each structure of the plurality of structures and the ground state value, and output at least one structure of the plurality of structures responsive to the convergence condition being satisfied.



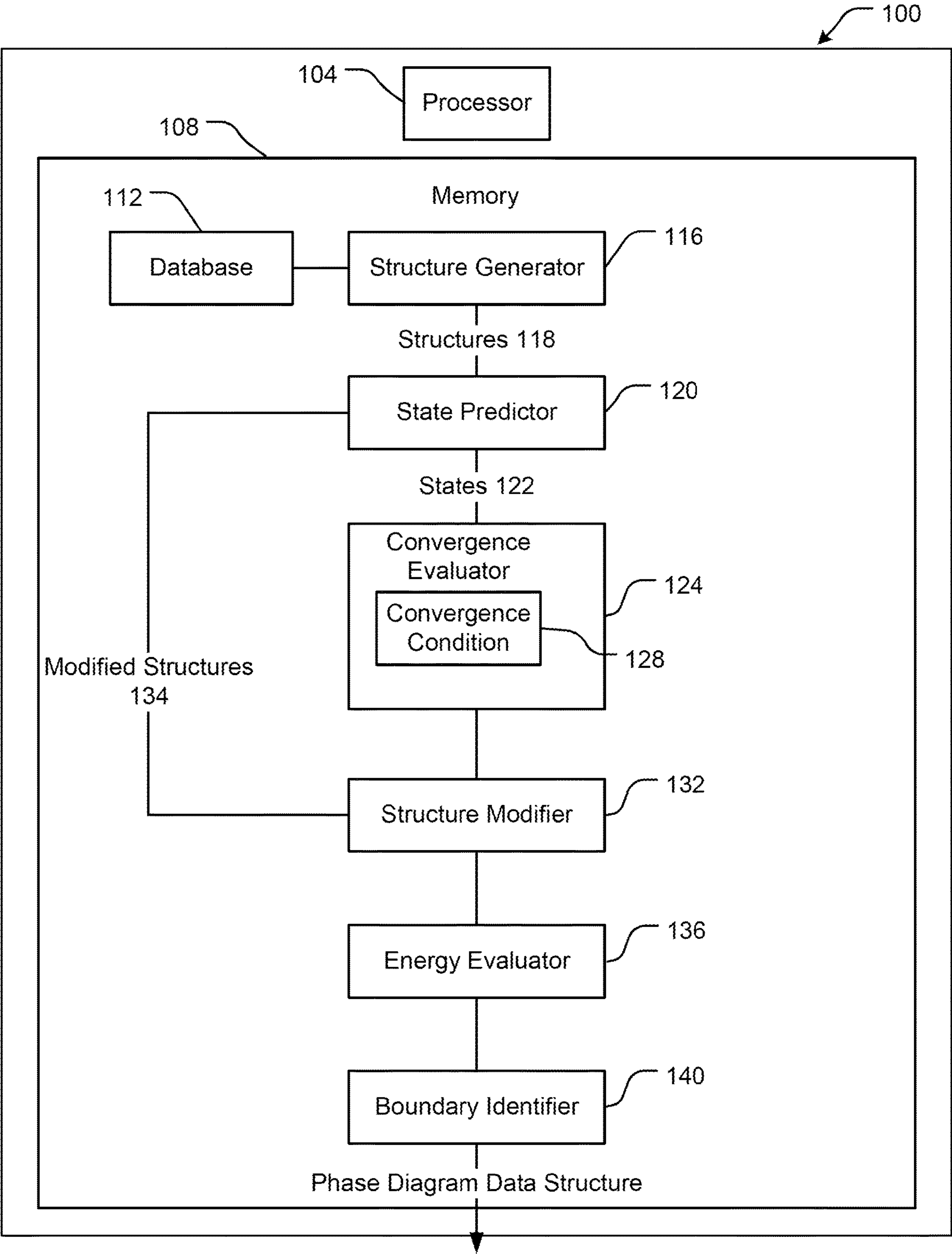


FIG. 1

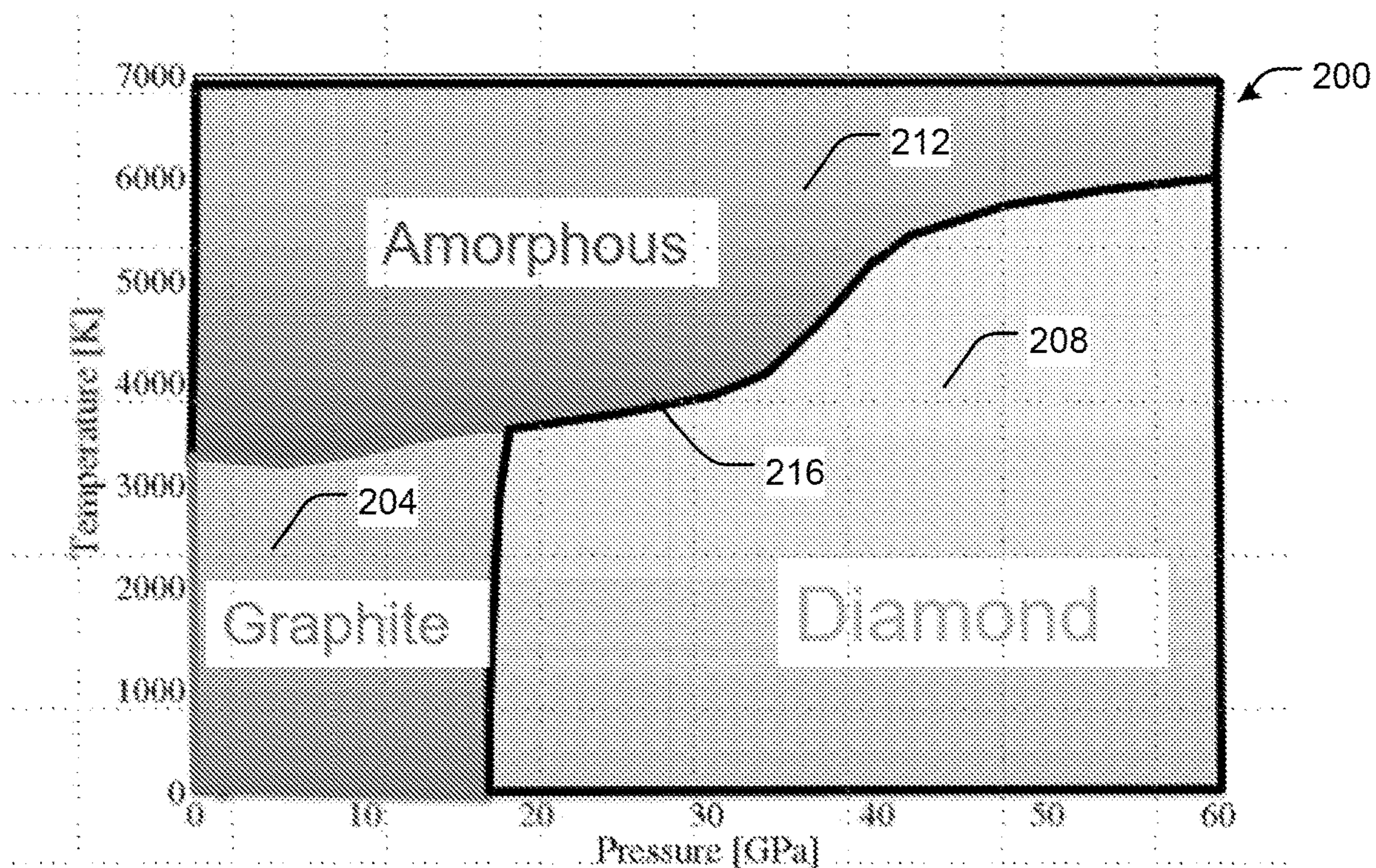


FIG. 2A

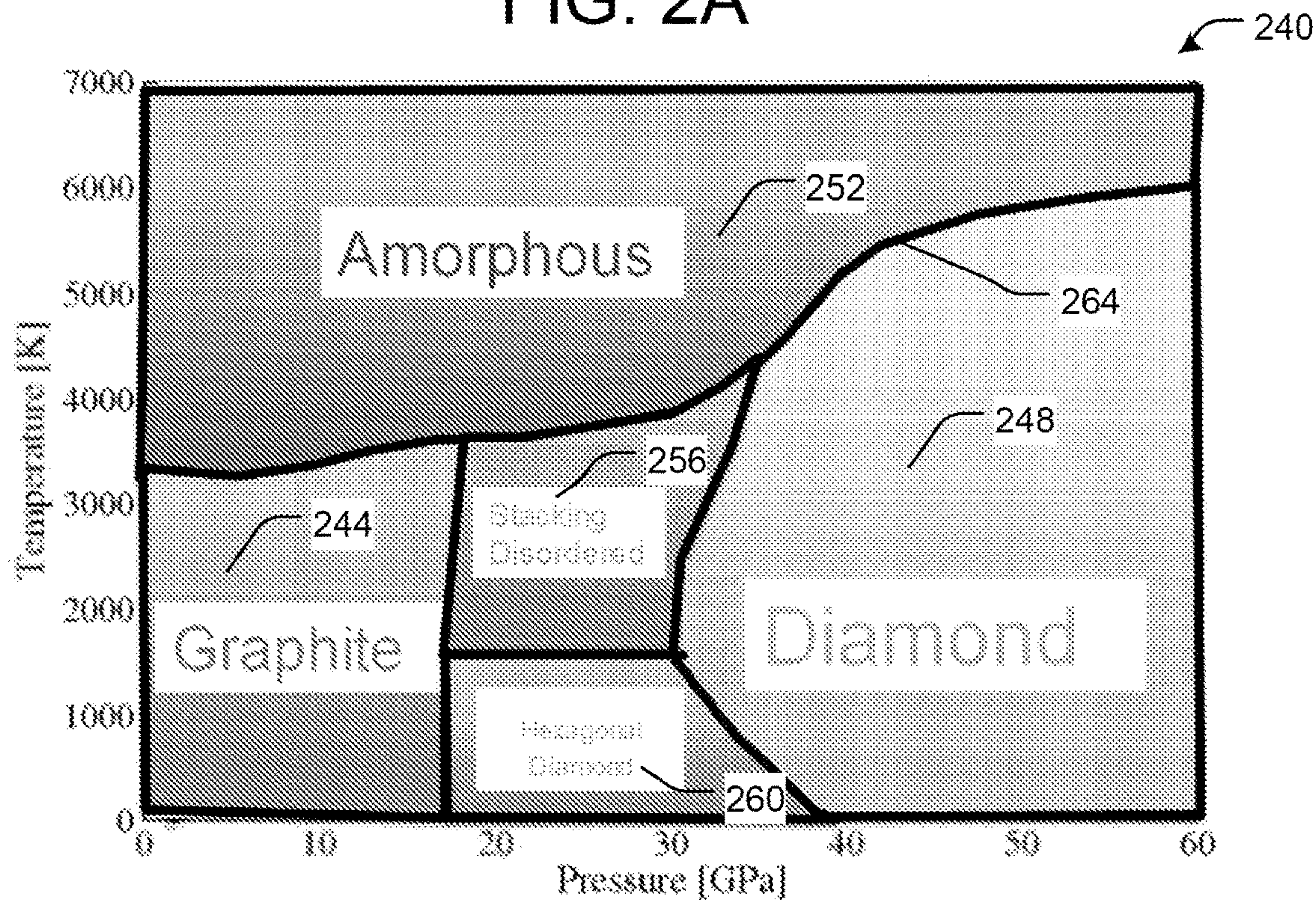


FIG. 2B

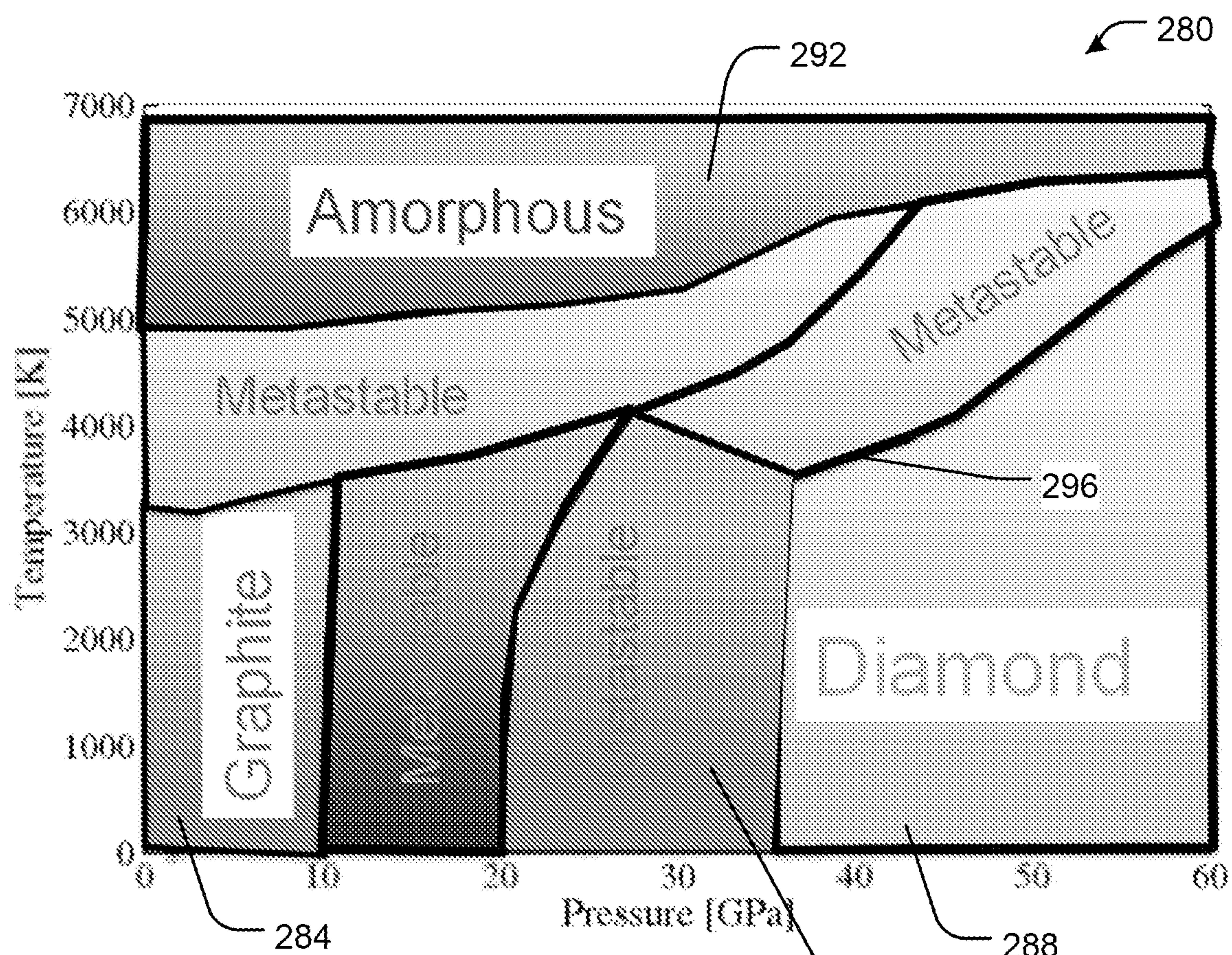


FIG. 2C

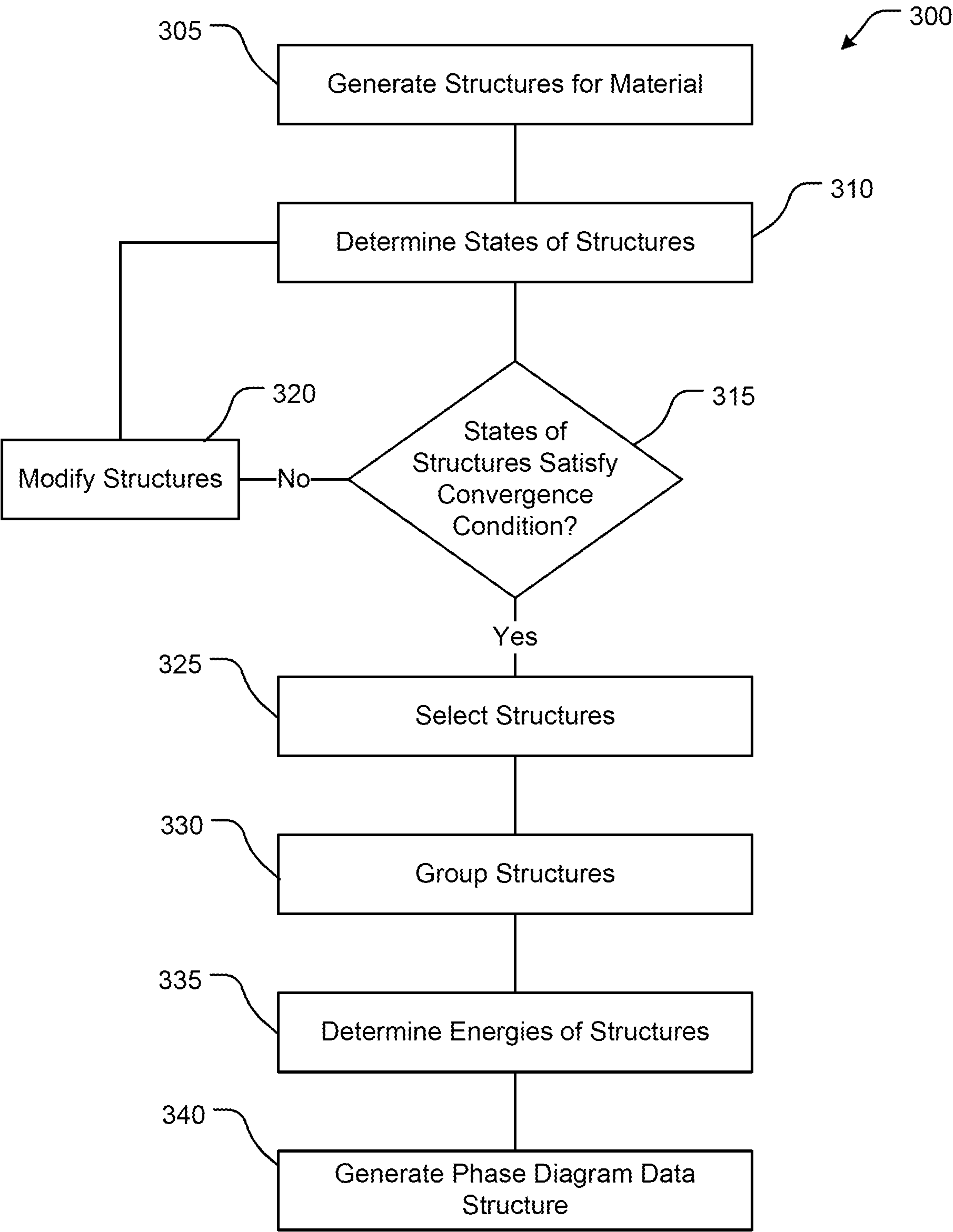


FIG. 3

SYSTEMS AND METHODS FOR GENERATING PHASE DIAGRAMS FOR METASTABLE MATERIAL STATES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 16/807,081, filed Mar. 2, 2020, the contents of which is incorporated herein by reference in its entirety.

STATEMENT OF GOVERNMENT INTEREST

[0002] This invention was made with government support under Contract No. DE-AC02-06CH11357 awarded by the United States Department of Energy to UChicago Argonne, LLC, operator of Argonne National Laboratory. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] The present invention relates generally to systems and methods of generating phase diagrams. Certain embodiments relate to generating phase diagrams for metastable states of materials.

BACKGROUND

[0004] Manufacturing and other processes may use phase diagrams to perform actions that depend on the state of materials under various conditions, such as temperature, pressure, or composition. Phase diagrams can provide information regarding states of materials at thermodynamic equilibrium, but may not provide information at states other than thermodynamic equilibrium.

