

CONTINUOUS PROCESS FOR CONVERTING NATURAL GAS TO LIQUID HYDROCARBONS

CROSS-REFERENCE TO RELATED APPLICATION

5 This application is based on and claims priority U.S. Provisional Patent Application No. 61/081,976, filed July 18, 2008, U.S. Provisional Patent Application No. 61/082,000, filed July 18, 2008, U.S. Provisional Patent Application No. 61/082,115, filed July 18, 2008, U.S. Provisional Patent Application No. 61/082,143, filed July 18, 2008, and U.S. Patent Application No. 12/496,348, filed July 1, 2009 which is a continuation of 11/703,358 filed February 5, 2007,
10 the entire contents of each provisional and application are incorporated by reference herein.

FIELD OF THE INVENTION

 This invention generally relates to carbon-carbon coupling and, more particularly, to methods for converting hydrocarbon feedstocks into useful products.

BACKGROUND OF THE INVENTION

15 Scientists have long sought efficient ways to convert methane and other hydrocarbons into longer chain hydrocarbons, olefins, aromatic hydrocarbons, and other products. CH bond activation has been the focus of intense research for decades, with mixed results. More efficient processes may create value in a number of ways, including facilitating the utilization of remotely located hydrocarbon feedstocks (such as stranded natural gas) through conversion into more
20 easily transportable and useful fuels and feedstocks, and allowing the use of inexpensive feedstocks (*e.g.*, methane and other light hydrocarbons) for end products often made from higher hydrocarbons.

 U.S. Pat. No. 6,525,230 discloses methods of converting alkanes to other compounds using a "zone reactor" comprised of a hollow, unsegregated interior defining first, second, and
25 third zones. Oxygen reacts with metal bromide in the first zone to provide bromine; bromine reacts with the alkane in the second zone to form alkyl bromide and hydrogen bromide; and the alkyl bromide reacts with metal oxide in the third zone to form the corresponding product. In one embodiment, the flow of gases through the reactor may be reversed to convert the metal oxide back to metal bromide and to convert the metal bromide back to the metal oxide. The reactor
30 may essentially operated in a cyclic mode.

 Other processes may include an oxidative halogenation process for producing alkyl halides from an alkane, hydrogen halide, and, preferably, oxygen, using a rare earth halide or

oxyhalide catalyst. A metal halide catalyst may also be used for oxidative halogenation of alkanes. Oxidative halogenation, however, has several disadvantages, including the production of perhalogenated products and an unacceptable quantity of deep oxidation products (CO and CO₂).

5 Other processes include a bromine-based process for converting gaseous alkanes to liquid hydrocarbons. Several basic steps may be used, including (1) reacting bromine with alkanes to produce alkyl bromides and hydrobromic acid (bromination), (2) reacting the alkyl bromide and hydrobromic acid product with a crystalline alumino-silicate catalyst to form higher molecular weight hydrocarbons and hydrobromic acid (coupling), (3) neutralizing the hydrobromic acid by
10 reaction with an aqueous solution of partially oxidized metal bromide salts (as metal oxides/oxybromides/bromides) to produce a metal bromide salt and water in an aqueous solution, or by reaction of the hydrobromic acid with air over a metal bromide catalyst, and (4) regenerating bromine by reaction of the metal bromide salt with oxygen to yield bromine and an oxidized salt. Potential drawbacks of the processes may include low methane conversions; short
15 space-times and the resulting potential for less than 100% bromine conversion; wasteful overbromination of ethane, propane, and higher alkanes, resulting in the formation of dibromomethane and other polybrominated alkanes, which will likely form coke under the disclosed reaction conditions; comparatively low alkyl bromide conversions; the need to separate the hydrocarbon product stream from an aqueous hydrohalic acid stream; and inadequate capture
20 of halogen during the regeneration of the catalyst to remove halogen-containing coke. In addition, the proposed venting of this bromine-containing stream may be both economically and environmentally unacceptable.

The process described above may also requires operation at relatively low temperatures to prevent significant selectivity to methane. One result may be incomplete conversion of alkyl
25 bromide species and, because the process relies on stream splitting to recover products, a considerable amount of unconverted alkyl bromides may leave the process with the products. This represents an unacceptable loss of bromine (as unconverted methyl bromide) and a reduced carbon efficiency.

The neutralization of hydrobromic acid by reaction with an aqueous solution of partially
30 oxidized metal bromide salts and subsequent reaction of the metal bromide salts formed with oxygen to yield bromine and an oxidized salt may also have a number of disadvantages. First, any carbon dioxide present may form carbonates in the slurry, which may not be regenerable. Second, the maximum temperature may be limited due to pressure increases which are intolerable above approximately 200 °C, thus preventing complete recovery of halogen. Third,
35 although the use of redox-active metal oxides (*e.g.*, oxides of V, Cr, Mn, Fe, Co, Ce, and Cu)

may contribute to molecular bromine formation during the neutralization of hydrobromic acid, incomplete HBr conversion due to the use of a solid bromide salt may in turn result in a significant loss of bromine from the system (in the water phase). Provided an excess of air was used, the bromide salt might eventually be converted to the oxide form, stopping any further loss of HBr in the water discard.

To separate water from bromine, a process may utilize condensation and phase separation to produce semi-dry liquid bromine and a water/bromine mixture. Other means for separating water from bromine, such as using an inert gas to strip the bromine from the water phase or using adsorption-based methods have also been proposed; however, such methods are minimally effective and result in a significant overall loss of halogen.

An oxychlorination process may first remove the water from HCl (a costly step) and then reacts the HCl with oxygen and hydrocarbon directly. Oxychlorination processes rely on the separation of HCl from the unreacted alkanes and higher hydrocarbon products by using water absorption, and subsequent recovery of anhydrous HCl from the aqueous hydrochloric acid.

Processes for the absorption of HCl in water may dissipate the heat of absorption by contacting the HCl gas with ambient air, and also by the vaporization of water. Such processes may produce aqueous hydrochloric acid with a concentration of at least 35.5 wt %. Other processes may allow for the recovery of anhydrous HCl gas by extractive distillation using a chloride salt. Still other processes allow for the production of gaseous HCl from dilute aqueous HCl using an amine together with an inert water-immiscible solvent.

Although researchers have made some progress in the search for more efficient CH bond activation pathways for converting natural gas and other hydrocarbon feedstocks into fuels and other products, there remains a tremendous need for a continuous, economically viable, and more efficient process.

SUMMARY

This invention generally relates to carbon-carbon coupling and, more particularly, to methods for converting hydrocarbon feedstocks into useful products.

An embodiment comprises a method comprising: providing a first halogen stream; providing a first alkane stream; reacting at least a portion of the first halogen stream with at least a portion of the first alkane stream in a first reaction vessel to form a first halogenated stream; providing a second alkane stream comprising C₂ and higher hydrocarbons; providing a second halogen stream; and reacting at least a portion of the second halogen stream with at least a portion of the second alkane stream in a second reaction vessel to form a second halogenated stream.

Another embodiment comprises a method comprising: providing a halogen stream; providing a first alkane stream; reacting at least a portion of the halogen stream with at least a portion of the first alkane stream to form a halogenated stream, wherein the halogenated stream comprises alkyl monohalides, alkyl polyhalides, and hydrogen halide; and contacting at least
5 some of the alkyl monohalides with a coupling catalyst to form a product stream that comprises higher hydrocarbons and hydrogen halide.

Still another embodiment comprises A method comprising: providing an alkyl halide stream; contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide; contacting the product stream with
10 an aqueous solution comprising a metal halide to remove at least a portion of the hydrogen halide from the product stream; separating at least some of the metal halide from the aqueous solution; and heating the separated metal halide to generate a corresponding halogen.

An embodiment comprises a method comprising: providing an alkyl halide stream; contacting at least some of the alkyl halides with a coupling catalyst to form a product stream
15 comprising higher hydrocarbons and hydrogen halide; contacting the product stream with a solid reactant to remove at least a portion of the hydrogen halide from the product stream; and reacting the solid reactant with a source of oxygen to generate a corresponding halogen.

Another embodiment comprises a method comprising: providing an alkyl halide stream; contacting at least some of the alkyl halides with a coupling catalyst to form a product stream
20 comprising higher hydrocarbons and hydrogen halide; separating at least some of the product stream from the hydrogen halide; and contacting the hydrogen halide with oxygen and an aqueous solution comprising a metal capable of forming multiple stable oxidation states to generate a corresponding halogen and water.

Still another embodiment comprises a system comprising: a coupling reactor comprising
25 a coupling catalyst for receiving an alkyl halide stream and contacting at least a portion of the alkyl halide stream with the coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide; a separator unit for separating at least some of the product stream from the hydrogen halide; and an oxidation reactor comprising an aqueous solution comprising a metal capable of forming multiple stable oxidation states for receiving a source of
30 oxygen and at least a portion of the hydrogen halide from the separator unit and generating a corresponding halogen and water..

An embodiment comprises a method comprising: providing a halogen stream; providing an alkane stream; providing a decoking agent; and reacting at least a portion of the halogen stream with at least a portion of the alkane stream in the presence of a halogenation catalyst and
35 the decoking agent to form a halogenated stream.

Another embodiment comprises a method comprising: providing a gas phase stream comprising an elemental halide; contacting the gas phase stream with a chilled brine in the liquid phase, wherein the chilled brine comprises an aqueous solution and a salt; separating the elemental halogen along with the chilled brine from the remainder of the gas phase stream that remains in the gas phase; and separating the elemental halide from the chilled brine.

Still another embodiment comprises a method comprising: providing an alkyl halide stream; contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide; separating the hydrogen halide from the product stream; and reacting the hydrogen halide with a source of oxygen in the presence of an oxidation catalyst to generate a corresponding halogen.

The features and advantages of the present invention will be apparent to those skilled in the art. While numerous changes may be made by those skilled in the art, such changes are within the spirit of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention;

FIG. 2 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon fuels according to the invention;

FIG. 3 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon fuels according to the invention;

FIG. 4 is a schematic view of a subprocess for reportionating polyhalides according to an alternate embodiment of the invention;

FIG. 5 is a schematic view of one embodiment of a continuous process for a halogenation reactor;

FIG. 6 is a schematic view of one embodiment of a monobromide separation column, for use in the practice of the invention;

FIG. 7 is a schematic view of one embodiment of a catalytic coupling reactor with multiple catalytic beds;

FIG. 8 is another schematic view of one embodiment of a catalytic coupling reactor with multiple catalytic beds;

FIG. 9 is a schematic view of one embodiment of an extractive distillation system, for use in the practice of the invention;

FIG. 10 is a schematic view of one embodiment of a temperature swing absorption system, for use in the practice of the invention;

FIG. 11 is a chart showing the solubility of HBr in water for one embodiment of an absorption system, for use in the practice of the invention;

FIG. 12 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention.;

5 FIG. 13 is a chart showing the absorptive capacity of a NiO catalyst for one embodiment of an adsorption system, for use in the practice of the invention;

FIG. 14 is a flow-chart showing one embodiment of a process for creating sol-gel granules;

10 FIG. 15 is a flow-chart showing one embodiment of a process for creating co-precipitation granules;

FIG. 16 is a schematic view of one embodiment of a liquid phase HBr oxidation system, for use in the practice of the invention;

FIG. 17 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention;

15 FIG. 18 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention;

FIG. 19 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention;

20 FIG. 20 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention;

FIG. 21 is a schematic view of one embodiment of a product separation sub-system, for use in the practice of the invention;

25 FIG. 22 is a simplified block diagram of one embodiment of a continuous process for converting alkanes into hydrocarbon products according to the invention, wherein water is separated from hydrocarbon products; and

FIG. 23 is a simplified block diagram of one embodiment of a continuous process for converting alkanes into hydrocarbon products according to the invention, wherein water is separated after the alkane bromination step.

30 FIG. 24 is a simplified block diagram of one embodiment of a continuous process for converting alkanes into hydrocarbon products according to the invention, wherein a cataloreactant is used.

FIG. 25 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention;

FIG. 26 is a simplified block diagram of one embodiment of a continuous process for converting alkanes into hydrocarbon products according to the invention, wherein a copper bromine capture agent is used;

5 FIG. 27 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention;

FIG. 28 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention;

FIG. 29 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention;

10 FIG. 30 is a schematic view of one embodiment of a continuous process for converting methane or natural gas into hydrocarbon chemicals according to the invention using a continuous flow zone reactor configuration;

FIG. 31 is a graph of bromobenzene conversion and benzene yield as a function of time, for an experiment conducted according to one embodiment of the invention; and

15 FIG. 32 is a graph of catalyst effectiveness as a function of time, for an experiment conducted according to one embodiment of the invention.

FIG. 33 is a graph of methyl bromide coupling results as a function of temperature, for an experiment conducted according to one embodiment of the invention.

20 FIG. 34 is another graph of methyl bromide coupling results as a function of temperature, for an experiment conducted according to one embodiment of the invention.

FIG. 35 is a graph of methane selectivity as a function of cycle number, for an experiment conducted according to one embodiment of the invention.

FIG. 36 is a graph of conversion efficiency as a function of retention time, for an experiment conducted according to one embodiment of the invention.

25 FIG. 37 is a graph of coke production, for an experiment conducted according to one embodiment of the invention.

DETAILED DESCRIPTION

30 This invention generally relates to carbon-carbon coupling and, more particularly, to methods for converting hydrocarbon feedstocks into useful products.

The present invention provides a chemical process that enables natural gas and other hydrocarbon feedstocks to be converted into higher molecular weight hydrocarbon products, using molecular halogen to activate C-H bonds in the feedstock. According to one aspect of the invention, a continuous process for converting a hydrocarbon feedstock into one or more higher
35 hydrocarbons may comprise the steps of (a) forming alkyl halides by reacting molecular halogen

with a hydrocarbon feedstock (preferably a feedstock containing methane), under process conditions sufficient to form alkyl halides and hydrogen halide, whereby substantially all of the molecular halogen is consumed; (b) contacting the reportionated alkyl halides with a first catalyst under process conditions sufficient to form higher hydrocarbons and additional hydrogen halide; (c) separating the higher hydrocarbons from the hydrogen halide; (d) regenerating molecular halogen under process conditions sufficient to form molecular halogen and water; and (e) repeating steps (a) through (d) a desired number of times. These steps can be carried out in the order presented or, alternatively, in a different order.

In each of the aspects and embodiments of the invention, it is intended that the alkyl halides formed in step (a) can be all the same (*e.g.*, 100% bromomethane) or, more typically, different (*e.g.*, mixtures of bromomethane, dibromomethane, dibromoethane, etc). Similarly, it is contemplated that the "higher hydrocarbons" formed in step (b) can be all the same (*e.g.*, 100% isooctane) or, more typically, different (*e.g.*, mixtures of aliphatic and/or aromatic compounds). As used herein, the term "higher hydrocarbons" refers to hydrocarbons having a greater number of carbon atoms than one or more components of the hydrocarbon feedstock, as well as olefinic hydrocarbons having the same or a greater number of carbon atoms as one or more components of the hydrocarbon feedstock. For instance, if the feedstock is natural gas--typically a mixture of light hydrocarbons, predominately methane, with lesser amounts of ethane, propane, and butane, and even smaller amounts of longer chain hydrocarbons such as pentane, hexane, etc.--the "higher hydrocarbon(s)" produced according to the invention can include a C₂ or higher hydrocarbon, such as ethane, propane, butane, C₅₊ hydrocarbons, aromatic hydrocarbons, etc., and optionally ethylene, propylene, and/or longer olefins. The term "light hydrocarbons" (sometimes abbreviated "LHCs") refers to C₁-C₄ hydrocarbons, *e.g.*, methane, ethane, propane, ethylene, propylene, butanes, and butenes, all of which are normally gases at room temperature and atmospheric pressure.

Nonlimiting examples of hydrocarbon feedstocks appropriate for use in the present invention include alkanes, *e.g.*, methane, ethane, propane, and even larger alkanes; olefins; natural gas and other mixtures of hydrocarbons. In most cases, the feedstock will be primarily aliphatic in nature. Certain oil refinery processes yield light hydrocarbon streams (so-called "light-ends," typically a mixture of C₁-C₃ hydrocarbons), which may be used with or without added methane as the hydrocarbon feedstock in one embodiment of the invention.

Representative halogens include bromine (Br₂) and chlorine (Cl₂). It is also contemplated that fluorine and iodine may be used, though not necessarily with equivalent results. Some of the problems associated with fluorine may likely be addressed by using dilute streams of fluorine (*e.g.*, fluorine gas carried by helium, nitrogen, or other diluent). It is expected, however, that

more vigorous reaction conditions will be required for alkyl fluorides to couple and form higher hydrocarbons, due to the strength of the fluorine-carbon bond. Similarly, problems associated with iodine (such as the endothermic nature of certain iodine reactions) may likely be addressed by carrying out the halogenation and/or coupling reactions at higher temperatures and/or pressures. The use of bromine or chlorine is preferred. While bromine and hydrogen bromide may be used in the descriptions contained herein, it should be understood that chlorine, fluorine, or iodine may be substituted unless otherwise specifically stated.