SUMMARY

[0005] At least one aspect relates to a system. The system can include one or more processors configured to access at least one parameter of a material, generate a plurality of structures of the material using the at least one parameter, determine a state of each structure of the plurality of structures using the at least one parameter, determine a difference between the state of each structure of the plurality of structures and a ground state value, evaluate a convergence condition responsive to determining the difference between the state of each structure of the plurality of structures and the ground state value, and output at least one structure of the plurality of structures responsive to the convergence condition being satisfied.

[0006] At least one aspect relates to a method for generating phases for metastable states of materials. The method can include accessing, by one or more processors, at least one parameter of a material, generating, by the one or more processors, a plurality of structures of the material using the at least one parameter, determining, by the one or more processors, a state of each structure of the plurality of structures using the at least one parameter, determining, by the one or more processors, a difference between the state of each structure of the plurality of structures and a ground state value, evaluating, by the one or more processors, a convergence condition responsive to determining the difference between the state of each structure of the plurality of structures and the ground state value, and outputting, by the

one or more processors, at least one structure of the plurality of structures responsive to the convergence condition being satisfied.

[0007] At least one aspect relates to a method. The method can include generating, by one or more processors, a plurality of candidate structures of a material, determining, by the one or more processors, an enthalpy of each candidate structure of the plurality of candidate structures, comparing, by the one or more processors, the enthalpy of each candidate structure to an energy threshold, selecting, by the one or more processors, a subset of the plurality of candidate structures, each candidate structure of the subset having an enthalpy less than the energy threshold, determining, by the one or more processors, a free energy of each candidate structure of the subset of the plurality of candidate structures for a plurality of temperature-pressure value pairs, determining, by the one or more processors, at least one boundary between phases represented by the subset of the plurality of candidate structures, and generating, by the one or more processors, a phase diagram data structure using the free energy of each candidate structure of the plurality of candidate structures and the at least one boundary.