FIGS. 1 and 2 schematically illustrate two nonlimiting embodiments of a process according to the invention, with FIG. 1 depicting a process for making hydrocarbon chemicals (e.g., benzene, toluene, xylenes, other aromatic compounds, etc.), and FIG. 2 depicting a process for making fuel-grade hydrocarbons, e.g., hydrocarbons comprising a predominant amount of C₅ and higher aliphatic hydrocarbons and (optionally) aromatic hydrocarbons. The primary difference in the two embodiments is that the process depicted in FIG. 2 lacks the first separation unit (SEP I) and does not return polybrominated species to the bromination reactor for "reproportionation." In the scheme shown in FIG. 2, the amount of polybromides produced may be reduced significantly by introducing light gasses into the bromination reactor. The polybromides (from methane bromination) may react with the light gasses to form monobromoalkanes. For convenience, the figures depict a bromine-based process. In alternate embodiments of the invention, however, chlorine or other halogens may be used.

As shown in FIG. 1, natural gas (or another hydrocarbon feedstock) and molecular bromine may be carried by separate lines 1, 2 into a heated bromination reactor 3 and allowed to react. Products (HBr, alkyl bromides, optionally olefins), and possibly unreacted hydrocarbons, exit the reactor and are carried by a line 4 into a first separation unit 5 (SEP I), where monobrominated hydrocarbons and HBr may be separated from polybrominated hydrocarbons. The polybromides may be carried by a line 6 back to the bromination reactor, where they may undergo "reproportionation" with methane and/or other light hydrocarbons, which may be present in the natural gas and/or introduced to the bromination reactor as described below.

Reproportionation of the polybromides formed during the bromination reaction enriches the outlet stream with monobromides and olefinic species, and reduces the amount of polybrominated hydrocarbons that enter the coupling reactor. This, in turn, may reduce the amount of coke that forms during the carbon-carbon coupling reactions. For large scale production of aromatic hydrocarbons, it may be possible to employ additional separation units, which may further purify the feed stream to the coupling reactor by separating and recycling the polybromides, thereby reducing the amount of coke and the overall bromine requirement.

Unreacted hydrocarbon feedstock, HBr, monobromides, and (optionally) olefins formed in the bromination reactor may be carried by a line 7, through a heat exchanger 8, and enter a heated coupling reactor 9, where the monobromides (and, optionally, any olefins present) may react in the presence of a coupling catalyst to form higher hydrocarbons. HBr, higher
5 hydrocarbons, and (possibly) unreacted hydrocarbons and alkyl bromides may exit the coupling reactor and be carried by a line 10, through another heat exchanger 11, and enter an HBr absorption unit 12. Water may be introduced into the unit through a separate line 13. HBr may be absorbed in this unit, which may be a packed column or other gas-liquid contacting device. The effluent, containing liquid hydrocarbons and aqueous HBr, may be carried by a line 14 to a
10 liquid-liquid splitter 15, which phase-separates liquid hydrocarbons from the aqueous HBr stream. The liquid hydrocarbon products may then be carried by a line 16 to a product clean-up unit 17 to yield final hydrocarbon products.

After HBr is separated from the hydrocarbon products and unreacted methane (and any other light hydrocarbons that may be present) in the HBr absorption unit, the methane (and other
15 light hydrocarbons, if any) may be carried by a line 18 into a second separation unit 19 (SEP II), which employs pressure- or temperature-swing absorption, membrane-based separation, cryogenic distillation (preferable for large scale production), or another suitable separation technology. Methane, and possibly other light hydrocarbons, may be returned to the bromination reactor via one or more lines 20, 21. In the embodiment shown, methane may be directed to an
20 upstream region or "zone" of the bromination reactor, while other light hydrocarbons may be directed to a mid- or downstream zone of the reactor (the latter to facilitate reproporationation of polybromides).

The aqueous HBr stream that evolves from the liquid-liquid splitter may be carried by a line 22 to a bromine generation unit 23. Oxygen, air, or oxygen-enriched gas may also be fed
25 into the unit through a separate line 24. Bromine may be regenerated by reacting HBr with oxygen in the presence of a suitable catalyst. The resulting stream may contain water, molecular bromine, oxygen, nitrogen if air was used as the source of oxygen, and possibly other gases. This product stream may be carried by a line 25 through a heat exchanger 26 into a flash vaporization unit 27, which separates most of the molecular bromine from water, oxygen, nitrogen, and other
30 gases (if any) that are present. Molecular bromine, either as a liquid or vapor and containing no more than a trace of H_2O , may be carried by a line 28 to a heat exchanger 29, and then returned to the bromination reactor.

Water from the flash vaporization unit containing up to about 3 wt % of molecular bromine may be sent by a line 30 to a distillation unit 31, which yields water as the bottoms

stream and bromine or bromine-water azeotrope as a distillate. The distillate may be returned through a line 32 back to the flash vaporization unit.

The gaseous products of the flash vaporization unit (*e.g.*, oxygen, nitrogen, optionally other gases, and no more than a minor or trace amount of bromine) may be carried by a line 33 to a bromine scavenging unit 34, which separates molecular bromine from the other gases. The recovered bromine may then be carried by a line 35 through a heat exchanger 29 and reintroduced into the bromination reactor. The amount of bromine entering the scavenger may be further reduced by increasing the amount of bromine recovered in the flash step by employing brine solutions and direct contact cooling to allow the use of temperatures below 0 °C. The other gases (*e.g.*, nitrogen, oxygen) may be vented to the atmosphere.

In another embodiment, shown in Figure 3, an HBr capture and oxidation scheme may be used to capture HBr from the products stream without using aqueous absorption and regenerate elemental bromine. In this embodiment, the products stream exiting the coupling reactor 49 may pass through a vessel 55 containing a solid reactant material. The solid reactant may react with the HBr to form a corresponding metal bromide and water, which may pass through the vessel along with the unaffected hydrocarbon products from the coupling reactor. The metal bromide may then be contacted with air or oxygen 58 to regenerate the original solid reactant material 63 and an elemental bromine stream 59, which can be recycled for use in the bromination reactor 43.

Various embodiments and features of individual subprocesses and other improvements for carrying out the invention will now be described in more detail.

Bromination

Bromination of the hydrocarbon feedstock may be carried out in a fixed bed, fluidized bed, or other suitable reactor, at a temperature and pressure such that the bromination products and reactants are gases, for example, about 1 to about 50 atm, about 150 °C to about 600 °C, more preferably about 400 °C to about 600 °C, even more preferably, about 450 °C to about 515 °C, with a residence time of about 1 to about 60 seconds, more preferably about 1 to about 15 seconds. Higher temperatures tend to favor coke formation, while low temperatures require larger reactors. Using a fluidized bed may offer the advantage of improved heat transfer.

Alkane bromination may be initiated using heat or light, with thermal means being preferred. In one embodiment, the reactor may also contain a halogenation catalyst, such as a zeolite, amorphous alumino-silicate, acidic zirconia, tungstates, solid phosphoric acids, metal oxides, mixed metal oxides, metal halides, mixed metal halides (the metal in such cases being, *e.g.*, nickel, copper, cerium, cobalt, etc.), and/or or other catalysts as described, *e.g.*, in U.S. Pat.

Nos. 3,935,289 and 4,971,664, which are incorporated herein in their entirety. In an alternate embodiment, the reactor contains a porous or non-porous inert material that provides sufficient surface area to retain coke formed in the reactor and prevent it from escaping. The inert material may also promote the formation of polyhalogenated hydrocarbons, such as tribromopropane. In still another embodiment, both a catalyst and an inert material are provided in the reactor. Optionally, the reactor may contain different regions or zones to allow, in one or more zones, complete conversion of molecular bromine to produce alkyl bromides and hydrogen bromide.

The bromination reaction may also be carried out in the presence of an isomerization catalyst, such as a metal bromide (*e.g.*, NaBr, KBr, CuBr, NiBr₂, MgBr₂, CaBr₂), metal oxide (*e.g.*, SiO₂, ZrO₂, Al₂O₃), or metal (Pt, Pd, Ru, Ir, Rh) to help generate the desired brominated isomer(s). Since isomerization and bromination conditions are similar, the bromination and isomerization may be carried out in the same reactor vessel. Alternatively, a separate isomerization reactor may be utilized, located downstream of the bromination reactor and upstream of the coupling reactor.

In an embodiment, a separate bromination reactor may be used to brominate a light hydrocarbon stream. Light hydrocarbon bromination of C₁-C₅ alkanes with bromine may occur at temperatures ranging from about 150 °C to about 550 °C, with the optimal temperature depending on the alkanes that are present and being brominated. In some embodiments, a polybrominated methane stream from an alkyl polybromide separator may be used to brominate the light hydrocarbon stream in the separate bromination reactor. Light hydrocarbon bromination may proceed more quickly at elevated pressures (*e.g.*, about 2 bar to about 30 bar). Polybromides produced during light bromination may be repropportionated to monobromides by allowing longer residence times. Polybromides of C₂-C₅ alkanes may react better and produce less coke in the coupling reactor than the C₁ polybromides.

Reproportionation

In some embodiments, a key feature of the invention is the "reproportionation" of polyhalogenated hydrocarbons (polyhalides), *i.e.*, halogenated hydrocarbons containing two or more halogen atoms per molecule. Monohalogenated alkanes (monohalides) created during the halogenation reaction may be desirable as predominant reactant species for subsequent coupling reactions and formation of higher molecular weight hydrocarbons. For certain product selectivities, polyhalogenated alkanes may be desirable. Reproportionation allows a desired enrichment of monohalides to be achieved by reacting polyhalogenated alkyl halides with nonhalogenated alkanes, generally in the substantial absence of molecular halogens, to control the ratio of mono-to-polyhalogenated species. For example, dibromomethane may be reacted

with methane to produce methyl bromide; dibromomethane may be reacted with propane to produce methyl bromide and propyl bromide and/or propylene; and so forth.

Reactive reproporationation may be accomplished by allowing the hydrocarbon feedstock and/or recycled alkanes to react with polyhalogenated species from the halogenation reactor, preferably in the substantial absence of molecular halogen. As a practical matter, substantially all of the molecular halogen entering the halogenation reactor is quickly consumed, forming mono- and polyhalides; therefore reproporationation of higher bromides may be accomplished simply by introducing polybromides into a mid- or downstream region or "zone" of the halogenation reactor, optionally heated to a temperature that differs from the temperature of the rest of the reactor.

Alternatively, reproporationation may be carried out in a separate "reproporationation reactor," where polyhalides and unhalogenated alkanes are allowed to react, preferably in the substantial absence of molecular halogen. FIG. 4 illustrates one such embodiment where, for clarity, only significant system elements are shown. As in FIG. 1, natural gas or another hydrocarbon feedstock and molecular bromine may be carried by separate lines 1, 2 to a heated bromination reactor 3 and allowed to react. Products (e.g., HBr, alkyl bromides) and possibly unreacted hydrocarbons, may exit the reactor and be carried by a line 4 into a first separation unit 5, where monobrominated hydrocarbons and HBr are separated from polybrominated hydrocarbons. The monobromides, HBr, and possibly unreacted hydrocarbons may be carried by a line 7, through a heat exchanger 8, to a coupling reactor 9, and allowed to react, as shown in FIG. 1. The polybromides may be carried by a line 6 to a reproporationation reactor 36. Additional natural gas or other alkane feedstock may also be introduced into the reproporationation reactor, via a line 37. Polybromides may react with unbrominated alkanes in the reproporationation reactor to form monobromides, which may be carried by a line 38 to the coupling reactor 9, after first passing through a heat exchanger.

In another embodiment of the invention (not shown), where the hydrocarbon feedstock comprises natural gas containing a considerable amount of C₂ and higher hydrocarbons, the "fresh" natural gas feed is introduced directly into the reproporationation reactor, and recycled methane (which passes through the reproporationation reactor unconverted) is carried back into the halogenation reactor.

Reproporationation may be thermally driven and/or facilitated by use of a catalyst. Nonlimiting examples of suitable catalysts include metal oxides, metal halides, and zeolites. U.S. Pat. No. 4,654,449, incorporated herein in its entirety, discloses the reproporationation of polyhalogenated alkanes with alkanes using an acidic zeolite catalyst. U.S. Pat. Nos. 2,979,541 and 3,026,361 disclose the use of carbon tetrachloride as a chlorinating agent for methane,

ethane, propane and their chlorinated analogues. All three patents are incorporated by reference herein in their entirety.

Reproportionation of C₁-C₅ alkanes with dibromomethane and/or other polybromides may occur at temperatures ranging from about 350 °C to about 550 °C, with the optimal temperature depending on the polybromide(s) that are present and the alkane(s) being brominated. In addition, reproportionation may proceed more quickly at elevated pressures (*e.g.*, about 2 bar to about 30 bar). By achieving a high initial methane conversion in the halogenation reactor, substantial amounts of di- and tribromomethane may be created; those species may then be used as bromination reagents in the reproportionation step. Using di- and tribromomethane may allow for controlled bromination of C₁-C₅ alkanes to monobrominated C₁-C₅ bromoalkanes and C₂-C₅ olefins. Reproportionation of di- and tribromomethane may facilitate high initial methane conversion during bromination, which may reduce the methane recycle flow rate and enrich the reactant gas stream with C₂-C₅ monobromoalkanes and olefins that couple to liquid products over a variety of catalysts, including zeolites.

In another embodiment of the invention, reproportionation may be carried out without first separating the polyhalides in a separation unit. This may be facilitated by packing the "reproportionation zone" with a catalyst, such as a zeolite, that allows the reaction to occur at a reduced temperature. For example, although propane reacts with dibromomethane to form bromomethane and bromopropane (an example of "reproportionation"), the reaction does not occur at an appreciable rate at temperatures below about 500 °C. The use of a zeolite may allow reproportionation to occur at a reduced temperature, enabling species such as methane and ethane to be brominated in one zone of the reactor, and di-, tri-, and other polybromides to be reproportionated in another zone of the reactor.

Bromine Recovery During Decoking

Inevitably, coke formation will occur in the halogenation and reproportionation processes. If catalysts are used in the reactor(s) or reactor zone(s), the catalysts may be deactivated by the coke; therefore, periodic removal of the carbonaceous deposits may be required. In addition, we have discovered that, within the coke that is formed, bromine may also be found, and it is highly desirable that this bromine be recovered in order to minimize loss of bromine in the overall process, which is important for both economic and environmental reasons.

Several forms of bromides may be present: HBr, organic bromides such as methyl bromide and dibromomethane, and molecular bromine. The invention provides means for recovering this bromine from the decoking process. In one embodiment, a given reactor may be switched off-line and air or oxygen may be introduced to combust the carbon deposits and

produce HBr from the residual bromine residues. The effluent gas may be added to the air (or oxygen) reactant stream fed to the bromine generation reactor, thereby facilitating complete bromine recovery. This process may be repeated periodically. In another embodiment, a given reactor may remain operational and bromination and decoking occur simultaneously in the same reactor.

In an embodiment while a given reactor is off-line, the overall process can, nevertheless, be operated without interruption by using a reserve reactor, which may be arranged in parallel with its counterpart reactor. For example, twin bromination reactors and twin coupling reactors may be utilized, with process gasses being diverted away from one, but not both, bromination reactors (or coupling reactors) when a decoking operation is desired. The use of a fluidized bed may reduce coke formation and facilitate the removal of heat and catalyst regeneration.

Another embodiment of the decoking process may involve non-oxidative decoking using an alkane or mixture of alkanes, which may reduce both the loss of adsorbed products and the oxygen requirement of the process.

In still another embodiment of the decoking process, an oxidant such as oxygen, air, or enriched air may be co-fed into the bromination section to convert the coke into carbon dioxide and/or carbon monoxide during the bromination reaction, thus eliminating or reducing the off-line decoking requirement. The reactor configuration may comprise a catalytic bed for the bromination of hydrocarbons followed by a metal bromide bed to capture any unreacted oxygen.

In the embodiment shown in FIG. 5, a bromination reactor capable of being decoked during operation may comprise one or more catalytic zones useful for the bromination of a hydrocarbon with a metal halide catalyst zone located near the center of the reactor. As a hydrocarbon and an elemental halide are introduced into the reactor, the halide may react with the hydrocarbon to form an alkyl halide and some coke on the halogenation catalyst. The oxygen present in the feed to the reactor may react with any coke formed during the halogenation of the hydrocarbons to produce oxidation products (e.g., CO, CO₂, water, etc.). In addition, the oxygen may react with a portion of the hydrocarbons or halogenated hydrocarbons to form oxidation products. Any oxygen reaching the metal halide catalyst zone may react with the metal halide to form a metal oxide and elemental halogen. This halogen may then further react with any unreacted hydrocarbons to form alkyl halides. The reactor may be cyclically operated in a forward and reverse mode to remove coke buildup on any catalyst present in either side of the metal halide zone. The reactor may be a fixed bed reactor, including a vertical fixed bed reactor, a radial bed reactor, or any other suitable fixed bed type reactor.