[0008] It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the subject matter disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several implementations in accordance with the disclosure and are therefore, not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings.

[0010] FIG. 1 is a block diagram of a metastable state phase diagram generation system.

[0011] FIGS. 2A-2C depict charts of an equilibrium state and metastable states of a material.

[0012] FIG. 3 is a flow diagram of a method for metastable state phase diagram generation.

DETAILED DESCRIPTION

[0013] Embodiments described herein relate generally to methods of generating metastable phase diagrams. Various technologies, including in material design and engineering, can involve using phase diagrams to identify properties of materials in order to perform processes using the identified properties. For example, heat can be applied to a system to cause a transition of the system from a first phase (e.g., solid phase) to a second phase (e.g., liquid phase).

[0014] A phase diagram can be represented using a data structure that maps one or more conditions of a material to one or more properties of the material. For example, the data structure can map values of temperature, pressure, and composition of the material to a corresponding free energy of the material. The phase diagram can be generated based

on experimental data points that indicate boundaries between phases. Phenomenological models can be used to interpolate between available experimental data points, and to extrapolate to experimentally inaccessible regions (e.g., regions of temperature, pressure, and/or composition that cannot be achieved using experimentation).

[0015] However, such phase diagrams may provide information regarding materials at thermodynamic equilibrium, but not at other states that materials may reach. For example, during synthesis, in operation, or during processing, materials may not reach a state of thermodynamic equilibrium, but instead may achieve local minima (e.g., local minima of free energy), such as metastable states. The properties of materials in metastable states may be different than those in states of thermodynamic equilibrium (e.g., global minima). For example, nanoscale synthesis of diamond from graphite in a high pressure and high temperature (HPHT) anvil goes through a series of intermediate metastable phases. Although these phases can be experimentally observed through transmission electron microscopy (TEM) imaging, the exact temperature and pressure ranges at which these phases appear during the synthesis may not be known and may be computationally expensive to determine by calculating free energies for a large number of temperature and pressure values.

[0016] Systems and methods performed in accordance with the present solution can generate metastable states of materials using a predictive machine learning framework, which can predict, determine, and validate phase diagrams in chemical systems, including to detect metastable states, without relying on experimental information. For example, Monte Carlo Tree Search (MCTS) and evolutionary algorithms can be implemented to sample a free energy space of a chemical system as a function of temperature, pressure, and composition. The present solution can determine free energies of locally ergodic regions of the free energy space, which may otherwise be computationally non-trivial. The present solution can estimate or validate experimental conditions for synthesizing materials in metastable phases. The present solution can significantly reduce computational requirements for detecting metastable phases, such as by avoiding the need to compute free energy values for a large number of candidate structures at numerous temperature and pressure values (e.g., by instead identifying a relatively small number of candidate structures that are expected to be physically realistic at metastable phases). For example, temperature-pressure ranges at which a phase is likely to be stabilized and an estimate of excitation energies (from ΔG) to synthesize a metastable phase can be determined, enabling a systematic approach in designing experiments at favorable conditions for synthesis. The present solution can reproduce the dominant diamond and graphite phase in the equilibrium phase diagram, as well as predict the synthesizability of a metastable phase. Mapping the metastable phase diagram and inspecting the neighboring phases can provide insight into possible phase transformations pathways and help in selecting the appropriate starting material for the synthesis of a target phase to improve computer-aided materials discovery.

[0017] For example, a system in accordance with the present solution can include one or more processors that access an input data structure regarding a material. The input data structure can include an identifier of the material and at least one parameter of the material, such as temperature,

pressure, or composition. The one or more processors can generate a plurality of structures of the material. The one or more processors can determine a state of each structure using the at least one parameter. The one or more processors can determine an error of the each state, and evaluate a convergence condition using the error. The one or more processors can modify the plurality of structures responsive to the convergence condition not being satisfied. The one or more processors can output the states of the structures responsive to the convergence condition being satisfied.

[0018] FIG. 1 depicts a system **100** for generating phase diagrams for metastable states of materials. The system **100** includes one or more processors **104** and memory **108**, which can be implemented as one or more processing circuits. The processor **104** may be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. The processor **104** may be configured to execute computer code or instructions stored in memory **108** (e.g., fuzzy logic, etc.) or received from other computer readable media (e.g., CDROM, network storage, a remote server, etc.) to perform one or more of the processes described herein. The memory **108** may include one or more data storage devices (e.g., memory units, memory devices, computer-readable storage media, etc.) configured to store data, computer code, executable instructions, or other forms of computer-readable information. The memory **108** may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. The memory **108** may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. The memory **108** may be communicably connected to the processor **104** and may include computer code for executing (e.g., by processor **104**) one or more of the processes described herein. The memory **108** can include various modules (e.g., circuits, engines) for completing processes described herein. The one or more processors **104** and memory **108** may include various distributed components that may be communicatively coupled by wired or wireless connections; for example, various portions of system **100** may be implemented using one or more client devices remote from one or more server devices. The memory **108** can include various software or firmware engines, modules, scripts, databases, or other computer code to implement the various components described herein, including the database **112**, structure generator **116**, state predictor **120**, convergence evaluator **124**, structure modifier **132**, energy evaluator **136**, boundary identifier **140**, or features or functions thereof. For example, the database **112**, structure generator **116**, state predictor **120**, convergence evaluator **124**, structure modifier **132**, energy evaluator **136**, boundary identifier **140** can be or include any function, operation, routine, logic, or instructions to perform functions described herein.

[0019] The system **100** can include a database **112**. The database **112** can include input data structures regarding materials for which metastable phases are to be determined. The input data structure can include an identifier of the material and one or more parameters of the material. The

identifier of the material can include identifiers of each atom, molecule, or chemical compound of the material, which can be used to retrieve properties of the material (e.g., properties that can be used to determine free energy of the material). The parameters of the material can include parameters such as temperature, pressure, and composition. The input data structure may include a state value corresponding to the one or more parameters of the material, such as enthalpy or free energy, which may be used for validating state values determined by the system 100. For example, the input data structure may include a free energy value determined through experimentation in order to validate outputs of the system 100. The input data structure may include various values of parameters (e.g., various values of temperature, pressure, and composition) of the material, which may be assigned corresponding values of free energy.

[0020] The system 100 can include a structure generator 116. The structure generator 116 can generate a structure 118 of the material using the one or more parameters of the material. The structure generator 116 may randomly generate the structure. The structure 118 can be a chemical structure of the material. For example, the structure 118 can represent one or more bonds between atoms or molecules of the material. The structure 118 can represent packing structures, layers, or other arrangements of the material. The structure 118 can be a crystal structure. As examples for a material that includes carbon, the structures 118 may include any of a variety of graphite structures (including but not limited to cubic, cubic first neighbor, cubic second neighbor, hexagonal, hexagonal first neighbor, or hexagonal second neighbor structures for graphite), diamond structures, or amorphous structures. The structure generator 116 can (randomly) generate N structures 118 for the material, for which state information (e.g., enthalpy, free energy) can be determined and used to confirm convergence of the structures 118 or trigger modification of the structures 118.