Appropriate catalyst types for the metal bromide zone may include any active catalyst or solid reactant useful in capturing oxygen and forming an elemental halide, as described in more

detail below. The active materials may be either redox active or non-redox active. Suitable materials may include, but are not limited to, oxides or halides of copper, manganese, yttrium, nickel, cobalt, iron, calcium, vanadium, molybdenum, chromium, manganese, zinc, lanthanum, tungsten, tin, indium, bismuth, or combinations thereof. An oxide of these metals may form a metal halide in situ upon exposure to any hydrogen halide generated during the halogenation reaction. In an embodiment, a non-redox active catalyst such as NiO/NiBr₂ may be preferred due to its high bromine capacity and stability at high temperature in the reactor. In an embodiment, a NiBr₂ catalyst may be used in the center of the reactor. This bromination configuration can prevent oxygen breakthrough where Br₂ is generated from a metal bromide (e.g., CuBr₂) for use in the bromination reaction, including use at high pressures. The oxygen flowrate through the reactor may be less than about 5% by volume, or alternatively, less than about 3% by volume during the decoking process. Further, the decoking process may occur periodically to oxidize any built-up coke deposits, or oxygen may be continuously fed to the reactor in a continuous decoking process.

Alkyl Halide Separation

The presence of large concentrations of polyhalogenated species in the feed to the coupling reactor may result in an increase in coke formation. In many applications, such as the production of aromatics and light olefins, it may be desirable to feed only monohalides to the coupling reactor to improve the conversion to products. In one embodiment of the invention, a specific separation step may be added between the halogenation/reproportionation reactor(s) and the coupling reactor.

For example, a distillation column and associated heat exchangers may be used to separate the monobromides from the polybrominated species by utilizing the large difference in boiling points of the compounds. The polybrominated species that are recovered as the bottoms stream may be reproportionated with alkanes to form monobromide species and olefins, either in the bromination reactor or in a separate reproportionation reactor. The distillation column may be operated at any pressure ranging from about 1 atm to about 50 atm. The higher pressures may allow higher condenser temperatures to be used, thereby reducing the refrigeration requirement.

FIG. 6 illustrates one embodiment of a separation unit for separating monobromides from polybrominated species. Alkyl bromides from the bromination reactor may be cooled by passing through a heat exchanger 70, and then provided to a distillation column 71 equipped with two heat exchangers 72 and 73. At the bottom of the column, heat exchanger 72 acts as a reboiler, while at the top of the column heat exchanger 73 acts as a partial condenser. This configuration allows a liquid "bottoms" enriched in polybromides (and containing no more than a minor

amount of monobromides) to be withdrawn from the distillation column. The polybromides may be passed through another heat exchanger 74 to convert them back to a gas before they are returned to the bromination reactor (or sent to a separate reproporationation reactor) for reproporationation with unbrominated alkanes. At the top of the column, partial reflux of the liquid from the reflux drum is facilitated by the heat exchanger 73, yielding a vapor enriched in lighter components including methane and HBr, and a liquid stream comprised of monobromides and HBr (and containing no more than a minor amount of polybromides).

Alternate distillation configurations may include a side stream column with and without a side stream rectifier or stripper. If the feed from the bromination reactor contains water, the bottoms stream from the distillation column will also contain water, and a liquid-liquid phase split on the bottoms stream may be used to separate water from the polybrominated species. Due to the presence of HBr in the water stream, it may be sent to a HBr absorption column or to the bromine generation reactor.

Catalytic Coupling of Alkyl Halides to Higher Molecular Weight Products

The alkyl halides produced in the halogenation/reproporationation step may be reacted over a catalyst to produce higher hydrocarbons and hydrogen halide. The reactant feed may also contain hydrogen halide and unhalogenated alkanes from the bromination reactor. According to the invention, any of a number of catalysts may be used to facilitate the formation of higher hydrocarbon products from halogenated hydrocarbons. Nonlimiting examples include non-crystalline alumino silicates (amorphous solid acids), tungsten/zirconia super acids, sulfated zirconia, zeolites, such as SAPO-34 and its framework-substituted analogues (substituted with, e.g., Ni or Mn), ZSM-5 and its ion-exchanged analogs, and framework substituted ZSM-5 (substituted with Ti, Fe, Ti+Fe, B, or Ga). Preferred catalysts for producing liquid-at-room-temperature hydrocarbons include ion-exchanged ZSM-5 having a $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio below about 300, preferably below about 100, and most preferably about 30 or less. Nonlimiting examples of preferred exchanged ions include ions of Ag, Ba, Bi, Ca, Fe, Li, Mg, Sr, K, Na, Rb, Mn, Co, Ni, Cu, Ru, Pb, Pd, Pt, and Ce. These ions can be exchanged as pure salts or as mixtures of salts. The preparation of doped zeolites and their use as carbon-carbon coupling catalysts is described in Patent Publication No. US 2005/0171393 A1, which is incorporated by reference herein in its entirety. In another embodiment, a fluorinated alumina based solid reactant, as described in more detail below, may be used as the catalyst or as a support for a catalytic material useful in the formation of higher hydrocarbon products. Use of a fluorinated alumina may allow for the simultaneous formation of higher hydrocarbons and capture of hydrogen halide formed in the reaction.

In one embodiment of the invention a Mn-exchanged ZSM-5 zeolite having a $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 30 is used as the coupling catalyst. Under certain process conditions, it can produce a tailored selectivity of liquid hydrocarbon products.

In one embodiment of the invention, a reduced aluminum content ZSM-5 zeolite may be used as a coupling catalyst. Generally, a dealumination treatment of the coupling catalyst may provide benefits such as higher selectivity towards BTX products while maintaining high conversion (> about 99 %). Additionally dealumination may extended the catalyst useful life, may improve short and long term thermal stability, and may also reduce coke generation. Dealumination of a zeolite catalyst may be done by selective treatment of the hydrogen-exchanged zeolite with a compound that specifically reacts with aluminum centers by forming either volatile compounds at high temperature or soluble complexes when treated in an aqueous solution. Examples of dealumination agents may include mineral acids, such as hydrochloric acid (HCl), hydrofluoric acid (HF), ethylenediaminetetraacetic acid (EDTA), oxalic acid, malonic acid; overheated water steam (steaming), and exchange reagents (SiCl_4 , $\text{NH}_4[\text{SiF}_6]$, NH_4HF_2 , AlF_3 , trialkyl phosphates, organic phosphites).

Coupling of haloalkanes may be carried out in a fixed bed, fluidized bed, or other suitable reactor, at a suitable temperature (*e.g.*, about 150 °C to about 600 °C, preferably about 275 °C to about 425 °C) and pressure (*e.g.*, about 0.1 atm to about 35 atm) and a residence time (τ) of from about 1 second to about 45 seconds. In general, a relatively long residence time favors conversion of reactants to products, as well as product selectivity, while a short residence time means higher throughput and (possibly) improved economics. It is possible to direct product selectivity by changing the catalyst, altering the reaction temperature, and/or altering the residence time in the reactor. For example, at a moderate residence time of 10 seconds and a moderate temperature of about 350 °C, xylene and mesitylenes may be the predominant components of the aromatic fraction (benzene + toluene + xylenes + mesitylenes; "BTXM") produced when the product of a methane bromination reaction is fed into a coupling reactor packed with a metal-ion-impregnated ZSM-5 catalyst, where the impregnation metal is Ag, Ba, Bi, Ca, Co, Cu, Fe, La, Li, Mg, Mn, Ni, Pb, Pd, or Sr, and the ZSM-5 catalyst is Zeolyst CBV 58, 2314, 3024, 5524, or 8014, (available from Zeolyst International, Valley Forge, Pa.). At a reaction temperature of about 425 °C and a residence time of about 40 seconds, toluene and benzene may be the predominant products of the BTXM fraction. Product selectivity may also be varied by controlling the concentration of dibromomethane produced or fed into the coupling reactor. Removal of reaction heat and continuous decoking and catalyst regeneration using a fluidized bed reactor configuration for the coupling reactor may be anticipated in some facilities.

In an embodiment, the coupling reaction may be carried out in a pair of coupling reactors, arranged in parallel. This allows the overall process to be run continuously, without interruption, even if one of the coupling reactors is taken off line for decoking or for some other reason. Similar redundancies can be utilized in the bromination, product separation, halogen generation, and other units used in the overall process.

In some embodiments, the catalytic coupling of alkyl halides to higher molecular weight products may result in the formation of olefins. In these embodiments, the alkyl halides produced in the halogenation / reproporationation step may be reacted over a catalyst to produce higher hydrocarbons and hydrogen halide. The reactant feed may also contain hydrogen halide and unhalogenated alkanes from the bromination reactor. In one embodiment, the coupling reactions take place in a single coupling vessel with a single catalyst system as shown in FIG. 7. In another embodiment two or more catalyst systems are used, each in its own reactor. FIG. 8 illustrates this for two catalyst systems, although more may be used. In another embodiment of the invention (not illustrated), two or more catalysts may be mixed together using a single reaction vessel. For convenience, the drawings illustrate fixed bed reactors. In other embodiments of the invention, the reactor systems may use fixed bed, moving bed, fluidized bed, or any other suitable reactors or combinations of these reactors types.

According to the invention, any of a number of catalysts or a combination of two or three of these catalysts may be used to facilitate the formation of light olefins from halogenated hydrocarbons. Nonlimiting examples include various crystalline silico-alumino-phosphates and alumino silicates, such as SAPO-34 and its framework-substituted analogues (substituted with, *e.g.*, Co, Ni, Mn, Ga or Fe), ZSM-5 and its metal doped analogs (doped with Mg, Ca, Sr, Ba, K, Ag, P, La, or Zn), erionite, ferrierite, ALPO-5, MAPO-36, ZSM-12, ZSM-57, ZSM-23, ZSM-22 and MCM-22. Catalysts for producing light olefins may include SAPO-34, CoSAPO-34 (Co substituted SAPO-34), alkaline earth metal doped ZSM-5 having a loading amount below about 20% in weight, preferably in the range of about 0.5% to about 10%. The synthesis and preparation procedures for these materials are described in the Examples herein.

Coupling of alkyl halides to olefins may be carried out in a fixed bed, moving bed, fluidized bed, or any other suitable reactor, at a suitable temperature (*e.g.*, about 300 °C to about 600 °C, preferably about 400 °C to about 500 °C) and pressure (*e.g.*, about 0.1 atm to about 10 atm.) and a residence time (τ) of from about 0.1 seconds to about 10 seconds. In general, a relatively short residence time may favor conversion of reactants to desired products, as well as improving product selectivity. It may be possible to direct product selectivity by changing the catalyst, altering the reaction temperature, and/or altering the residence time in the reactor. For example, with a ZSM-5 based catalyst (*e.g.* 5%Mg/8014), at a short residence time (<1 s) and

moderate temperature (about 400 °C), propylene is the predominant component of light olefins. With a SAPO-34, at a reaction temperature higher than 450°C, ethylene is the predominant component of the light olefins. Removal of reaction heat and continuous decoking and catalyst regeneration using a fluidized bed reactor configuration for the coupling reactor may be anticipated in some embodiments of the invention.

In other embodiments, the catalytic coupling of alkyl halides to higher molecular weight products may result in the formation of alcohols or oxygenates. In an embodiment, the resulting MeBr may be reacted over a suitable catalyst (e.g., Ca silicate as described in more detail herein) to form alcohols or other oxygenates, generating HBr and H₂O in the process.

In another embodiment, the formation of oxygenates may take place in a single reaction vessel. In this embodiment an aqueous solution of SeO₂ may be used to form alcohols and/or other oxygenates. The use of an aqueous SeO₂ solution is described in more detail below.

In some embodiments, the catalytic coupling of alkyl halides to higher molecular weight products may result in the formation of aromatic compounds such as mesitylene. In one embodiment, a suitable catalyst to form mesitylene may be a modified ZSM-5 catalyst. One example of a suitable modified ZSM-5 catalyst may be a copper oxide (CuO)/zinc oxide (ZnO) modified ZSM-5 catalyst synthesized using a wet-impregnation technique.

One example of a suitable wet-impregnation technique may include using a metal nitrate solution to coat a catalyst support followed by calcining. For example, copper nitrate and zinc nitrate may be dissolved in de-ionized water to form a solution. If necessary, the pH value of the solution may be adjusted by adding a base, such as ammonium hydroxide. A ZSM-5 zeolite catalyst may then be added to the solution and allowed to soak. In some embodiments, the catalyst may soak in the solution for about 24 hours. After the catalyst has been soaked in solution, the excess water may be removed under vacuum and the catalyst may be dried and calcined. The material may be heated to between about 100 °C and about 150 °C for about 12 hours to remove at least some water. The dried material may then be calcinated at about 450 °C to about 850 °C for about 6 hours using a heating rate of about 1°C/min. One example of a suitable modified ZSM-5 catalyst is an about 7% CuO/0.5% ZnO impregnated ZSM-5 catalyst with a silica to aluminum ratio of about 55.

Reduction of Coke in the Catalytic Coupling Reaction

As previously noted, the process of producing higher hydrocarbons using alkyl halides may generate coke (a carbon rich solid residue) as an undesired byproduct on the catalyst and reactor walls. Furthermore, it may reduce productivity due to the need for de-coking on a regular basis. In some embodiments, a Lewis base molecule, such as water, carbon dioxide and carbon

monoxide, may be added to the catalyst to reduce the amount of coke that is generated. It is believed that the Lewis base molecule, such as water, reacts with the most reactive carbocations on the surface of the catalyst preventing the elimination of hydrogen rich fragments and consecutive conversion to coke. In addition, the Lewis base molecule may react with the Lewis
5 acidic sites on the catalyst, thereby preventing them from generating coke. In some embodiments, it may be desirable to continuously supply Lewis base molecules as the adsorption of the Lewis base on the catalytic acidic centers is reversible at the conditions of the reaction. In an embodiment, less than about 15%, or alternatively less than about 10% by weight of the Lewis base may be added to control the formation of coke.

10 **Hydrocarbon Product Separation and Halogen Recovery**

The coupling products may include higher hydrocarbons and HBr. In the embodiments shown in FIGS. 1 and 2, products that exit the coupling reactor may first be cooled in a heat exchanger and then sent to an absorption column. HBr may be absorbed in water using a packed
15 column or other contacting device. Input water and the product stream may be contacted either in a co-current or counter-current flow, with the counter-current flow preferred for its improved efficiency. HBr absorption may be carried out either substantially adiabatically or substantially isothermally. In one embodiment, the concentration of hydrobromic acid after absorption ranges from 5 to 70 wt %, with a preferred range of 20 to 50 wt %. The operating pressure may range from about 1 atm to about 50 atm, more preferably from about 1 atm to about 30 atm. In the
20 laboratory, a glass column or glass-lined column with ceramic or glass packing may be used. In a pilot or commercial plant, one or more durable, corrosion-resistant materials, as described in more detail below, may be utilized.

In one embodiment of the invention, the hydrocarbon products may be recovered as a liquid from the HBr absorption column. This liquid hydrocarbon stream may be phase-separated
25 from the aqueous HBr stream using a liquid-liquid splitter and sent to the product cleanup unit. In another embodiment, the hydrocarbon products are recovered from the HBr column as a gas stream, together with the unconverted methane and other light gases. The products may then be separated and recovered from the methane and light gases using any of a number of techniques. Nonlimiting examples include distillation, pressure swing adsorption, and membrane separation
30 technologies.

In some embodiments, the product clean-up unit may comprises or include a reactor for converting halogenated hydrocarbons present in the product stream into unhalogenated hydrocarbons. For example, under certain conditions, small amounts of C₁-C₄ bromoalkanes, bromobenzene, and/or other brominated species may be formed and pass from the coupling

reactor to the liquid-liquid splitter 15 and then to the product clean-up unit 17 as shown in FIG.

1. These brominated species may be "hydrodehalogenated" in a suitable reactor. In one embodiment, such a reactor comprises a continuous fixed bed, catalytic converter packed with a supported metal or metal oxide catalyst. Nonlimiting examples of the active component may include copper, copper oxide, palladium, and platinum, with palladium being preferred. Nonlimiting examples of support materials include active carbon, alumina, silica, and zeolites, with alumina being preferred. The reactor may be operated at a pressure of about 0 psi to about 150 psi, preferably from about 0 psi to about 5 psi, and a temperature of about 250 °C to about 400 °C, preferably about 300 °C to about 350 °C, with a GHSV of about 1200 hr⁻¹ to about 60 hr⁻¹, preferably about 240 hr⁻¹. When bromobenzene (*e.g.*) is passed over such a reactor, it is readily converted to benzene and HBr, with some light hydrocarbons (*e.g.*, C₃-C₇) produced as byproducts. Although carbon deposition (coking) may deactivate the catalyst, the catalyst may be regenerated by exposure to oxygen and then hydrogen at, *e.g.*, 500 °C and 400 °C, respectively.

After HBr is separated from the hydrocarbon products, the unconverted methane may leave with the light gases in the vapor outlet of the HBr absorption unit. In one embodiment of the invention, unconverted methane may be separated from the light gases in a separation unit ("SEP II" in the FIGS.), which operates using pressure or temperature swing adsorption, membrane-based separation, cryogenic distillation (preferable for large-scale production), or some other suitable separation process. Low methane conversions in the bromination reactor may result in the coupling products being carried with the light gases, which in turn may necessitate the recovery of these species from the lights gases. Separation technologies that may be employed for this purpose include, but are not limited to, distillation, pressure or temperature swing adsorption, and membrane-based technologies.

In another aspect of the invention, a process for separating anhydrous HBr from an aqueous solution of HBr is provided. HBr forms a high-boiling azeotrope with water; therefore, separation of HBr from the aqueous solution requires either breaking the azeotrope using an extractive agent or bypassing the azeotrope using pressure swing distillation. FIG. 9 illustrates one embodiment of an extractive distillation unit for separating HBr from water. Water may be extracted in a distillation column 80 and HBr may be obtained as the distillate stream 81. The distillate stream may also contain small amounts of water. In one embodiment, the distillation column 80 is a tray-tower or a packed column. Conventional ceramic packing may be preferred over structured packing. Aqueous bromide salt, such as CaBr₂, may be added at the top of the distillation column, resulting in the extraction of water from aqueous HBr. A condenser may not be required for the column. A reboiler 83 may be used to maintain the vapor flow in the

distillation column. The diluted stream of aqueous CaBr_2 82 may be sent to the evaporation section 86, which, optionally has a trayed or packed section. The bottoms stream from the column may be heated before entering the evaporation section. Stream 87 may comprise mostly water (and no more than traces of HBr) and may leave the evaporation section.

5 In one embodiment, HBr may be displaced as a gas from its aqueous solution in the presence of an electrolyte that shares a common ion (Br^- or H^+) or an ion (*e.g.* Ca^{2+} or SO_4^{2-}) that has a higher hydration energy than HBr . The presence of the electrolyte pushes the equilibrium $\text{HBr}_{\text{aq}} \leftrightarrow \text{HBr}_{\text{gas}}$ towards gas evolution, which may be further facilitated by heating the solution.

10 Aqueous solutions of metal bromides such as CaBr_2 , MgBr_2 also KBr , NaBr , LiBr , RbBr , CsBr , SrBr_2 , BaBr_2 , MnBr_2 , FeBr_2 , FeBr_3 , CoBr_2 , NiBr_2 , CuBr_2 , ZnBr_2 , CdBr_2 , AlBr_3 , LaBr_3 , YBr_3 , and BiBr_3 may be used as extractive agents, with aqueous solutions of CaBr_2 , MgBr_2 , KBr , NaBr , LiBr or mixtures thereof being preferred. The bottoms stream of the distillation column may contain a diluted solution of the extracting agent. This stream may be sent to another distillation column or a vaporizer where water may be evaporated and the extracting agent may
15 be concentrated before sending it back to the extractive distillation column. Sulfuric acid may be used as an extracting agent if its reaction with HBr to form bromine and sulfur dioxide may be minimized. Experiments carried out to demonstrate the separation of anhydrous HBr from an aqueous solution of HBr are described in Examples 2 and 3.

20 In another aspect of the invention shown in Figure 10, a process for separating anhydrous HBr from an aqueous solution of HBr is provided using temperature swing absorption. As described above, HBr may be absorbed from the products stream using an aqueous solution. The effect of temperature on the solubility of HBr in water is shown in Figure 11. The HBr absorption column may use aqueous HBr as the feed such that the overall feed concentration is at least about 48% by weight HBr , and after absorbing HBr , the outlet concentration may be
25 between about 50% and about 80% HBr by weight. In an embodiment, the outlet of the absorption system may be a concentrated aqueous HBr stream with a concentration of at least about 48% HBr by weight, with a preferred concentration between about 55% and about 75% HBr by weight. The concentrated aqueous HBr stream may be sent to the evaporation state for HBr recovery. In an embodiment, the absorption column may be glass lined carbon steel or
30 polymer lined carbon steel. Graphite heat exchangers may be used in the process.

35 In an embodiment, the absorption column may be a packed column. In another embodiment, a tray column may be used. The absorption column may operate at a temperature of about 150 °C or lower. As a large amount of heat may be generated during HBr absorption, the heat may be removed using an external circulation heat exchanger. The hydrocarbon products may leave in the gas outlet.

Higher boiling hydrocarbons may condense and leave with the outlet, where they may be separated using a liquid-liquid phase separator (not depicted in the drawing), since aqueous HBr and hydrocarbons phase separate. At pressures above about 5 atm, the liquid hydrocarbons may be easily separated from light gases and HBr by cooling the stream and using flash separation before introducing the gas into the absorption column. As a general trend, the temperature required for an HBr stripper may increase with pressure. After phase separation, aqueous HBr is sent to a heater where the temperature is increased. The decrease in HBr solubility at this temperature results in HBr removal in the gas phase. In some embodiments, trace amount of water may be removed with the HBr. However, in most cases, measurements in the laboratory did not detect any water present in the HBr vapor. The aqueous HBr may exit the heater/evaporator and may be cooled before recirculation to the absorption column.

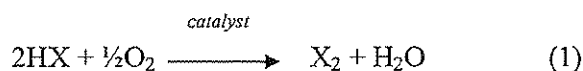
In another aspect of the invention, various approaches to product clean-up (separation and/or purification) are provided. A number of bromide species may be present in the unpurified product stream: HBr, organic bromides such as methyl bromide and dibromomethane, and bromo-aromatics. In one embodiment of the invention, hydrocarbon products may be separated from brominated species by passing the product stream over copper metal, NiO, CaO, ZnO, MgO, BaO, or combinations thereof. Preferably, the products may be run over one or more of the above-listed materials at a temperature of from about 25 °C to about 600 °C, more preferably, about 400 °C to about 500 °C. This process may be tolerant of any CO₂ that may be present.

In still another embodiment, HBr may be separated from the hydrocarbon products stream using distillation. Since HBr is the largest component in the C-C coupling product stream and has the lowest boiling point (about -67 °C at 1 atm), the distillation process must be performed at a higher pressure. A schematic for the separation system is shown in Figure 12. If the products from coupling are at a lower pressure, they may be compressed to a pressure of about 10 atm or higher and the first column (Col 1) may separate methane and light gases from HBr and higher boiling components. The distillate may consist of a small amount of HBr. The distillate stream is compressed to a pressure of about 15 atm or higher to increase the condenser temperature for the demethanizer (Col 2). The bottoms stream of the demethanizer consists of ethane with a small amount of HBr. The bottom stream from the first column (Col 1) may be sent to a series of distillation columns (Cols. 3 and 4) where HBr may be separated and sent to the bromine generation section (not shown), and the light gases and liquid hydrocarbon products are obtained as the distillate and bottoms, respectively. Compression needs may be reduced if the coupling reactor is operated at a higher pressure. In certain embodiments, the coupling product inlet to the separation system may be at a high pressure of about 15 atm to about 40 atm and hence compression may not be needed downstream.

In another embodiment, particularly for large-scale production of hydrocarbons, unconverted methane may be separated from other light hydrocarbons as well as heavier products (*e.g.*, benzene, toluene, etc.) using distillation. For example, in FIGS. 1 and 2, methane and other light hydrocarbons exit the absorption column through a gas outlet and are directed to a separation unit (SEP. II). Any unconverted methyl bromide may be removed with the light gases and may be recycled back to the bromination/reproportionation reactor. Heavier hydrocarbons may be removed as a liquid distillate.

Molecular Halogen Generation

In one embodiment of the invention, catalytic halogen generation may be carried out by reacting hydrohalic acid and molecular oxygen over a suitable catalyst. The general reaction may be represented by equation (1):

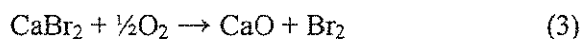
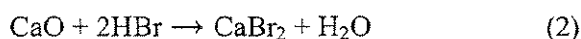


The process may occur at a range of temperatures and mole ratios of hydrohalic acid (HX) and molecular oxygen (O₂), *e.g.*, about 4:1 to about 0.001:1 HX/O₂, preferably about 4:1 (to fit the reaction stoichiometry), more preferably about 3.5:1 (to prevent eventual HBr breakthrough).

Halogen may be generated using pure oxygen, air, or oxygen-enriched gas, and the reaction may be run with a variety of inert nonreacting gases such as nitrogen, carbon dioxide, argon, helium, and water steam being present. Any proportion of these gases may be combined as pure gases or selected mixtures thereof, to accommodate process requirements.

A number of materials have been identified as halogen generation catalysts. It is possible to use one type of catalyst or a combination of any number, configuration, or proportion of catalysts. Oxides, halides, and/or oxy-halides of one or more metals, such as Cu, Ag, Au, Fe, Co, Ni, Mn, Ce, V, Nb, Mo, Pd, Ta, or W are representative, more preferably Mg, Ca, Sr, Ba, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, or Ce. The most preferable catalysts are oxides, halides, and/or oxy-halides of Cu. These materials may be considered cataloreactants as discussed in more detail below.

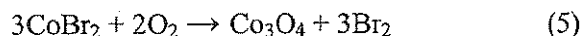
Although not bound by theory, the following equations are considered representative of the chemistry believed to take place when such materials are used to catalyze halogen formation:



for metal oxides in which the metal does not change oxidation states, and

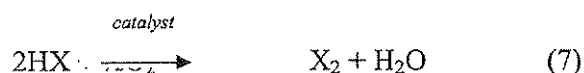


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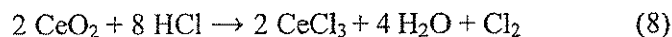
for metal oxides in which the metal does change oxidation states. The net reaction for equations (2)+(3) and equations (4)+(5) is equation (7):

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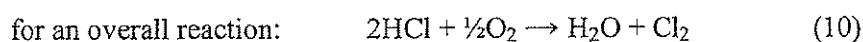
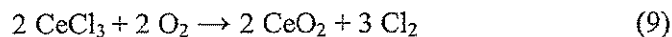


which is equivalent to equation (1).

15 In one embodiment of the invention, chlorine is used as the halogenating agent, and ceria (CeO_2) is used to catalyze the generation of chlorine from hydrochloric acid. The following equations are considered representative:



20



which is also equivalent to equation (1).

25

This use of ceria is quite novel, as it allows essentially complete consumption of HCl. In contrast, previous reactions of metal oxides, HCl, and oxygen have typically yielded HCl/Cl₂ mixtures. Thus, ceria can advantageously be employed as a halogen regeneration catalyst, particularly where chlorine is used for alkane halogenation, with chlorine's attendant lower cost and familiarity to industry.

30

In one embodiment of the invention, the halogen generation catalyst(s) may be supported on porous or nonporous alumina, silica, zirconia, titania or mixtures thereof, or another suitable support. A range of temperatures may be employed to maximize process efficiency, *e.g.*, about 200 °C to about 600 °C, more preferably about 350 °C to about 450 °C.

Solid reactant Removal of Hydrogen Halide and Halide Regeneration

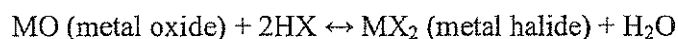
In another embodiment, the hydrogen halide generated during catalytic coupling may be separated from the product stream and regenerated using a cataloreactant. A cataloreactant may facilitate carbon-carbon coupling, *e.g.*, hydrocarbon oligomerization or metathesis. The term “cataloreactant” may refer to an inorganic compound that (a) contains at least one metal atom and at least one oxygen atom, and (b) facilitate the production of a higher hydrocarbon. Nonlimiting examples of cataloreactants include zeolites, doped zeolites, metal oxides, mixed metal oxides, metal oxide-impregnated zeolites, and similar materials, mixtures of such materials, as well as any other material described herein for capturing and converting hydrogen halides. Nonlimiting examples of dopants include alkaline-earth metals, such as calcium and magnesium, and their oxides and/or hydroxides. A nonlimiting list of metal oxides may include oxides of copper, magnesium, yttrium, nickel, cobalt, iron, calcium, vanadium, molybdenum, chromium, manganese, zinc, lanthanum, tungsten, tin, indium, bismuth, and mixtures thereof.

Without wishing to be limited by theory, it is believed that a cataloreactant may differ from a true catalyst as it may be converted to a metal halide when exposed to a hydrogen halide. The metal oxide may then be regenerated by treating the metal halide with oxygen or air (preferably at an elevated temperature) to allow at least some of the cataloreactant to be recycled within the process. The cataloreactant may also act as a halogen release and sequestering agent, offering the possibility of obtaining a tunable coupling product distribution. The choice of cataloreactant may allow the product distribution to include the ability to produce oxygenates if desired. The overall chemical cycle may result in water being created as the only byproduct of the reaction. When used solely for hydrogen halide capture, a cataloreactant may be referred to as a solid reactant. Further, the use of a solid reactant for hydrogen halide capture and elemental halide recovery reduces halogen inventory, simplifies the process operations and may reduce the overall capital cost.

In an embodiment, a cataloreactant may be redox or non-redox active. As used herein, the term “non-redox active” may refer to a metal or a metal oxide that has a single, stable oxidation state. For example, a non-redox active metal or metal oxide may include, but is not limited to, Ni, Ca, Mg, or Ba. Non-redox active metals or metal oxides may capture and sequester a hydrogen halide without releasing an elemental halide in the process. For example, equations (2) and (3) presented above demonstrate a non-redox active cataloreactant that may effectively capture a hydrogen halide. As used herein, the term “redox active” may refer to a metal or metal oxide that has more than one stable oxidation state. For example, a redox active metal or metal oxide may include, but is not limited to, Cu, Co, Ce, or Fe. An advantage of using redox active metal oxides is that they may be regenerated at a lower temperature, enabling

a substantial decrease in the energy needed in the overall process. Redox active metals or metal oxides may generate elemental halide when used in the hydrogen halide capture and regeneration cycle. For example, equations (4) and (5) presented above demonstrate a redox-active cataloreactant in the context of a bromine based system that may release elemental bromine during the hydrogen bromide capture reaction. The amount of element halogen released, if any, by a redox-active system may depend on the halide used, the conditions of the reactor, and the choice of cataloreactant material.

In an embodiment, a solid reactant may be used to capture and oxidize hydrogen halide. In this embodiment, a stream containing a hydrogen halide may be passed over the solid reactant to generate the corresponding metal halide. The solid reactant may be a redox or non-redox active material. The hydrogen halide capture reaction may be generalized as:

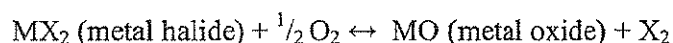


for a non-redox active solid reactant.

In an embodiment, the stream containing the hydrogen halide may come from a variety of sources. For example, the hydrogen halide may be generated as a result of an aqueous absorption of the hydrogen halide from the products stream exiting the coupling reactor. Alternatively, the stream containing the hydrogen halide may be the products stream leaving the bromination reactor or the coupling reactor. In still another embodiment, the stream containing the hydrogen halide may have been partially separated from the products stream exiting the coupling reactor. For example, any hydrogen halide may be separated from the products stream along with a methane stream or a light hydrocarbon stream before being passed to a vessel containing a solid reactant. In these embodiments, the solid reactant may be used to capture any hydrogen halide contained within the stream, resulting in a stream that may be essentially free of hydrogen halide.

A solid reactant material that has been converted into a metal halide may be regenerated by treatment with air or oxygen to release an elemental halogen and convert the solid reactant back into the original oxide material. As used herein, the term "air or oxygen" may include any number of oxygen-based or oxygen-containing gas streams. Examples include, without limitation, ordinary air, pure oxygen gas (O_2), oxygen gas containing minor amounts of other gaseous components, dilute streams of oxygen gas in a carrier gas (*e.g.*, helium), oxygen-enriched air, etc. Exposure to air or oxygen may regenerate the metal halide species back into the corresponding metal-oxygen species. Upon regeneration, the elemental halide that is release

may be recycled for use in the bromination reactor or elsewhere in the process. The reaction in the regeneration section may generally be represented as:



5

In an embodiment, the performance characteristics of the solid reactant may be important as well as determine the reactor configuration best suited for a specific application. Important characteristics may include, but are not limited to, a high capacity for holding regenerable bromine, the stability of the bromine capacity over thousands of cycles, and the ability to rapidly
10 neutralize HBr and regenerate the original solid reactant upon contact with air or oxygen.

In an embodiment, the solid reactant materials may be formed by using sol gel formulations, co-precipitation formulations, and wet impregnation, as disclosed herein. In addition, a solid reactant may comprise small amounts of enabling chemicals to enhance the stability of the solid and the rate of bromine regeneration. For example, potassium oxide and
15 yttrium-stabilized zirconium may enhance the stability and reaction rates of the solid reactants during the HBr capture and bromine generation reactions.