[0021] The structure generator 116 can generate a plurality of structures 118 (e.g., candidate structures) using the one or more parameters of the material. For example, the structure generator 116 can use the one or more parameters to determine lengths of bonds between atoms of the material, spacing of atoms, arrangements of atoms or molecules, or other features of the structure 118. The structure generator 116 can use various models, rules, or policies to determine the structure 118. For example, the structure generator 116 can use rules based on atomic volume, minimum bond length, and maximum bond length constraints to determine the structure 118.

[0022] The system 100 can include a state predictor 120. The state predictor 120 can determine a state 122 of each structure 118. For example, the state predictor 120 can determine the state 122 of each structure 118 using the structure 118 and the one or more parameters of the material. The state predictor 120 can determine the state 122 to be or include an enthalpy or free energy of the material using the structure 118 and the one or more parameters of the material.

[0023] The state predictor 120 can determine the state 122 of the structure 118 using various models. For example, the state predictor 120 can use a classical potential model to determine the state 122, which can model forces between atoms or molecules using the one or more parameters of the material to determine the state 122 (e.g., by performing a

molecular dynamics simulation). The state predictor 120 can use a density functional theory (DFT) model to determine the state 122.

[0024] The state predictor 120 can determine the state 122 at a particular set of parameters. For example, the state predictor 120 can determine state 122 for the structure 118 at a temperature of zero Kelvin and one or more pressures (e.g., determine enthalpy $H(T=0, P)$). The state predictor 120 can maintain in the database 112 data including the state 122 of the structure 118 for the corresponding one or more parameters (e.g., enthalpy at a particular temperature and pressure for the structure 118), which can increase the speed of searching for minimas and avoid sampling of unphysical configurations. By using the state predictor 120 to determine the state as an enthalpy at $T=0$, the system 100 can more efficiently evaluate a large number of structures 118 to identify the structures 118 that are most likely to be physically realistic for achieving a metastable phase, particularly a metastable phase that can be reached during synthesis of the material (e.g., by perturbing the material using laser energy).

[0025] The state predictor 120 can assign a rank to each of the N structures 118 using the state 122 of the respective structure 118 (e.g., using enthalpy of each structure 118). The state predictor 120 can assign relatively high ranks to structures 118 with relatively low state values, and relatively low ranks to structures with relatively high state values, as the state values can represent a stability of the structure 118 or a likelihood of the structure 118 being physically possible at the corresponding pressure (and temperature).

[0026] The state predictor 120 can determine a selection probability score for the structure 118. The selection probability score can indicate a fitness of the structure 118, which can be used for modifying the structure 118 (e.g., for genetic operations described herein). The state predictor 120 can determine the selection probability score using the state 122 of the structure 118, such as to determine a relatively higher probability for relatively lower state values. The state predictor 120 can determine the selection probability score using the rank assigned to the structure 118, such as by applying the rank as an input to a mapping data structure (e.g., lookup table) or function that outputs the selection probability score responsive to the rank.

[0027] The system 100 can include a convergence evaluator 124. The convergence evaluator 124 can determine whether the states 122 of the structures 118 satisfy one or more convergence conditions, in order to determine whether to output the structures 118 or modify the structures 118. The convergence condition 128 can include one or more rules, policies, heuristics, functions, or thresholds that the convergence evaluator 124 can use to determine that the structures 118 have converged.

[0028] The convergence condition 128 can include a threshold, such as an energy threshold or enthalpy threshold. The threshold can represent an energy cutoff above which structures would not be expected to form as a metastable state. The threshold may be based on an excitation energy, such as expected amount of energy that can be provided from an external source (e.g., laser) to perturb the material from a structure at thermal equilibrium (e.g., at a ground state, such as having an enthalpy of zero) to a metastable structure. As such, the threshold may represent whether it is physically realistic for a particular structure 118 to be achieved as a metastable structure of the material (e.g., the

closer the enthalpy of the particular structure **118** is to the ground state, the more likely it is that the material will form the particular structure **118**). For example, the threshold may be on the order of 100 meV/atom to 1 eV/atom. The threshold may be greater than 300 meV/atom and less than 800 meV/atom. The threshold may be greater than 500 meV/atom and less than 750 meV/atom. The threshold may be 670 meV/atom. The threshold may be adjusted to be lower to reduce the number of structures **118** selected or increased to evaluate metastable phases at high excitation energies. If the state (e.g., enthalpy, free energy) of the ground state is greater than zero, the state of the ground state may be summed with the threshold for comparing with the states **122** of the structures **118**.

[0029] The convergence evaluator **124** can determine the convergence condition **128** to be satisfied responsive to the state **122** of at least a subset of the structures **118** being less than the threshold. The convergence evaluator **124** can select the subset of the structures **118**, compare each state **122** of the corresponding structure **118** of the subset to the threshold, and determine the convergence condition **128** to be satisfied responsive to the state **122** of each structure **118** of the subset being less than the threshold (or less than or equal to the threshold). For example, the convergence evaluator **124** can determine the convergence condition **128** to be satisfied responsive to one half, one quarter, one eighth, one tenth, or various other subsets of the structures **118** to have states **122** that are less than the threshold (e.g., $N/2$, $N/4$, $N/8$, $N/10$, etc.).

[0030] The system **100** can include a structure modifier **132**. The structure modifier **132** can modify the structures **118** to generate modified structures **134**. The structure modifier **132** can use features of the structures **118**, such as atoms, groups of atoms, or bonds between atoms or molecules, to generate the modified structures **134**. The structure modifier **132** can use the structures **118** as parent structures to generate the modified structures **134** as child structures. The structure modifier **132** may select a subset of the structures **118** to use for modification using the selection probability score assigned to each structure by the state predictor **120**, such that structures **118** that are more likely to be physically realistic (e.g., have lower state values) are more likely to be used to generate candidate structures for evaluation in subsequent iterations.

[0031] The structure modifier **132** can apply one or more genetic operations to the structures **118** to generate the modified structures **134**, such as to combine features from structures **118** to generate the modified structures **134**. The structure modifier **132** can apply a crossover operation to generate the modified structure **134** to include features of at least two parent structures **118**. The structure modifier **132** can apply a mutation operation to generate the modified structure **134** to include at least one randomly modified (e.g., mutated) feature relative to the parent structure **118**. For example, the structure modifier **132** can mutate features such as atomic position or cell parameters to generate the modified structure **134**.

[0032] The structure modifier **132** can provide the modified structures **134** to the state predictor **120**. The state predictor **120** can determine the state values (e.g., enthalpy, free energy) of the modified structures **134**, enabling the system **100** to iteratively evaluate structures **118** and modify the structures **118** (by generating modified structures **134**)

until the structures **118** have converged. The structures **118** that converge can represent metastable phases of the material.

[0033] The system **100** can include an energy evaluator **136**. The energy evaluator **136** can incorporate features of the state predictor **120**. The energy evaluator **136** can receive the structures **118** that satisfied the convergence condition **128** (e.g., had enthalpies less than the cutoff enthalpy) and determine a free energy (e.g., Gibbs free energy) of each received structure **118**. The energy evaluator **136** can assign the free energy values to the structures **118** in the database **112**. The energy evaluator **136** can determine the free energy for various temperature-pressure value pairs.