The various steps of hydrogen halide capture and release may be carried out in a vessel, container, or reactor at appropriate pressures and temperatures. Factors that may affect the reactor conditions include, but are not limited to, the feedstock or composition of the hydrogen
20 halide stream, the solid reactant composition, the flow rates, and the reactor type. In an embodiment, the reactor may be operated at, or slightly above, atmospheric pressure. In another embodiment, the reactor may be operated at a pressure ranging from about 1 atmosphere to about 200 atmospheres. In an embodiment, the reactor may be operated between about 0 °C to about 600 °C, alternatively between about 200 °C to about 500 °C to facilitate hydrogen halide capture
25 depending on the solid reactant material selected. For example, NiO or CaO may be used to capture HBr at a temperature between about 425 °C and about 500 °C for a non-redox active material based processes, while cobalt oxide or cerium oxide may be used for HBr capture at a temperature between about 300 °C and about 450 °C for a redox active material based process. In an embodiment, the reactor may be operated between about 0 °C to about 650 °C, alternatively
30 between about 200 °C to about 600 °C during halogen oxidation and release. This may regenerate the metal halide species back into the corresponding metal-oxygen species. Upon regeneration, elemental halide will be released, which may be recycled for use in the bromination reactor or elsewhere in the process. For example, NiBr₂ or CaBr₂ may be reacted with air or oxygen at a temperature between about 400 °C and about 600 °C to regenerate
35 bromine in a non-redox active material based process, while cobalt bromide or cerium bromide

may be reacted with air or oxygen at a temperature between about 200 °C and about 550 °C to regenerate bromine in a redox active material based process.

Materials for Hydrogen Halide Removal and Regeneration

In an embodiment of the processes described herein, various materials may act as a catalyst or cataloreactant active material, or a support. In some embodiments, gaseous HBr may be selectively removed from the product stream through the use of a calcium silicate based solid reactant. In this embodiment, as the gaseous HBr is removed from the product stream it may be directly converted to Br₂ in a second step using a suitable oxidant, for example oxygen. Generally, it is desirable that the calcium silicate based solid reactant have a high bromine capacity, *e.g.* greater than 4 mmol Br₂/cm³, cyclically stable over many cycles, be in a form such that it may be used in either fixed, moving, or fluidized bed reactors, and have a minimal environmental, health and safety risk. In one embodiment, a suitable calcium silicate based solid reactant may be synthesized using a wet-impregnation technique. Using the wet-impregnation technique, a metal nitrate may be used to prepare the solid reactant, however any soluble compound would be suitable. In one embodiment, calcium nitrate and ethanol may be mixed in an amount sufficient such that the calcium nitrate dissolves. Additional metal nitrates, such as potassium nitrate, may also be added. The solute may then be combined with a suitable silica material of appropriate particle size. The mixture may then be refluxed at a temperature of approximately 100 °C for approximately three to five hours and then allowed to dry. The dried material may then be heated to 200 °C to remove the NO_x component and then the materials may be calcined at approximately 550°C for six hours at a heating rate of about one to five °C/min.

While calcium silicate based solid reactants suitable for use in the present invention may be prepared in a variety of ways, calcium silicate based solid reactants prepared using the wet-impregnation technique described herein have been tested at neutralization temperatures of 400°C and regeneration temperatures of 500°C for 100 cycles with no apparent loss of capacity, other than an initial break in period of 5-20 cycles. Additionally, calcium silicate based solid reactants prepared by this method may be in a useable form as synthesized (up to ~2mm pellets) and may require no additional binding agent for fixed bed applications. Calcium silicate based solid reactants may provide stable bromine capacities of about 1.5 mmol Br₂/g-solid to about 3 mmol Br₂/g-solid or greater. In some embodiments, the basicity of the calcium silicate based solid reactants may be increased via the addition of alkali metals, which may increase regeneration rates. For example, the addition of potassium in a molar ratio of about 5:20:75 (K:Ca:SiO₂) may increase reaction rates about 5 times when compared with materials with only calcium.

In an embodiment, a nickel oxide (NiO)-based nano-composite may be used as a solid reactant for selective capture of HBr and its subsequent conversion to Br₂. The materials used for the NiO based-nano composite may exhibit high capacity (about 4 mmol Br₂/g or higher), fast Br₂ generation rates, and long term cycle stability. As used herein, the term "cycle stability" is defined to mean that key properties of the solid reactant, such as, but not limited to, capacity, capture and regeneration rates, etc., do not change appreciably as the solid is repeatedly cycled between the oxide and bromide states, as well as between low and high temperature. Various wet-chemical embodiments may be used to synthesize nano-composite solid reactants, including sol-gel, sol-gel coupled with oil-drop, and co-precipitation based methods, as described in more detail below. While these embodiments may be described in terms of NiO-based solid reactants for HBr capture/Br₂ regeneration, the synthesis techniques may also be applicable for other metal oxide based solid reactants. Non-limiting examples include cobalt, copper, calcium, and iron oxides for capture/Br₂ regeneration. In addition, these techniques may also be applicable for regenerable solid reactants for CO₂ removal ($\text{ZnO} \leftrightarrow \text{ZnCO}_3$) and chemical looping combustion (NiO $\leftrightarrow$ Ni).

In another embodiment, gaseous HBr may be selectively removed from the product stream through the use of a fluorinated alumina based materials. A metal oxide doped fluorinated alumina (*e.g.*, FAl_2O_3) may be a stable solid reactant for hydrogen halide capture and elemental halogen regeneration. In some embodiments, a fluorinated alumina material, such as a calcium oxide doped fluorinated alumina, may be used as a cataloreactant for methanol synthesis. As a catalyst FAl_2O_3 may be effective in converting some olefins (*e.g.*, isobutylene) to higher hydrocarbons, and may be used as a catalyst or component of a catalyst for alkyl halide coupling into higher hydrocarbons. Fluorinated alumina materials may exhibit a stable bromine capacity of about 2.0 to about 2.5 mmol Br₂/g for many cycles, for example up to about 500 cycles. The fluorinated alumina materials may exhibit high catalytic activity due to strong interactions between the fluorinated support crystal structure and any additional metals or metal oxides doped or ion exchanged with the material. The presence of fluorine in the material may result in enhanced Lewis acidity which may also account for a high level of catalytic activity. Catalysts or cataloreactants prepared using a fluorinated alumina material may be suitable for use in fixed, moving, and fluidized bed applications.

Additional materials may be used with a fluorinated alumina material to form a catalyst or cataloreactant for use in the production of higher hydrocarbons. For example, NiO and CaO may be supported on a high surface area fluorinated alumina. These materials may be doped with one or more alkali or alkali earth metals, which may increase the elemental halide regeneration rates when these materials are used. While not intending to be limited by theory, it

is believed that unlike an inert support, a fluorinated alumina material may react with an active material (e.g., a metal oxide such as NiO, CaO, etc.) as a consequence of the material's Lewis acidity, which may result in surface immobilization of the active material. The immobilization of the active material may reduce or eliminate sintering, which may lead to catalyst or cataloreactant degradation.

High surface area fluorinated alumina (FAI_2O_3) may be synthesized by impregnating a high surface area alumina with an aqueous solution of ammonium fluoride, which is used as a fluorinating agent. After stirring the mixture for a sufficient amount of time at room temperature, the excess solution may be evaporated. The resulting material may be dried in an oven, followed by calcination under N_2 . Additional materials may then be further added to the fluorinated alumina. For example, nickel nitrate or calcium nitrate may be used to wet impregnate the fluorinate alumina followed by calcining to produce a NiO or CaO doped fluorinated alumina, respectively.

In an embodiment, an active material may comprise less than about 30%, or alternatively, less than about 15% by weight fluorine in an alumina structure. The base alumina may be any suitable alumina and may include, for example, spheres, ellipsoids, toroids, etc. In an embodiment, an alumina sphere about 2 to about 3 millimeters (commercially available as Davicat Al-2750 from W.R. Grace & Co. of Columbia, MD) may be used as the starting material for the synthesis of a fluorinated alumina.

In another embodiment, hydrogen halide generated in the process described herein may be removed using a metal halide salt with a plurality of oxidation states. In an embodiment, the metal may be copper, which may form two stable oxidation states with a halide such as bromine. In an embodiment in which the halogen is bromine, copper may form both CuBr and CuBr_2 . By cycling between the two oxidation states of Cu, a closed recycle loop of bromine may be created wherein bromine is mostly retained as a bromide salt.

In an embodiment, brominated alkyls from the bromination reactor may be coupled by contact with an appropriate catalyst to yield products and HBr. Gases from the coupling reactor may be cooled and contacted with water to absorb HBr and allow the mostly HBr-free coupling products to be sent to product separation and recovery. The aqueous solution of HBr may be contacted with CuBr , which may be recycled from a bromine generation step described below. Air or oxygen may be utilized to facilitate a reaction between HBr and CuBr resulting in the conversion of the CuBr to CuBr_2 and water. In another embodiment, an aqueous solution of $\text{CuBr}/\text{CuBr}_2$ may be used as the absorbent in the contact separation of the coupling reactor products from the HBr.

The CuBr_2 , unreacted CuBr solids, and water may be separated using any technique capable of removing solids from an aqueous solution. For example, suitable separation techniques may include, but are not limited to, crystallization or evaporative crystallization followed by filtration or centrifugation. The CuBr_2 crystals, which may still contain water, may be dried at a temperature low enough to avoid bromine release. In an embodiment, the drying temperature may be below about 200 °C. The dried CuBr_2 crystals may then be sent to a bromine generation unit.

In an embodiment, the bromine generation unit may comprise a heating chamber for heating the CuBr_2 to about 275 °C, resulting in the conversion of the CuBr_2 to CuBr and the release of bromine as a vapor. In this embodiment, a carrier gas may be used to remove the bromine generated by the CuBr_2 in the bromine generation unit. In an embodiment, the carrier gas may be methane or any other light hydrocarbon stream. The bromine generation unit products, including bromine and any light hydrocarbons making up the carrier gas, may be separated from the solid CuBr and sent to a bromination reactor where the bromination reaction may be carried out. The bromine generation unit products may be heated in order to raise the temperature of the mixture to the temperature desired in a bromination reactor. The solid CuBr that is generated may be recycled to the HBr capture reactor. In some embodiments, the bromine generation reactor and the bromination reactor may take place in the same vessel.

In another embodiment, the copper bromide based process described above may be used as a scavenging material to capture any hydrogen halide passing to a process stream exiting the process. For example, an aqueous solution or a dry bed of CuBr may be used as a final HBr trap prior to any vent streams leaving the process. Such traps may prevent any HBr from escaping the process and allow the HBr to be subsequently captured and converted to elemental bromine for reuse in the process.

Methods of Preparing Catalysts and Cataloreactants

Any of the materials useful as coupling catalysts, or even bromination or oxidation catalysts, may be synthesized using a variety of methods. As mentioned above, a NiO based nano-composite (*e.g.*, powder form) solid reactant may be synthesized using a sol-gel based procedure. One example of a typical sol-gel based procedure for the synthesis of nano-composite solid reactant (powder form) is described in Fig. 13. For example, to synthesize a $\text{NiO-K}_2\text{O-Y}_2\text{O}_3\text{-ZrO}_2\text{-Al}_2\text{O}_3$ nano-composite, an aluminum precursor (*e.g.*, aluminum isopropoxide or aluminum tri-sec-butoxide) and zirconium propoxide may be dissolved in isopropanol. The overall concentration of Al(III) may be about 0.6 M (generally controlled in the range of about 0.1 to about 1.0 M). Deionized water may then be added drop-wise. Hydrolysis

may occur upon adding the water and may be promoted by stirring at about 60 °C (generally at about 40 to about 90°C) to produce a sol solution. A nickel precursor (*e.g.*, nickel nitrate or chloride), potassium nitrate and yttrium nitrate, all of which are at least partially water soluble, may be dissolved in deionized water with a concentration of about 3.0 M (generally about 1 to about 6 M). The Ni/K/Y solution may be added and the resulting sol solution may then be stirred for approximately 30 minutes with heating when the total volume of the sol solution is reduced by about 30 to about 50% by evaporation. The sol gel may be peptized at 60°C by adding 1 M nitric acid (the amount of the acid may be determined by the molar ratio of protons to Al(III) of about 0.05 to about 0.4), which may result in the formation of a gel. To ensure good mixing of all the cations, the gel mixture may then be further stirred for several hours. The gel may be dried in an oven at about 110°C to about 150 °C, where the exact temperature may depend on the amount of nickel precursor used. The dried material may be calcined at about 450 °C to about 850 °C for about 6 hours using a heating rate of about 1°C/min. The resulting material may have a nominal composition of about 51%NiO-2%K₂O-0.6%Y₂O₃-4.4%ZrO₂-42%AlO₃.

Another method for synthesizing nano-composite solid reactants may utilize sol-gel techniques coupled with oil-drop (*e.g.*, pellet form). One example of this method is described in Fig. 14. For example, in order to synthesize a NiO-AlO₃ nano-composite pellet, nickel nitrate of an appropriate amount may be added and mixed with an aqueous sol of boehmite at 75°C for about 2 hours. Nitric acid may then be added to peptize the sol solution, with pH controlled in the range of about 0 to about 5. A wet gel may be obtained after heating and stirring at about 50°C for another hour. An organic acid such as acrylic acid may also be added to the gel as a polymerization initiator. The wet gel may be dropped into an immiscible paraffin oil layer and spherical shaped granules may form. The granules may pass through the oil layer and fall into an ammonia solution containing a predetermined concentration of nickel nitrate, where they may be aged from about 1 hour to about 5 days. During the aging process, the wet gel granules may become rigid gel particles (*e.g.*, pellets). The solid granules may then be removed and washed with water and ethanol, which may be followed by drying at about 100 °C to about 150 °C. Calcination may be conducted at about 450 °C to about 850 °C for about 6 hours with a heating rate of about 1°C/min.

Fig. 15 illustrates a co-precipitation method, which is yet another example of a method for synthesizing nano-composite solid reactants. For example, in order to synthesize a NiO-AlO₃ nano-composite solid reactant, an aqueous solution of nickel nitrate and aluminum nitrate may be stirred at about 45 °C while an about 5.8% NH₃·H₂O solution may be added drop-wise. The hydroxides of nickel and aluminum may start to precipitate and the final pH may be controlled in the range of about 8 to about 11. The whole solution may then be aged at about 45°C for about

one day before it is filtered. The precipitates may be washed with deionized water and dried at about 100 °C to about 150 °C. The dried powder may then be calcined at about 450 °C to about 750 °C for about 6 hours with a heating rate of about 1°C/min.

5 Examples of other suitable nano-composite solid reactants may include about 30% NiO-Al₂O₃ by sol-gel; about 30% NiO-Al₂O₃ with K doping by sol-gel; about 50% NiO-Al₂O₃ with K and YSZ doping by sol-gel; and about 42% NiO-La₂O₃-Al₂O₃ by co-precipitation.

10 All the above synthesis methods may yield a nano-composite material comprising a metal oxide (*e.g.*, NiO) and one or more additional components (*e.g.*, AlO₃, K, YSZ, or La₂O₃). The main variables in the synthesis procedure may be the different components in the composite and their respective compositions, pH, aging time/temperature, concentration of the metal oxide in the ammonia aging solution, and calcination temperature.

The composition of the metal oxide in the nano-composite has been found to have an important impact on both the capacity of the material as well as its stability. If the composition of the metal oxide is too low, then the material will have a small, but stable capacity (*e.g.*, NiO composition at about 30% results in a stable capacity of about 1 mmol Br₂/g, which may be too small for commercial applications). However, if the composition of the metal oxide is too high, the material may exhibit a high initial capacity, which may start to decrease rapidly with repeated oxide/bromide cycles. (*e.g.*, an about 70% NiO-AlO₃ nano-composite material prepared using a sol-gel synthesis procedure may show an initial capacity of about 7.0 mmol Br₂ /g, which may then decrease to about 2 mmol Br₂/g after less than about 250 cycles).

20 While the exact mechanism by which these nano-composite materials exhibit their desired properties (*e.g.*, cycle stability, fast reaction rates, etc.) as a solid reactant is not known, it is believed that they are due to a combination of the structure of the nano-composite material itself as well as the nature and compositions of the other components within the nano-composite.

25 The near molecular level dispersion of the active metal oxide within the nano-composite material may result in thermodynamic properties that do not favor particle sintering as the material cycles between the oxide and bromide states. In addition, it is also believed that surface reactions between the metal oxide and at least some of the other components may immobilize the metal oxide, thereby preventing, or significantly reducing, loss of surface area due to sintering. For example, NiO-La₂O₃-AlO₃ and NiO-AlO₃ nano-composites exhibit stable capacities of about 4.0 mmol Br₂/g and about 3.0 mmol Br₂/g, respectively, while a NiO-SiO₂ nano-composite may lose capacity quickly as it cycles (*e.g.*, the material has an initial capacity of about 3.0 mmol Br₂/g, but drops to about 1.5 mmol Br₂/g after about 180 cycles it). These trends may hold true even if all three materials are synthesized using a similar techniques and conditions.

30

In addition to impacting the cycle stability of the materials, the other components in the composite may also affect the rate of Br₂ generation. For example, adding alkaline metals (*e.g.*, Li, Na, K and Cs) may significantly increase the Br₂ regeneration rates of NiO nano-composites. Also oxygen-ion conducting compounds have also been found to be effective in enhancing the Br₂ generation rates of these materials. For example, it is believed that Y₂O₃-ZrO₂ in the composite may react in part to form yttria-stabilized-zirconia, YSZ, which may be an oxygen conducting compound.

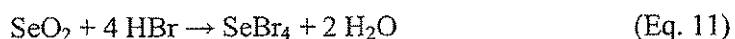
In some embodiments, the nano-composite solid reactants may be encapsulated. It may be desirable to encapsulate a nano-composite to stabilize the particle size and surface area. In one embodiment, encapsulation may be achieved by water-in-oil microemulsion, organic template directing solution evaporation, or Stober-like methods. Factors to be considered when encapsulating a solid reactant include porosity/pore size and void space inside the shell.

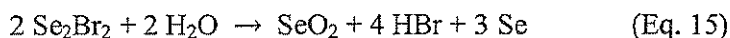
Aqueous Process for Hydrogen Halide Removal and Halide Regeneration

In an embodiment, hydrogen halide may be oxidized to generate a corresponding elemental halide using an aqueous solution with an appropriate catalyst. The catalyst may take advantage of the change in the oxidation state of a material with multiple oxidation states. In various embodiments, the aqueous based process may be described in connection with HBr and Br₂ and the semi-metals Se and Te, but it should be apparent to one skilled in the art that the process is not limited to the described embodiments. Both selenium and tellurium are semi-metals that have several oxidation states including -2, 2, 4 and 6. Additional elements with multiple oxidation states include, without limitation, Cu(II)/Cu(I), Fe(III)/Fe(II), Sb(V)/Sb(III), Mn(IV)/Mn(II), V(V)/V(IV), As(V)/As(III), and Ru(IV)/Ru(III). The following description uses selenium as example although the same description applies to tellurium and the other elements with multiple oxidation states unless noted otherwise.

The aqueous based oxidation process takes advantage of the reduction capability of Se (I) and Se(II) compounds towards oxygen from the air, which may be oxidized to Se(IV). The Se(IV) state is a sufficiently strong oxidizer and may be capable of oxidizing HBr/Br⁻ to elemental bromine. In such a cycle the selenium may shuttle between the two oxidation states and converts the HBr to Br₂ using air or oxygen at relatively mild conditions.

The cycle starts with Se(IV) compound such as SeO₂, which may be in an acidic environment (an acidic environment may enhance the oxidation power of Se(IV)). A first series of reactions (Eq. 11 to Eq. 17) has the net effect of converting HBr into Br₂ and H₂O and converting Se(IV) to Se(II).

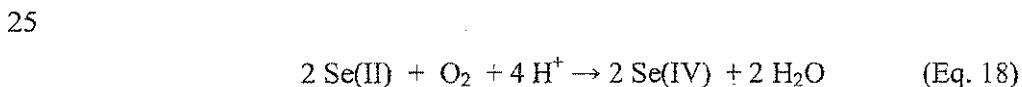




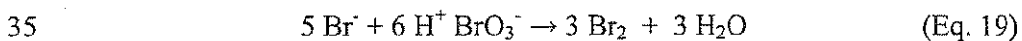
SeBr₄ is an orange red crystalline solid that may dissociate at temperatures exceeding 70 °C yielding Se, Se₂Br₂, SeBr₂, and Br₂. Heating HBr and SeO₂ in a closed vessel above 45 °C may lead to sublimation of SeBr₄ crystals. Similarly, heating in an open container or in the presence of inert pass through gas may result in free Br₂ being liberated along with the other products- metallic selenium, which may appear as a solid powder precipitate upon cooling, and the lower bromides Se₂Br₂ and SeBr₂ observed as refluxing red oily liquid (Se₂Br₂ is dark red, pungent oily liquid which boils at about 225 °C to about 230 °C).

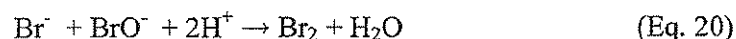
The reaction according to Eq. 11 may take place at approximately room temperature or lower while the remainder of the equations may take place at a temperature ranging from about 65 °C to about 300 °C and a pressure ranging from about 0.1 atm to about 40 atm. At the temperature of the reaction the bromine may be evaporated from the reactor along with water vapor due to the reactions shown in Eq. 12 through Eq. 14. Despite the existence of an HBr-water azeotrope, HBr may not escape the system because practically all of the bromine may be bound as selenium species and the solution may contain relatively low HBr concentrations at or below the azeotropic composition. However, the process may be tolerant to the presence of small amounts of HBr in the vapor phase.

A second series of reactions (eq. 18 – eq. 20) may result in the regeneration of the active Se(IV). This may be done either simultaneously or sequentially with the first set of reactions:



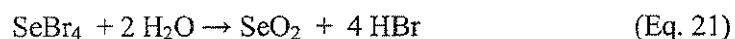
Se(IV) may not oxidize Br₂ to BrO₃⁻. The electrode potential for the Br₂ to BrO₃⁻ reaction is about 1.482 V which is above the oxidation potential of Se(IV)/Se(II). The electrode potential for Br₂/BrO⁻ is about 1.574 V, which may be high enough so that the reaction to hypobromite does not occur. The selenium redox potentials are not as high, making any such oxidation unlikely to occur. Even if generated in small amounts BrO⁻ and BrO₃⁻ may not leave the system due to the following reactions in the acidic environment in the reactor:





These reactions may maintain a low concentration of any selenium oxybromides as they may react as soon as they are formed. The two main products leaving the system may include bromine and water. Under normal operating conditions, these components may leave as vapor. The other components of the reaction mixture may generally be nonvolatile. However, trace components other than bromine and water may appear in the products stream depending on the conditions and type of the reactor.

A benefit of this process is the safety of operation. Although some of the reactants may be volatile and toxic compounds (e.g., SeBr_4 and Se_2Br_2), the hazard may be reduced or eliminated by using a large amount of water in the event of a spill. Water may rapidly change the toxic, volatile bromides to inert solids (Se) and non-volatile aqueous species (e.g., SeO_2). For example, equations 11 and 12 demonstrate the reactions of SeBr_4 and Se_2Br_2 with water.



In an embodiment using iodine and selenium, or iodine and tellurium, the same set of equations may apply (e.g., Eq. 11- Eq. 22), and thus, selenium or tellurium may be used as a catalyst for the oxidation of hydrogen iodide to iodine. In this embodiment, the pressure may range from about 0.1 atm to about 40 atm, while the operating temperature may be lower as HI is a stronger reducing agent. For example, the temperature of the system may range from about 0 °C to about 120 °C. In some embodiments, tellurium and selenium may be used to convert hydrochloric acid to chlorine, though higher temperatures may be required. For example, the temperature may range from about 150 °C to about 500 °C, which may result in the reactions occurring in the gas phase. Such reactions may generally be described by equations 11 through 14. Tellurium may be used as a catalyst for the bromine generation from hydrogen bromide with chemical processes identical to those described for the selenium system above; however the temperatures may be higher than for selenium. In an embodiment that utilizes tellurium to generate bromine from hydrogen bromide, the reaction temperature may range from about 100 °C to about 350 °C.

Figure 16 illustrates a schematic embodiment of a reactor system for the conversion of HBr to Br_2 . In this embodiment, a stream containing HBr 90 and a stream containing air or oxygen 91 may be fed to a reactor 92 containing an aqueous solution of selenium bromide, various oxybromides (e.g., SeOBr_2 , Se_2Br_2 etc.), or any combination thereof. Selenium oxide, if

present during the reaction, may be in a slurry phase. Products may be removed from the reactor as a vapor stream. The reactor outlet stream 93 may contain selenium bromide and HBr. Due to the presence of the HBr-water azeotrope and the fact that the boiling point of selenium bromide is higher than either bromine or water, it may be possible to use a reactive distillation system 94 to fractionate the reactor outlet 93 whereby only bromine, water, unconverted oxygen, and nitrogen leave the system in the product mixture 95. The bottoms stream 96 may return any selenium compounds to the reactor 92. In an embodiment, the performance of the system may be improved by changing the feed stage and number of stages of the fractionator 94. In another embodiment, the performance of the system may be improved by adding an additional reboiler, by varying the reflux and reboil ratios, or a combination thereof. The product mixture 95 containing bromine, water, oxygen and nitrogen may be processed using any of the methods disclosed herein.

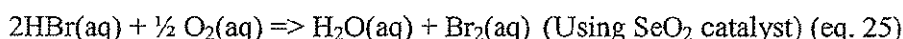
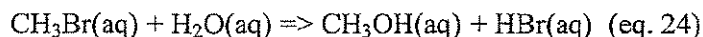
In another embodiment, any hydrogen halide generated in the coupling reactor may be separated from the coupling products, any unreacted feedstock, and any other inert gases by passing the entire coupling reactor product stream through the aqueous Se catalyst system. In this embodiment, the coupling reactor products stream may be cooled prior to entering the aqueous Se catalyst system to prevent overheating and boiling of the aqueous reaction medium. The HBr may be adsorbed by the aqueous phase and phase separate from any hydrocarbons, including any products and unreacted feedstock. The aqueous Se system enriched in HBr may then be recirculated back to the bromine generation reactor where it may be converted to bromine. This approach may eliminate the need for a separate HBr/coupling products reactor, thus reducing the overall capital costs. In this embodiment, the aqueous Se system may be oxidized to convert the Se species to highly water soluble H_2SeBr_6 and H_2SeO_3 before being contacted with the coupling reactor product stream. Such oxidation may help prevent transferring any of the Se compounds into the organic phase and contaminating the final product stream.

The reactor depicted in FIG. 16 may be a CSTR (continuous stirred tank reactor), however other conventional reactors such as CSTRs in series, PFR (plug flow reactor), packed columns, reactors with multiple inlets and vapor outlets, multiple reactors in series, and other reactor types known to those skilled in the art may also be used.

In another embodiment, the MeBr created in the bromination reaction may be reacted directly in the aqueous oxidation process to Br_2 . This would require operation at mildly acidic conditions. An advantage would be the simplicity of the process.

The process may require three reaction stages characterized by the following equations:





First, methane may be brominated (eq. 23). The resulting bromomethane may be fed to a reactor containing water, and hydrolysis to produce methanol may take place (eq. 24). Hydrogen bromide may be produced in both Eq. 23 and Eq. 24. Hydrogen bromide may be oxidized in an aqueous solution by the action of oxygen in the presence of catalytic selenium dioxide (eq. 15)

Thermal bromination of methane proceeds according to (eq. 13). Conversion of methyl bromide to methanol and aqueous HBr (eq. 14) is based on the well known reactivity of alkyl halides towards hydrolysis. In general this reaction may be fast for alkyl bromides at temperatures at about 100 °C and pressures at about 1 to about 10 atm. Eq. 15 may be achieved at about 100 °C through the use of SeO₂ as a catalyst.

Recovery and Recycle of Molecular Halogen

Halogen generation produces both water and molecular halogen. Water may be separated from halogen and removed before the halogen is reacted with the hydrocarbon feedstock. Where the halogen is bromine, a bromine-water, liquid-liquid phase split may be achieved upon condensation of a mixture of these species. For example, in an embodiment, a liquid-liquid flash unit may be used to separate most of the bromine from water, simply and inexpensively. The bromine phase typically contains a very small amount of water, and may be sent directly to the bromination reactor. The water phase, however, may contain 1-3 wt % bromine. However, if air is used in the bromine generation step, nitrogen and unconverted oxygen may be present with the bromine and water stream that enters the flash.

The gas leaving the flash unit primarily consists of nitrogen and unconverted oxygen, but carries with it some bromine and water. The amount of bromine leaving with the vapor phase may depend on the temperature and pressure of the separation unit. The flash may be operated at temperatures ranging from about 0 °C to about 50 °C; however, a lower temperature (e.g., about 2 °C to about 10 °C) is preferred to reduce bromine leaving in the vapor stream. In an embodiment, the operating pressure is about 1 bar to about 50 bar, more preferably about 1 bar to about 30 bar. In an embodiment, the vapor stream may be sent to the bromine scavenging section for bromine recovery, as described below.

Bromine contained in the water-rich phase leaving the liquid-liquid flash may be effectively recovered by distillation. The presently described distillation subprocess may produce bromine or bromine-water azeotrope as a distillate, which may be recycled back to the flash unit or to a hydrogen halide oxidation process, as disclosed herein. The bottoms stream

may consist mainly of water. Bromine may react reversibly with water to form small amounts of HBr and HOBr. In the distillation scheme, therefore, ppm levels of HBr (and/or HOBr) may be present in the bottoms stream. A side-stream rectifier or stripper may be utilized to reduce the bromine content of the bottoms stream to produce a pure water stream. Other alternatives that may reduce the bromine content of the water to below 10 ppm range include, but are not limited to, the addition of acids such as sulfuric acid, hydrochloric acid, and phosphoric acid, in very small quantities to reduce the pH of the water stream. Lowering the pH may drive the HBr and HOBr stream back to bromine and water, thereby substantially reducing the loss of bromine in the water stream. HBr present in the water stream may also be recovered using ion-exchange resins or electrochemical means.

Recovery of All Halogen for Reuse

Various streams in the process may contain some halogen that may be recovered prior to venting or otherwise allowing the stream to exit the process. Such streams may result from separation of the bromine from lighter components such as nitrogen or oxygen. For example, condensation, vapor-liquid separation, gas-solid adsorption/reaction, or any combination thereof may be used to separate residual bromine in a vapor stream from the other components of the stream. The vent streams may be treated in order to recover the halogen prior to venting the other components of the stream. In an embodiment, any scavenging method may be used that is capable of recovering at least some elemental halogen or hydrogen halide from a process stream. For example, a chilled liquid process or a solid scavenging process may be used to recover any halogen.

In an embodiment, the scavenging process may consist of a single pass technique, or a variety of techniques may be used in series. In some embodiments, a general scavenging technique such as a chilled brine process may be used to remove the majority of the halogen in a stream prior to treating the stream with a high capture efficiency scavenging technique such as solid adsorption/reaction. Such an embodiment may allow a high capture efficiency while avoiding an excessive burden on the final bromine adsorption/reaction, which may be the most expensive portion of the scavenging process. To achieve low levels of residual bromine the temperature of the stream being treated may need to be reduced to about 10 °C to about -30 °C. The process stream being cooled may contain a variety of components such as water and bromine, which may freeze under these conditions. Therefore, simple cooling by indirect heat transfer may not suffice due to icing of the heat transfer surface. Such a problem may be overcome by introducing a brine coolant which may directly contact the process stream containing the halogen. Due the low freezing point associated with brines, the use of a brine may

enable cooling to the desired temperature. Vaporizing the bromine by heating the brine can then occur, with further heating employed to facilitate concentration (*e.g.*, evaporative concentration) of the brine for re-use. This approach to bromine recovery may be carried out either continuously or in batch mode.

5 In an embodiment, the brine solution may be composed of any salt or combination of salts that is at least partially soluble in an aqueous solution. In an embodiment, suitable salts may include commonly available salts such as NaCl or CaCl₂, or any salt of a halide corresponding to the halogen being recovered from the process stream. For example, if bromine is being recovered from a process stream, NaBr or CaBr₂ may be used to form the brine solution.

10 As used herein, the term brine refers to an aqueous salt solution at, below, or above saturation. This may include salts that are undersaturated or super-saturated, depending on the process conditions. In an embodiment, the brine may have from about 0.1 % to about 60 % by weight salt in an aqueous solution. In another embodiment, the brine may have from about 10 % to about 30 % by weight salt in an aqueous solution. The aqueous solution may include any fluid

15 containing water and may be derived from any source. For example, a water stream generated in the process may be used to form at least a portion of the brine solution.

 In an embodiment, the brine solution may be directly contacted with the stream containing the halogen to be recovered. The brine coolant and liquid halogen formed by direct contact cooling may be separated from any other light gases present in the process stream in a

20 vapor-liquid-liquid separator. Liquid from the separator may consist of two phases, a brine phase and the a liquid halogen phase. The liquid halogen phase may join a previously condensed halogen in the process or may be recycled in the process for further purification. The brine phase may be cooled and returned to the direct contact cooling operation.

 In another embodiment, if the halogen captured in the direct contact cooler is dissolved in

25 the brine and does not phase separate, then recovery of this halogen may be effected by heating the brine to vaporized the halogen in the brine. The vaporized halogen may be combined with vapor from a halogen generation operation, re-circulated to an upstream process, or any combination thereof.

 In an embodiment, the chilled brine process may be operated using a brine with a

30 temperature between about 0 °C and about -30 °C during the direct contact operation. In another embodiment, the chilled brine process may be operated using a brine with a temperature between about -5 °C and about -15 °C during the direct contact operation. Any pressure between about 1 atm to about 50 atm may be used, with a pressure between about 2 atm and about 30 atm being used in some embodiments.

In another embodiment, a solid halogen scavenging process may be used, either alone or in combination with a chilled liquid process. Bromine scavenging may be carried out in a bed containing solid CuBr or MnBr₂, either loaded on a support or used in powder form, to capture Br₂ from a gas stream that may also contain H₂O, CO₂, O₂, methane &/or N₂. In one embodiment of the invention, bromine scavenging is performed within a range of temperatures, *e.g.*, from about -10 °C to about 200 °C. When bromine scavenging is complete, molecular bromine may be released from the bed by raising the temperature of the bed to about 220 °C or higher, preferably above about 275 °C. It is important that there be little if any O₂ in the bed during bromine release, as O₂ will oxidize the metal and, over time, reduce the bromine-scavenging capacity of the bed.