[0034] The energy evaluator **136** may group the received structures **118** into one or more groups, which can reduce the number of candidate structures for which free energy is to be determined, and thus reduce computations to be performed by the energy evaluator **136**. The energy evaluator **136** can group the structures **118** using characteristics such as radial distribution function and angular distribution function. For example, hexagonal graphite, orthorhombic graphite, and rhombohedral graphite may be grouped together, and the energy evaluator **136** can assign a same free energy value to each of the structures **118** of the group based on determining the free energy value for one of the structures **118** of the group.

[0035] The energy evaluator **136** can use various models, functions, or other algorithms to determine the free energy of the structures **118**. The energy evaluator **136** can determine the free energy at various (discretized) points in [temperature, pressure] space (even as the states **122** determined by the state predictor **120** are for a temperature of zero Kelvin). The energy evaluator **136** may determine a volume of the structure **118** based on temperature and pressure, and use the volume to determine the free energy. The energy evaluator **136** may determine a vibrational free energy of the structure **118**, such as to facilitate determining entropy of the structure **118** (e.g., a—temperature times entropy term in the Gibbs free energy calculation) to be approximated using the vibrational free energy. The energy evaluator **136** can determine the enthalpy at a given temperature and pressure using a molecular dynamics model, such as by equilibrating under an isothermal-isobaric ensemble (e.g., NPT ensemble), and determine the entropic part of the free energy from a phonon spectra computation. The phonon spectra and the corresponding vibrational free energies can be determined at the equilibrium density obtained from molecular dynamics simulations. The energy evaluator **136** can perform the molecular dynamics simulations using Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) and the phonon spectra using PHONOPY.

[0036] The system **100** can generate a phase diagram data structure that assigns the free energy values determined by the energy evaluator **136** to corresponding values of temperature and pressure. For example, each data point of the phase diagram data structure may include an identifier of the structure, a temperature, a pressure, and a free energy. The system **100** can identify metastable phases (along with equilibrium phases) by parsing the phase diagram data structure using a free energy value. For example, for a particular free energy value, the system **100** can identify, for one or more sets of temperature and pressure values, the corresponding phase assigned to the temperature and pres-

sure values for which the free energy determined by the energy evaluator **136** is greater than or equal to the particular free energy value. For example, for a given temperature and pressure, there may be multiple phases possible for the structure, depending on the free energy value; as the free energy is adjusted from zero through the cutoff energy value (e.g., the threshold of convergence condition **128**), various phases may be identified based on whether the free energy for the phase is greater than or equal to the adjusted free energy.

[0037] The system **100** can include a boundary identifier **140**. The boundary identifier **140** can determine boundaries between data points representing phases of the phase diagram data structure, including between metastable phases. The boundary identifier **140** can include a classifier, such as a support vector machine (SVM), that receives the phase diagram data structure as input and classifies the data points of the phase diagram data structure based on the phases of the data points to generate boundaries between phases. The boundary identifier **140** may use a multiclass SVM that does not use decomposition, such as a non-homogenous fourth-order polynomial kernel, to classify the phases of the phase diagram data structure. By using a single SVM, the boundary identifier **140** can reduce computational requirements for determining the boundaries. The boundaries determined by the boundary identifier **140** can indicate the phase of the material under particular conditions (e.g., temperature, pressure, composition), including for values of conditions for which free energies have not been explicitly determined.

[0038] The system **100** can use the boundaries identified by the boundary identifier **140** to output a phase of a material responsive to receiving parameters of the material. For example, the system can receive a temperature, pressure, and free energy of a material, and apply the boundary to the temperature, pressure, and free energy to determine the phase of the material (including for metastable phases at free energies greater than zero).

[0039] FIGS. 2A-2C depict phase diagrams **200**, **240**, **280** for carbon at various free energy levels for temperatures ranging from 0 to 7000 Kelvin and pressures ranging from 0 to 60 GPa. The phase diagrams **200**, **240**, **280** can be generated in accordance with features of the system **100**. The phase diagram **200** can be for carbon at thermal equilibrium (e.g., $\Delta G = \text{zero}$), and indicates that carbon can be in graphite **204**, diamond **208**, or amorphous **212** phases under various temperature and pressure conditions. In addition, the phase diagram **200** includes boundaries **216** between the phases, which can be determined using the boundary identifier **140**, enabling determination of the phase of carbon even for temperatures and pressures for which free energy (and phase information) has not been explicitly determined through experimentation or direct computation. For example, the system **100** may not include a data point having a free energy value assigned to a temperature of 2000 Kelvin and a pressure of 20 GPa (e.g., as determined through experimentation or computation using a free energy function), but the system **100** can output a prediction indicating the phase to be diamond for the temperature of 2000 Kelvin and the pressure of 20 GPa using the phase diagram **200** (and the boundaries **216** thereof).

[0040] The phase diagram **240** indicates phases for carbon at metastable states having a free energy of $\Delta G = 10$ meV/atom. The phase diagram **240** identifies graphite **244**, diamond **248**, and amorphous **252** phases, as well as phases not

identified by the phase diagram **200**, including stacking disordered **256** and hexagonal diamond **260** phases. The phase diagram **240** includes boundaries **264** between phases. As compared to the phase diagram **200**, which indicates the phase to be diamond for the temperature of 2000 Kelvin and the pressure of 20 GPa, the phase diagram **240** indicates the phase to be the metastable stacking disordered **256** phase for the temperature of 2000 Kelvin and the pressure of 20 GPa.

[0041] The phase diagram **280** indicates phases for carbon at metastable states having a free energy of $\Delta G = 100$ meV/atom. The phase diagram **280** identifies graphite **284**, diamond **288**, and amorphous **292** phases, as well as phases not identified by the phase diagram **200**, including several metastable phases, including metastable phase **296**. The phase diagram **240** includes boundaries **298** between phases. As compared to the phase diagram **200**, which indicates the phase to be diamond for the temperature of 2000 Kelvin and the pressure of 20 GPa, the phase diagram **280** indicates the phase to be the metastable phase **296** for the temperature of 2000 Kelvin and the pressure of 20 GPa. The phase diagrams **240**, **280** thus represent slices of the temperature-pressure-free energy space (which has been classified into different phases depending on temperature, pressure, and free energy) at various free energies corresponding to potential metastable energy levels.

[0042] FIG. 3 depicts a method **300** for generating phase diagrams for metastable phases of materials. The method **300** can be performed using various systems and components described herein, such as the system **100**. The method **300** can be performed to determine and control process conditions for synthesizing materials at metastable phases, such as to determine temperature and pressure for causing a material to achieve a selected metastable phase.

[0043] At **305**, structures of a material are generated. The structures can be randomly generated, such as for a first iteration of structure generation. The structures can be a chemical structure of the material. For example, the structures can represent one or more bonds between atoms or molecules of the material. The structures can represent packing structures, layers, or other arrangements of the material. The structures can be a crystal structure. N structures can be generated for the material.

[0044] The structures can be generated using one or more parameters of the material, such as composition, temperature, and pressure. The structures can be generated using the one or more parameters and various models, rules, or policies. For example, the structures can be generated based on atomic volume, minimum bond length, and maximum bond length constraints. The structures can be generated to indicate bonds between atoms and the lengths of the bonds between atoms.

[0045] At **310**, states of the structures are determined. The states of a particular structure can be determined by applying the one or more parameters of the material and the particular structure as input to one or more of various models. The state can be determined to include an enthalpy or a free energy of the particular structure.