Hydrocarbon Product Separation

The processes of the present invention may produce a hydrocarbon product stream that may comprise water. For example, if a cataloreactant process is used to capture and regenerate HBr with the entire product stream passing through the cataloreactant, then water may be produced and pass along with the product stream. Alternatively, in an aqueous based hydrogen halide capture process, the product stream leaving the contact tower may contain water vapor that may be removed prior to passing the product hydrocarbons out of the process for sale. Once any water present in the product stream is removed, a product recovery system may be used to further separate and recycle the hydrocarbon product stream prior to the hydrocarbons leaving the system.

In the product recovery system shown in Fig 17, a product stream 110 leaving a hydrogen halide removal process (*e.g.*, an aqueous absorption process, a solid reactant based capture process, etc.) may be substantially hydrogen halide free. The product stream 110 may be cooled using a heat exchanger 112 and partially condensed in a vessel 114 to yield a vapor phase and two immiscible liquid phases. The two liquid phases may be further separated to yield an aqueous phase stream 116, which may be primarily water with a small amount of dissolved hydrocarbons, and an organic phase stream 118 consisting of higher hydrocarbons.

The aqueous phase stream may exit the process or be utilized for various processes within the system. For example, the water may be used as a water source for another process within the system, such as a water source or makeup water source for an aqueous hydrogen halide absorption process. In another embodiment shown in Fig. 18, some of the water 116 recovered in the product recovery section 108 may be mixed with the coupling product stream in a quench column 142 and recycled to the hydrogen halide capture sub-process (*e.g.*, a solid reactant HBr capture sub-process). In an embodiment, the quench column 142 may be a packed

bed, spray tower, or equivalent unit operation. The amount of water recycled may be chosen such that the temperature of the mixed coupling product stream as well as the product gas stream leaving the hydrogen halide capture sub-process, may be above their respective dew points to insure that little to no liquid condensation occurs in the hydrogen halide capture sub-process.

5 This embodiment may improve the economics of the entire process by reducing the cooling load in the hydrogen halide capture sub-process and transferring it to the product recovery system. This may result in a process with a lower capital cost as the materials of construction used for the heat transfer surfaces in the solid reactant sub-process may be significantly more expensive than those used in the product recovery system due to the presence of a hydrohalic acid. Further, the
10 mixing may reduce the range of the temperature cycling in the hydrogen halide capture sub-process, which may be useful if a solid based reactant process is used in the hydrogen halide capture sub-process.

Referring to Fig. 17, the vapor stream 120 may be primarily composed of light gases such as N_2 , methane, and other light hydrocarbons (*e.g.*, C_2 , C_3 , C_4), and may be saturated with higher
15 hydrocarbons (*e.g.*, C_5+) and water. For embodiments using relatively large gas flowrates in the process, the vapor stream 120 may contain a significant fraction of the total liquid hydrocarbon product (*e.g.*, C_5+). In some embodiments, the vapor stream 120 may then flow to an absorber 122 where a solvent may be used to absorb at least some of the higher hydrocarbons (*e.g.*, C_5+). The solvent may be either a pure non-volatile hydrocarbon (*e.g.*, $C_{12}H_{26}$, mesitylene (C_9H_{12}),
20 etc.) or a mixture of non-volatile hydrocarbons (*e.g.*, diesel, a mixture of high boiling coupling products, etc.). In addition to absorbing at least some of the C_5 and higher hydrocarbons, the solvent may also absorb some of the C_3 and C_4 hydrocarbons, along with small amounts of the light hydrocarbons and gases. The gas stream 124 leaving the absorber 122 may contain most of the N_2 , CH_4 , C_2 , and potential some C_3 and C_4 . Stream 124 may be recycled if the amount of
25 nitrogen is not excessive, or it may be flared, vented, recycled to the solid reactant sub process as a diluent for purposes of mitigating the temperature rise in the reactors, or otherwise used within the system, for example as a fuel stream. The liquid stream from the absorber 126 may pass to a separation sub-system 128, which may comprise one or more distillation sequences for recovering (a) the solvent for recycle to the absorber, (b) any C_3 and C_4 which may be further
30 refined to LPG or recycled to lights bromination; and (c) any liquid hydrocarbon products (*e.g.*, C_5+). While this separation process may be feasible at both low and high pressure, high pressure may be preferred in order to minimizing the solvent flowrate and use cooling water, rather than refrigeration, in any distillation columns condensers.

An embodiment of a product recovery system with a distillation sequence is shown in
35 Fig. 19. In this embodiment, two distillation columns may be used to sequentially recover the

light hydrocarbons, the heavy hydrocarbons, and the solvent. In the first column 130 at least some of the light hydrocarbons comprising C_3 and C_4 may be separated as a vapor stream 132. The heavier hydrocarbons, which may have some C_3 and C_4 dissolved therein, may be passed to a second distillation column 136. The second distillation column 136 in this embodiment may
5 separate any remaining product hydrocarbons as a liquid stream 138 and the solvent as a liquid stream 140. The liquid stream comprising the products 138 may be combined with the organic phase stream 118 from the initial separation vessel 114 in the product separation sub-process. The solvent stream 140 from the second distillation column 136 may be recycled back to the absorber 122. Distillation columns 130 and 136 may use a total or partial condenser such that
10 the light hydrocarbon stream 132 and the product hydrocarbon stream 138 and may be either a vapor or liquid depending on the operating conditions. The operating pressures for the two distillation columns are selected so as to minimize the reboiler temperatures, minimize the use of any refrigerants in the column condensers, and maximize the opportunity for energy integration with other sub processes in the system. Using this process and diesel as a solvent, may result in a
15 recovery of about 100% of the C_5+ hydrocarbons, about 50% of C_4 , and about 17% of C_3 . The resulting overall carbon efficiency may be up to about 60%.

Still another embodiment is shown in Fig. 20. In this embodiment, feedback expansion cooling may be used to obtain a high recovery of the light hydrocarbons. As used herein, the term "high recovery of the light hydrocarbons" may refer to a separation process capable of
20 recovering more than about 60% of the C_4 , and more than about 25% of the C_3 in the inlet stream. In this process, the stream 124 may first pass through a dehydration bed (not shown), and then leaving the absorber 122 may be at high pressure. In an embodiment, stream 124 may be at a pressure greater than about 10 atm, or alternatively greater than about 20 atm. This stream 124 may be cooled using a cold process stream in a heat exchanger 144 and phase
25 separated in a separation vessel 146 to yield a liquid stream 157 comprising C_3 and C_4 , along with some C_2 and C_1 and a vapor stream 148 containing N_2 , CH_4 and C_2 hydrocarbons. The pressure of vapor stream 148 may be reduced from the high pressure to a much lower pressure using an expansion turbine 150, resulting in a significant decrease in the temperature of the stream. In an embodiment, the pressure of stream 148 may be reduced to between about 1 atm to
30 about 5 atm in the expansion turbine 150. The resulting cold gas stream 152 may be used to cool the absorber exit gas stream 124 in the heat exchanger 144. The low pressure stream 154 may then be vented, recycled if the nitrogen content is not excessive, recycled to the solid reactant sub process as a diluent for purposes of mitigating the temperature rise in the reactors, or otherwise used within the process, for example as a fuel stream. The cold liquid stream 157 may
35 also be used to provide some of the cooling required to cool the absorber exit stream 124 in heat

exchanger 144. In another embodiment, especially in the case where the amount of the nitrogen in the absorber exit stream is not excessive, the expansion turbine 150 may be replaced by a Joule-Thompson valve. In yet another embodiment, the order of the expansion turbine, or the Joule-Thompson valve, and the separation vessel 146 may be reversed. The feedback cooling mechanism may allow the absorber gas outlet stream 124 to be cooled to a temperature low enough to condense at least some C_3 and C_2 , without the use of refrigeration. Using this process, it may be possible to increase the overall recovery of any C_4 hydrocarbons to about 99%, any C_3 to greater than about 95%, and any C_2 to greater than about 30%. The resulting overall carbon efficiency may be up to about 75%.

Another embodiment of the product recovery sub-process is shown in Fig. 21. In this embodiment, feedback expansion cooling may be used to achieve the products separation without a solvent based absorption sub-process. The high pressure gas stream 156 leaving the flash drum 114 may first pass through a dehydration bed (not shown), and then may be cooled using a heat exchanger 158 and a flash drum 162 to recover a substantial portion of the C_3+ hydrocarbons in the liquid phase. In this embodiment, a network of heat exchangers and flash drums may be used to sequentially cool and separate the hydrocarbons. The plurality of heat exchangers and flash drums may be used to prevent heavy hydrocarbons from crystallizing in heat exchangers. The required cooling for this process may be provided by expansion cooling of the gas stream 166 leaving the heat exchanger/flash network, and optionally the heating and vaporization of the cold liquid stream 164. In the case where the amount of the nitrogen in the absorber exit stream 156 is not excessive, the expansion turbine 168 may be replaced by one or a series of Joule-Thompson valves. In addition, the order of some of the flash drums and the expansion turbine (or Joule Thompson valve) may be reversed. The resulting liquid stream 164 from the feedback expansion cooling process may be distilled in one or more columns to yield a liquid stream 174 comprising a hydrocarbon product (e.g., C_5+) and a vapor stream 176 comprising the LPG stream (e.g., C_3 and C_4).

In an embodiment, the product separation process may utilize some heat integration with other sub-processes in the system. For example, the separation process may not require any external heat as all of the energy required in the process may be provided by other process streams. One source of potential heat may be solid reactant sub-process if it is used to remove the hydrogen halide from the product stream.

Construction of Critical Process Elements with Unique Corrosion-Resistant Materials

Corrosion induced by any halogen-containing process, whether in the condensed phase or the vapor phase, presents a significant challenge in the selection of durable materials for the

construction of reactors, piping, and ancillary equipment. Ceramics, such as alumina, zirconia, and silicon carbides, offer exceptional corrosion resistance to most conditions encountered in the process described herein. However, ceramics suffer from a number of disadvantages, including lack of structural strength under tensile strain, difficulty in completely containing gas phase reactions (due to diffusion or mass transport along jointing surfaces), and possibly undesirable thermal transport characteristics inherent to most ceramic materials. Constructing durable, gas-tight, and corrosion resistant process control equipment (*i.e.* shell and tube type heat-exchangers, valves, pumps, etc.), for operation at elevated temperatures and pressures, and over extended periods of time, may likely require the use of formable metals such as Au, Co, Cr, Fe, Nb, Ni, Pt, Ta, Ti, and/or Zr, or alloys of these base metals containing elements such as Al, B, C, Co, Cr, Cu, Fe, H, Ha, La, Mn, Mo, N, Nb, Ni, O, P, Pd, S, Si, Sn, Ta, Ti, V, W, Y, and/or Zr.

According to one embodiment of the invention, the process and subprocesses described herein may be carried out in reactors, piping, and ancillary equipment that are both strong enough and sufficiently corrosion-resistant to allow long-term continued operation. Selection of appropriate materials of construction depends strongly on the temperature and environment of exposure for each process control component.

Suitable materials for components exposed to cyclic conditions (*e.g.* oxidizing and reducing), as compared to single conditions (oxidizing or reducing), may differ greatly. Nonlimiting examples of materials identified as suitable for exposure to cyclic conditions, operating in the temperature range of from about 150 °C to about 550 °C, include Au and alloys of Ti and Ni, with the most suitable being Al/V alloyed Ti (more specifically Ti Grd-5) and Ni--Cr--Mo alloys with high Cr, low Fe, and low C content (more specifically ALLCOR[®], Alloy 59, C-22, 625, and HX). Nonlimiting examples of materials identified as suitable for exposure to either acid halide to air, or molecular halogen to air cyclic conditions, in the temperature range about 150 °C to about 550 °C, either acid halide to air, or molecular halogen to air include alloys of Fe and Ni, with the most suitable being alloys of the Ni--Cr--Mo, and Ni--Mo families. Nonlimiting examples of materials identified as suitable for single environment conditions, in the temperature range of from about 100 °C to about 550 °C, include Ta, Au, and alloys of Fe, Co, and Ni. For lower temperature conditions (< about 280 °C), suitable polymer linings can be utilized such as PTFE, FEP, and more suitably PVDF. All materials may be used independently or in conjunction with a support material such as coating, cladding, or chemical/physical deposition on a suitable low-cost material such as low-alloy steels.

Additional Process Configurations

FIG. 22 schematically illustrates an alternate mode of operation for a continuous process for converting methane, natural gas, or other alkane feedstocks into higher hydrocarbons. Alkanes may be brominated in the bromination section in the presence of water formed during bromine generation, including recycled water. The bromination products may pass either through a reproporationation reactor or through the reproporationation section of the bromination reactor, where the light gases may be reproporationated to form olefins and alkyl bromides by using the polybromides as brominating agents. The reproporationation products, which include olefins, alkyl monobromides, some polybromides, and HBr, along with any unreacted alkanes, may then be sent to the coupling reactor. The coupling products may be sent to a vapor-liquid-liquid flash. Higher hydrocarbon products may be removed as an organic phase from the vapor-liquid-liquid flash, while aqueous HBr may be removed as the heavier phase. The gas stream from the flash may be sent to a separation system to recover methane and light gases, which may be recycled back to the bromination and reproporationation sections, respectively.

Nitrogen must be removed from the gas recycle stream if air is used as an oxidant in bromine generation. The aqueous HBr stream coming out of the vapor-liquid-liquid flash may be sent to the HBr/water separation system, where water may be recovered. The separation may be carried out in a distillation column, where pure water may be taken out as a distillate and the bottoms stream may be an aqueous solution of HBr (having a higher concentration of HBr than the feed to the distillation column). The aqueous HBr stream may be sent back to the bromine generation section, where bromine may be generated from aqueous HBr in the presence of air or oxygen.

Alternatively, extractive distillation may be used to separate HBr from water. The separated HBr may be sent to the bromine generation reactor and bromine may be generated from aqueous HBr in the presence of air or oxygen. Complete conversion of HBr is not necessary in the bromine generation reactor. Periodic decoking may be carried out for the bromination, reproporationation, and/or coupling reactors, with the bromine-containing decoking product stream being routed to the bromine generation reactor.

Another continuous process alternative is shown in FIG. 23. Alkanes may be brominated in the bromination section in the presence of water formed during bromine generation, including recycled water. The bromination products (which include monobromides and polybromides) may pass through either a reproporationation reactor or the reproporationation section of the bromination reactor, where the light gases may be reproporationated to form alkyl bromides, using the polybromides as brominating agents. The reproporationation products--alkyl monobromides, olefins, a small amount of polybromides, and HBr--and any unreacted alkanes

may then be sent to a separation unit where aqueous HBr may be separated from the alkyl bromides. Monobromides in the alkyl bromide stream may be separated from the polybromides. The polybromides may be recycled to the reproporation section where polybromides may react with the recycle gases to form olefins and monobromides.

5 The aqueous HBr separation from the alkyl bromides may be carried out in a distillation column coupled with a liquid-liquid flash. The alkyl bromide stream may contain HBr. The monobromides may be fed into the coupling section, and the products may be sent to a water absorption column where HBr produced in the coupling reactor is removed from the products and unconverted gas. The liquid outlet of the absorption column may be fed to a vapor-liquid-
10 liquid flash separation unit, where higher hydrocarbon products may be removed as an organic phase and aqueous HBr may be removed as the heavier phase. The gas outlet from the absorption column may be sent to a separation system to separate methane from the light gases. The recovered methane may be recycled back to the bromination section, while the light gases may be recycled to the reproporation section.

15 Nitrogen may be separated before the gases are recycled if air is used as an oxidant in bromine generation. The aqueous HBr stream from the vapor-liquid-liquid flash may be combined with the aqueous HBr stream from the alkyl bromide separation section and sent to the HBr/Water separation system. The separation may be carried out in a distillation column, where pure water may be taken out as a distillate and the bottoms stream may be an aqueous solution of
20 HBr having a higher concentration of HBr compared with the feed to the distillation column. The aqueous HBr stream may be sent back to the bromine generation section, where bromine may be generated from aqueous HBr in the presence of air, oxygen or enriched air.

 Alternatively, extractive distillation may be used to separate HBr from water. The separated HBr may be sent to the bromine generation reactor, where bromine may be generated
25 from aqueous HBr in the presence of air, oxygen, or enriched air. Complete conversion of HBr to bromine is not required during bromine generation. Periodic decoking of the bromination, reproporation and coupling reactors may be carried out, with the bromine-containing decoking product stream being routed to the bromine generation reactor.