[0046] For example, the enthalpy can be determined by using temperature, pressure, and the particular structure as inputs to a classical potential model or a DFT model. The enthalpy may be determined at parameters of temperature=zero Kelvin and at various pressures. The

enthalpy can be assigned to a data structure representative of the particular structure, which may later be queried for generating a phase diagram.

[0047] The structures can be ranked using the states of the structures. Structures having relatively higher state values (e.g., relatively higher enthalpies or free energies) may be assigned relatively lower ranks, and vice versa, in order to identify structures that are closest to ground state (and thus more likely to be physically realistic).

[0048] A selection score (e.g., selection probability score) can be assigned to the particular structure using at least one of the state of the particular structure or the rank assigned to the particular structure. The selection score can be used to determine whether to use the structure or features or portions thereof for generating future generations of structures to evaluate. Relatively higher selection scores can be assigned to structures having relatively higher ranks (e.g., having relatively lower state values, such as relatively lower enthalpies). The selection score can be determined by applying the rank or state value as an input to a mapping data structure (e.g., lookup table) or function that outputs the selection probability score responsive to the rank or state value.

[0049] At **315**, it is determined whether the states of the structures satisfy a convergence condition. The convergence condition can include a threshold that represents an energy cutoff above which structures would not be expected to form as a metastable state. The threshold may be based on an excitation energy, such as expected amount of energy that can be provided from an external source (e.g., laser) to perturb the material from a structure at thermal equilibrium (e.g., at a ground state, such as having an enthalpy of zero) to a metastable structure.

[0050] The state value of the structures (e.g., value of at least one of enthalpy or free energy) can be compared to the threshold. The threshold can be determined to be satisfied for a particular structure responsive to the state value for the structure being less than (or less than or equal to) the threshold. The convergence condition can be determined to be satisfied responsive to at least a subset of the particular structures having state values that satisfy the threshold. For example, the structure generation and modification processes described herein can use a number N of structures on the order of tens or hundreds, many of which may have relatively high state values. By determining convergence condition to be satisfied responsive to a subset of the N total structures to have state values less than the threshold, a sufficient number of structures for metastable phases and phase diagram generation can be identified without requiring excessive iterations through the process. The number of structures to be determined for a sufficiently large subset can include $N/2$, $N/4$, $N/8$, $N/10$, etc. structures. For example, one hundred structures can be initially (e.g., randomly) generated, and the convergence condition can be determined to be satisfied responsive to identifying ten structures for which the at least one of the enthalpy or free energy is less than the energy cutoff.

[0051] At **320**, responsive to the convergence condition not being satisfied (e.g., not enough structures were determined to have enthalpies or free energies less than a corresponding cutoff threshold), one or more structures can be modified to generate modified structures. The modified structures can be generated by modifying features of the structures such as bonds, bond lengths, atoms, or groups of atoms.

[0052] Structures can be selected for modification using the selection score. For example, a relatively higher selection score may indicate that a structure is a better candidate to have its features included in the modified structures for evaluation in future iterations. Structures can be selected for modification by randomly selecting structures based on respective selection scores.

[0053] As depicted in FIG. 3, the states of the modified structures can be determined responsive to generating the modified structures. A number of modified structures may be less than N , such that at least some of the structures from the previous generation may be used for further evaluation. The structures used from the previous generation may be selected based on the respective selection scores, or based on being structures having state values less than the threshold (e.g., once a structure is determined to have a state value less than the threshold, it may be held for later processing, and subsequent iterations can be used to search for fewer additional structures that satisfy the threshold).

[0054] The structures may be modified using one or more genetic operations, such as to combine features from structures to generate the modified structures. A crossover operation can be applied to generate a modified structure to include features of at least two parent structures. A mutation operation can be applied to generate a modified structure to include at least one randomly modified (e.g., mutated) feature relative to the parent structure. For example, features such as atomic position or cell parameters can be modified to generate the modified structure.

[0055] At **325**, responsive to the convergence condition being satisfied, structures can be selected for use for metastable phases. For example, each structure (e.g., of the subset) for which the state value is less than or equal to the threshold can be selected.

[0056] At **330**, at least some of the selected structures can be assigned to a group. The group may include structures that are similar, such that a first free energy can be determined for a first structure of a group and assigned to each remaining structure of the group, reducing a number of total free energy calculations to be performed. Structures can be assigned to groups using characteristics such as radial distribution function and angular distribution function.

[0057] At **335**, energies (e.g., free energies) of the selected structures can be determined. Various models, functions, or other algorithms to determine the free energy. The free energy can be determined at various (discretized) points in [temperature, pressure] space. A volume of the structure can be determined based on temperature and pressure, and used to determine the free energy. A vibrational free energy of the structure can be determined, such as to facilitate determining entropy of the structure (e.g., a —temperature times entropy term in the Gibbs free energy calculation) to be approximated using the vibrational free energy. The enthalpy of the structure can be determined at a given temperature and pressure using a molecular dynamics model, such as by equilibrating under an isothermal-isobaric ensemble (e.g., NPT ensemble), and to determine the entropic part of the free energy from a phonon spectra computation (e.g., where free energy G =enthalpy H −temperature T times entropy S). The phonon spectra and the corresponding vibrational free energies can be determined at the equilibrium density obtained from molecular dynamics simulations. The molecular dynamics simulations can be performed using

Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) and the phonon spectra performed using PHONOPY.

[0058] At **340**, a phase diagram data structure can be generated using the energies of the selected structures. The phase diagram data structure can include data points indicating variables such as temperature, pressure, composition, free energy (e.g., difference in free energy relative to ground state), and structure or phase (including identifiers for metastable phases or the associated structures). Generating the phase diagram data structure can include determining boundaries between phases, such as by using a classifier (e.g., SVM) to classify the data points based on phases.

[0059] Generating the phase diagram data structure can include providing phase information at a particular free energy or range of free energies, such as indicating which phases (e.g., structures) correspond to particular values of temperature and pressure at the particular free energy or range of free energies. For example, a free energy of 10 meV/atom can be used as an input to identify metastable phases at various values of temperature and pressure for the free energy of 10 meV/atom.

[0060] Various processes and devices can be operated using the metastable phase information represented by the phase diagram data structure. For example, to synthesize a material to be in a particular metastable phase, the phase diagram data structure can be searched to identify the metastable phase, and the temperature and pressure associated with the particular metastable phase can be retrieved. A reaction or other process to synthesize the material can be controlled to operate at the retrieved temperature and pressure, and an energy source (e.g., laser) can be applied to the material to modify the material from a ground state phase (e.g., thermal equilibrium phase) to the metastable phase. In addition, experimentation can be validated or supplemented using the phase diagram data structure. For example, a structure of a material in a metastable phase can be identified through imaging (but for which parameter data, such as temperature and pressure information, is not available). The phase diagram data structure can be parsed to identify the structure corresponding to the structure identified through imaging, and the temperature(s) and pressure(s) corresponding to the structure identified in the phase diagram data structure can be retrieved.

Definitions

[0061] As utilized herein, the terms “approximately,” “about,” “substantially,” and similar terms are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. It should be understood by those of skill in the art who review this disclosure that these terms are intended to allow a description of certain features described and claimed without restricting the scope of these features to the precise numerical ranges provided. Accordingly, these terms should be interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and claimed are considered to be within the scope of the disclosure as recited in the appended claims.

[0062] The term “coupled,” as used herein, means the joining of two members directly or indirectly to one another. Such joining may be stationary (e.g., permanent or fixed) or moveable (e.g., removable or releasable). Such joining may

be achieved with the two members coupled directly to each other, with the two members coupled to each other using a separate intervening member and any additional intermediate members coupled with one another, or with the two members coupled to each other using an intervening member that is integrally formed as a single unitary body with one of the two members. Such members may be coupled mechanically, electrically, and/or fluidly.

[0063] The term “or,” as used herein, is used in its inclusive sense (and not in its exclusive sense) so that when used to connect a list of elements, the term “or” means one, some, or all of the elements in the list. Conjunctive language such as the phrase “at least one of X, Y, and Z,” unless specifically stated otherwise, is understood to convey that an element may be either X, Y, Z; X and Y; X and Z; Y and Z; or X, Y, and Z (i.e., any combination of X, Y, and Z). Thus, such conjunctive language is not generally intended to imply that certain embodiments require at least one of X, at least one of Y, and at least one of Z to each be present, unless otherwise indicated.

[0064] References herein to the positions of elements (e.g., “top,” “bottom,” “above,” “below,” etc.) are merely used to describe the orientation of various elements in the FIGURES. It should be noted that the orientation of various elements may differ according to other exemplary embodiments, and that such variations are intended to be encompassed by the present disclosure.

[0065] The hardware and data processing components used to implement the various processes, operations, illustrative logics, logical blocks, modules and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general purpose single- or multi-chip processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, or, any conventional processor, controller, microcontroller, or state machine. A processor also may be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. In some embodiments, particular processes and methods may be performed by circuitry that is specific to a given function. The memory (e.g., memory, memory unit, storage device, etc.) may include one or more devices (e.g., RAM, ROM, Flash memory, hard disk storage, etc.) for storing data and/or computer code for completing or facilitating the various processes, layers and modules described in the present disclosure. The memory may be or include volatile memory or non-volatile memory, and may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. According to an exemplary embodiment, the memory is communicably connected to the processor via a processing circuit and includes computer code for executing (e.g., by the processing circuit and/or the processor) the one or more processes described herein.

[0066] The present disclosure contemplates methods, systems and program products on any machine-readable media

for accomplishing various operations. The embodiments of the present disclosure may be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0067] Although the figures and description may illustrate a specific order of method steps, the order of such steps may differ from what is depicted and described, unless specified differently above. Also, two or more steps may be performed concurrently or with partial concurrence, unless specified differently above. Such variation may depend, for example, on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations of the described methods could be accomplished with standard programming techniques with rule-based logic and other logic to accomplish the various connection steps, processing steps, comparison steps, and decision steps.

[0068] It is important to note that the construction and arrangement of the fluid control systems and methods of fluid control as shown in the various exemplary embodiments is illustrative only. Additionally, any element disclosed in one embodiment may be incorporated or utilized with any other embodiment disclosed herein. Although only one example of an element from one embodiment that can be incorporated or utilized in another embodiment has been described above, it should be appreciated that other elements of the various embodiments may be incorporated or utilized with any of the other embodiments disclosed herein.

1. A method for generating phases for metastable states of materials, comprising:

- accessing, by one or more processors, at least one parameter of a material;
- generating, by the one or more processors, a plurality of structures of the material using the at least one parameter;
- determining, by the one or more processors, a state of each structure of the plurality of structures using the at least one parameter;
- determining, by the one or more processors, a difference between the state of each structure of the plurality of structures and a ground state value;
- evaluating, by the one or more processors, a convergence condition responsive to determining the difference

between the state of each structure of the plurality of structures and the ground state value; and

outputting, by the one or more processors, at least one structure of the plurality of structures responsive to the convergence condition being satisfied.

2. The method of claim **1**, wherein outputting the at least one structure comprises generating, by the one or more processors, a phase diagram data structure representing the at least one structure.

3. The method of claim **2**, further comprising applying, by the one or more processors, a classifier to the phase diagram data structure to determine one or more boundaries between phases of the phase diagram data structure.

4. The method of claim **1**, wherein the at least one parameter comprises at least one of a temperature, a pressure, or a composition of the material.

5. The method of claim **1**, wherein the state of each structure comprises an enthalpy of the structure, and determining the state of each structure comprises providing, by the one or more processors, the structure of the material and the at least one parameter of the material as input to a density functional theory model.

6. The method of claim **1**, further comprising modifying, by the one or more processors, the plurality of structures by applying, by the one or more processors, a genetic function to the plurality of structures.

7. The method of claim **1**, comprising modifying, by the one or more processors, one or more first structures of the plurality of structures of the material responsive to the convergence condition not being satisfied.

8. The method of claim **7**, further comprising wherein modifying the one or more first structures comprises applying, by the one or more processors, a genetic operation to the one or more first structures.

9. The method of claim **7**, further comprising:

- assigning, by the one or more processors, a selection score to each of the one or more first structures based on a respective state of the one or more first structures; and
- modifying, by the one or more processors, each of the one or more first structures based on the selection score assigned to the corresponding one or more first structures.

10. The method of claim **1**, wherein a threshold of the convergence condition based on which the difference between the state of each structure of the plurality of structures and the ground state value is evaluated is greater than 10 meV/atom and less than 1 eV/atom.

11. A method, comprising:

- generating, by one or more processors, a plurality of candidate structures of a material;
- determining, by the one or more processors, an enthalpy of each candidate structure of the plurality of candidate structures;
- comparing, by the one or more processors, the enthalpy of each candidate structure to an energy threshold;
- selecting, by the one or more processors, a subset of the plurality of candidate structures, each candidate structure of the subset having an enthalpy less than the energy threshold;
- determining, by the one or more processors, a free energy of each candidate structure of the subset of the plurality of candidate structures for a plurality of temperature-pressure value pairs;

determining, by the one or more processors, at least one boundary between phases represented by the subset of the plurality of candidate structures; and

generating, by the one or more processors, a phase diagram data structure using the free energy of each candidate structure of the plurality of candidate structures and the at least one boundary.

12. The method of claim **2**, further comprising retrieving, by the one or more processors from the phase diagram data structure, a temperature and a pressure for controlling a process to synthesize the material.

13. The method of claim **2**, wherein the phase diagram data structure indicates a phase of the material for a particular free energy or range of free energies.

14. The method of claim **7**, wherein modifying the one or more first structures comprises modifying at least one of a bond, a bond length, an atom, or a group of atoms of the one or more first structures.

15. The method of claim **1**, wherein the state comprises at least one of enthalpy or free energy.

16. The method of claim **11**, further comprising retrieving, by the one or more processors from the phase diagram data structure, a temperature and a pressure for controlling a process to synthesize the material.

17. The method of claim **11**, wherein the phase diagram data structure indicates a phase of the material for a particular free energy or range of free energies.

18. The method of claim **11**, further comprising modifying, by the one or more processors, one or more candidate structures having an enthalpy greater than the energy threshold.

19. The method of claim **11**, wherein the plurality of candidate structures comprise at least one of a chemical structure of the material or a crystal structure of the material.

20. The method of claim **11**, wherein the energy threshold is greater than 10 MeV/atom and less than 1 eV/atom.

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