 Another continuous process configuration is shown in FIG. 3. In this embodiment a non-
30 redox active solid reactant may be used to capture and regenerate the hydrogen halide generated in the halogenation reactor and the coupling reactor. In this embodiment, an alkane feedstock stream 41 may be brominated in a bromination reactor 43. The bromination products 44 may be separated in a separator 45 to allow the monobrominated stream 47 to pass to the coupling reactor 48, while the polybrominated stream 46 may be recycled to a reproporation reactor
35 (not shown) or a reproporation section of the bromination reactor 43. If a separation and

reproportionation scheme is used, the light gases may be reproportionated to form olefins and alkyl bromides through the use of the polybrominated species as brominating agents. The reproportionated products, which may include olefins, alkyl monobromides, some polybromides, and HBr, along with any unreacted alkanes, may then be sent to the coupling reactor 48. The
5 coupling reactor products 49 may then be sent to an HBr capture reactor 55 that contains a solid reactant. The solid reactant may capture the HBr by forming a metal bromide corresponding to the metal-oxide solid reactant. The product stream 50 from the HBr capture reactor 55 may be substantially free of HBr and may pass to a products separation unit 51. The product stream 50 may be dehydrated to remove any water 54, such as any water produced during the reaction of
10 the HBr with the solid reactant. The product stream 50 may be further separated to allow methane 53 or other light hydrocarbons to be separated from a heavier products stream 52 and be recycled to the inlet of the process or used as fuel.

The halogen capture process shown in the embodiment depicted in Figure 3 may generate a metal bromide 56. The metal bromide 56 may be regenerated to the original metal oxide solid
15 reactant in a regeneration reactor 57 through the introduction of air or oxygen 58. The air or oxygen 58 may react with the metal bromide 56 entering the regeneration reactor 57 to generate a regeneration products stream 59 containing elemental bromine along with any inert gases contained in the air or oxygen containing stream 58. The regeneration product stream 59 may be separated in a separator 60 in order to remove and any inert gases 61 from the process, such as
20 nitrogen if air is used as the oxygen source. The separator 60 may also result in an elemental bromine stream 62 that may be passed back to the bromination reactor 43 in order to brominate the incoming alkane feedstock 41, recycled hydrocarbons, or any combination thereof. The regenerated metal oxide solid reactant may be transported back to the HBr capture reactor 55 through recycle line 63. The metal bromide conversion to metal oxide and regeneration cycle in
25 the embodiment shown in Figure 3 may be carried out in any type of reactor capable of containing a solid solid reactant material. Reactor configurations that may be used include, but are not limited to, fixed beds, fluidized beds, and moving beds.

In another embodiment, the solid reactant may be contained in three or more alternating fixed bed reactors in parallel (not shown). At any given time, one of the reactors is on-line for
30 hydrogen halide capture/neutralization; one of the reactors is on-line for elemental halide regeneration; while the remaining reactors are offline for purge, and cooling/heating of the fixed bed reactors to the desired capture and regeneration temperatures. In this manner the overall process can be operated continuously without interruption.

In an embodiment illustrated in Figure 3, the coupling reactor 48, which may contain a
35 coupling catalyst, may be carried out in any type of reactor. Reactor configurations that may be

used to create higher hydrocarbons include, but are not limited to, fixed beds, fluidized beds, and moving beds. In an embodiment, the coupling reactor 48 may be contained in a plurality of alternating fixed bed reactors (not shown). While a given reactor is off-line for decoking, the overall process can, nevertheless, be operated without interruption by using a reserve reactor, which is arranged in parallel with its counterpart reactor. For example, twin coupling reactors may be utilized, with process gasses being diverted away from one, but not both, reactors.

In an embodiment illustrated in Figure 3, the coupling reactor 48 may be a moving bed reactor or a fluidized bed reactor. In this embodiment, the coupling reactor 48 may receive a regenerated coupling catalyst 64 and contact the regenerated coupling catalyst 64 with a brominated hydrocarbon stream 47. Coke may be produced during the coupling reaction resulting in decreased reactivity of the coupling catalyst. In order to restore the catalytic reactivity of the coupling catalyst, a decoking process may be carried out in a decoking reactor 65 that may receive the coked catalyst stream 68 and air or oxygen 66 to facilitate the removal of the coke from the coupling catalyst. The decoking products stream 67, which may contain bromine, may be routed to the bromine generation reactor 57. The regenerated coupling catalyst 64 may be transported back to the coupling reactor 48 to complete the cycle.

Still another continuous process configuration is shown in Figure 24. In this embodiment, a single reactor may be used to couple the alkyl bromide reactants and capture the HBr generated during the bromination reaction and the coupling reaction. In this embodiment, the catalyst used may act as both a coupling catalyst and solid reactant for capturing HBr, which may be a non-redox active solid reactant. For example, a alumino silicate zeolite catalyst with wet-impregnated metal oxide may be used. In another embodiment, separate materials may be used. For example, a zeolite without a metal oxide may be used to act as a catalyst for coupling and a separate metal oxide doped zeolite may be used to capture HBr. This embodiment may allow the separate materials to be incorporated into the reactor as a uniform mixture of the materials, or allow for layering of the materials to form zones within the reactor. In an embodiment in which the reactor is a fluidized bed or moving bed reactor and separate materials are used to couple the alkyl bromides and capture the produced HBr, the particles may be similarly sized to avoid separation of the material into distinct phases during transport or use. The catalyst may be regenerated in the regeneration section by oxidation of coke, and the solid reactant may be regenerate to release bromine in the reaction of the metal bromide with air or oxygen.

In the embodiment shown in Figure 24, an alkane feedstock stream 301 may be brominated in a bromination reactor 303. The bromination products 304 may be separated in a separator 305 to allow the monobrominated stream 307 to pass to the coupling reactor 309, while

the polybrominated stream 306 may be recycled to a reproporation reactor (not shown) or a reproporation section of the bromination reactor 303. If a separation and reproporation scheme is used, the light gases may be reproporated to form olefins and alkyl bromides through the use of the polybrominated species as brominating agents. The reproporated products, which may include olefins, alkyl monobromides, some polybromides, and HBr, along with any unreacted alkanes, may then be sent to the coupling reactor 362 that may also contain a solid reactant for capturing HBr.

In the embodiment shown in Figure 24, the coupling reactor may also contain a solid reactant for capturing any HBr in the incoming brominated stream and any HBr produced during the coupling reaction. The product stream from the coupling reactor 362 may be substantially free of HBr and may pass to a products separation unit 315. The products may be dehydrated to remove any water 330 contained in the system, such as the water produced during the reaction of the HBr with the solid reactant. The products 314 may be further separated to allow methane 320 or light hydrocarbons to be recycled to the inlet of the process or used as fuel.

In an embodiment in which the coupling reactor also contains a solid reactant for capturing HBr, the coupling reaction may deactivate the coupling catalyst and convert the solid reactant to a metal bromide phase solid reactant. The coupling catalyst may be deactivated due to a number of reasons including, but not limited to, coke formation on the catalyst or within the interstitial space between the catalyst particles.

In order to regenerate the coupling catalyst and the solid reactant, the material may be regenerated in a regeneration reactor 360 through the introduction of air or oxygen 324. The air or oxygen may react with any coke to generate CO_2 along with a number of other combustion products including brominated species, and the metal bromide solid reactant may react to form a metal oxide and elemental bromine. The product stream 358 from the regeneration reactor may be separated in a separator 327 in order to remove and any inert gases 333 from the process, such as nitrogen if air is used as the oxygen source. The CO_2 generated in the regeneration reactor may be removed in separator 327 or may pass through the process to be removed in the products separation reactor 315. The separator 327 may also result in an elemental bromine stream that may be passed back to the bromination reactor 303 in order to brominate the incoming alkane feedstock, recycled hydrocarbons, or any combination thereof.

In the embodiment shown in Figure 24, the coupling reaction, HBr capture reaction, and regeneration reaction cycle may be carried out in any type of reactor capable of containing a solid coupling catalyst and solid reactant material. Reactor configurations that may be used include, but are not limited to, fixed beds, fluidized beds, and moving beds.

In another embodiment, the solid reactant may be contained in three or more alternating fixed bed reactors in parallel (not shown). At any given time, one of the reactors is on-line for hydrogen halide capture/neutralization; one of the reactors is on-line for elemental halide regeneration; while the remaining reactors are offline for purge, and cooling/heating of the fixed bed reactors to the desired capture and regeneration temperatures. In this manner the overall process can be operated continuously without interruption.

In an embodiment illustrated in Figure 24, a moving bed reactor configuration or a fluidized bed reactor configuration may be utilized where the solid reactant is cyclically transported from the coupling reactor 362 to the regeneration reactor 360 and back. In this embodiment, the coupling reactor 362 may receive a regenerated material stream 361 comprising a regenerated coupling catalyst, solid reactant, or combination thereof and contact the regenerated material with a brominated hydrocarbon stream 307. The coupling catalyst may be deactivated in the coupling reactor and the solid reactant may be converted to a metal bromide in a reaction with any HBr present. The deactivated coupling catalyst and the metal bromide solid reactant may exit the reactor as a deactivated catalyst stream 359, which may be transported to a regeneration reactor 323 to be regenerated and decoked with an air or oxygen stream 324. After regeneration, a regenerated catalyst stream 361 may be transported back to the coupling reactor 350 to complete the cycle.

In an embodiment shown in Figure 25, a redox active solid reactant material may be used in a process for making higher hydrocarbons. In this embodiment, natural gas or another hydrocarbon feedstock and molecular bromine may be carried by separate lines 401, 402 into a heated bromination reactor 403 and allowed to react. Products (e.g., HBr, alkyl bromides, olefins, etc.), and possibly unreacted hydrocarbons, may exit the reactor and may be carried by a line 404 into a first separation unit 405, where monobrominated hydrocarbons and HBr may be separated from polybrominated hydrocarbons. The products may pass through a heat exchanger 450 between the bromination reactor 403 and the first separation unit 405 depending on the product stream temperature desired in the first separation unit 405. The polybromides may be carried by a line 406 back to the bromination reactor, where they may undergo "reproportionation" with methane and/or other light hydrocarbons, which may be present in the natural gas and/or introduced to the bromination reactor as described below. For large scale production of higher hydrocarbons, additional separation units may be employed, which may further purify the feed stream to the coupling reactor by separating and recycling the polybromides, thereby reducing the amount of coke and the overall bromine requirement.

In reference to Figure 25, unreacted hydrocarbon feedstock, HBr, monobromides, and (optionally) olefins formed in the bromination reactor 403 may be carried by a line 407, through

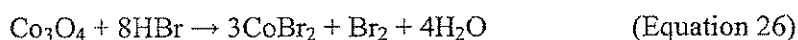
a heat exchanger 408, and enter a heated coupling reactor 409, where at least some of the monobromides (and, optionally, any olefins present) may react in the presence of a coupling catalyst to form higher hydrocarbons. The coupling reactor products stream comprising HBr, higher hydrocarbons, and (possibly) unreacted hydrocarbons and alkyl bromides may exit the coupling reactor and be carried by a line 410, through an optional compressor 452, if required, and enter a products separation train. Any number or type of separation units, which may employ pressure- or temperature-swing adsorption, membrane-based separation, cryogenic distillation that may be preferable for large scale production, or another suitable separation technology, may be used to generate a desired product distribution. Unreacted methane may be separated in a first products separation unit 454 to allow the methane to be recycled to the inlet of the process or used for fuel. A second products separation unit 456 may be employed to separate other light hydrocarbons and HBr from the products stream. One or more additional product separation units as described above may be used to yield final hydrocarbon products.

In reference to FIG. 25, the coupling reactor 409 may have a fixed bed, circulating moving bed, or circulating fluidized bed reactor configuration. In an embodiment, a fixed bed configuration (not shown in Figure 25) may be used to perform the coupling reaction. In this embodiment, a plurality of reactors may be used with the brominated product stream 411 being diverted from one reactor while the other may receive air or oxygen to decoke the coupling catalyst. The process flows may then be cycled so that the coupling process may be operated continuously.

In an embodiment shown in Fig. 25, the coupling reactor 409 may be operated using a moving bed reactor configuration or a fluidized bed reactor configuration. In this embodiment, the coupling catalyst may be cyclically transported between the coupling reactor 409 and a decoking reactor 412. In this embodiment, coupling reactor 409 may receive a regenerated coupling catalyst 413 and contact the regenerated coupling catalyst with the brominated products stream 411 to form a coupling reactor products stream 410. The coupling catalyst may form at least some coke during the coupling reaction. The coked coupling catalyst may exit the coupling reactor and be transported to the decoking reactor 412 where air or oxygen 414 may be introduced to decoke at least a portion of the coupling catalyst. A stripping gas stream 416 (*e.g.*, steam, hydrocarbons, etc.) may be introduced into the coked coupling catalyst as it is transported between the coupling reactor 409 and the decoking reactor 412 to remove any hydrocarbons from the coked coupling catalyst prior to the coked coupling catalyst being contacted with a stream containing air or oxygen 414. Gas stripping may be done by a discrete piece of hardware, or it may be part of the pneumatic transport system between zones. The decoking reaction may produce carbon dioxide as any coke and remaining hydrocarbons adsorbed on the coupling

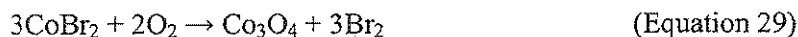
catalyst combusts (*i.e.*, oxidizes). These combustion products may pass out of the decoking reactor 412 along with any inert components of the air or oxygen stream, such as nitrogen if air is used, in a decoking products stream 415. The decoking products stream may be sent to the regeneration reactor 464 or another scrubbing section in order to recover any bromine adsorbed on the coked coupling catalyst. The regenerated coupling catalyst 413 may be transported back to the coupling reactor 409 to complete the cycle. A coupling catalyst vessel 417 may be used to hold the decoked coupling catalyst from the decoking reactor 412 before being transported to the coupling reactor 409. A heat exchanger 418 may be used to heat or cool the coupling catalyst to a desired temperature at which the coupling reaction may occur.

As shown in Figure 25, the HBr and light hydrocarbons may be carried by line 419 into an HBr capture reactor 458 after the HBr and the light hydrocarbons are separated from the hydrocarbon products in the products separation train. The conditions of the HBr capture reactor containing a redox active solid reactant may result in a metal bromide being generated along with bromine, which may react with the light gases to produce alkyl bromides. Using cobalt oxide, a redox active solid reactant, as an example, the following overall reaction occurs during HBr capture:



Alkyl bromides from the HBr capture reactor 458 may pass through a heat exchanger 461, if necessary, before being separated from water by liquid-liquid or liquid-liquid-vapor phase separation 460 and sent to a lights bromination reactor 462, which may also receive additional bromine from line 468. Heat exchanger 463 may be a heater or cooler, as necessary, to bring the stream from the separator 460 to the appropriate temperature for the lights bromination reactor 462. The products of the lights bromination reactor 462 may be combined with the products of the bromination reactor 403 before entering the coupling reactor 409.

As shown in Figure 25, the metal bromide produced in the HBr capture reactor 458 may be regenerated with air or oxygen to regenerate the original solid reactant materials. In an embodiment, the metal bromide may be sent to the bromine regeneration reactor 464, where the following overall reaction occurs:



The products stream 474 from the regeneration reactor may contain bromine and any inert gases contained in the air or oxygen stream 472, such as nitrogen. The products stream 474 may pass through a heat exchanger 476 to cool the stream prior to entering a separator 478. In an embodiment, the bromine may be separated from any other components using liquid-vapor separation, for example, using a flash tank. As the bromine may have a boiling point well below that of other components of the stream, the bromine may condense and form a liquid phase. The liquid phase may be drawn off and passed through a heat exchanger 484 before being routed to the lights bromination reactor 462, the bromination reactor 403, or both. In another embodiment, the liquid bromine may be passed to the reactor and vaporized within the reactor vessels. The vapor stream leaving the liquid vapor separator 478 may pass through a bromine scavenging unit 480 prior to exiting the system. Any bromine recovered in the bromine scavenging unit may be recycled to the system, such as for example passing through line 482 to be combined with the liquid bromine stream for use in the bromination reactors.

A fixed bed, circulating moving bed, or circulating fluidized bed reactor configuration may be used for HBr capture and bromine regeneration. In an embodiment, a fixed bed configuration (not shown in Figure 25) may be used to perform HBr capture and regeneration. In this embodiment, a plurality of reactors may be used with the stream containing the light hydrocarbons and HBr from the products separation train being diverted from one reactor while the other may receive air or oxygen to regenerate the solid reactant. The process flows may then be cycled so that the process may be operated continuously.

In an embodiment shown in Figure 25, a moving bed reactor configuration or a fluidized bed reactor configuration may be utilized where the solid reactant is physically cycled between the HBr capture reactor 458 and the regeneration reactor 464. In this embodiment, an HBr capture reactor 458 may receive a regenerated solid reactant 468 and contact the regenerated solid reactant with the stream containing the light hydrocarbons and HBr 419 from the products separation train. The regenerated solid reactant 468 may be converted to a metal bromide in the HBr capture reactor 458 and may produce water as a byproduct. Any hydrocarbons entering the HBr capture reactor 458 may react with any bromine generated by a redox active solid reactant. The solid reactant that is converted in the HBr capture reactor 458 may exit the HBr capture reactor as a metal bromide stream 470. The metal bromide stream 470 may be transported to a regeneration reactor 464 where air or oxygen 472 may be introduced to regenerate at least a portion of the metal bromide to the original solid reactant. A stripping gas stream 485 may be introduced into the metal bromide as it is transported between the HBr capture reactor 458 and the regeneration reactor 464 to remove any lights or brominated lights from the metal bromide prior to the metal bromide being contacted with a stream containing air or oxygen 472. The

regenerated solid reactant stream 468 may be transported back to the HBr capture reactor 458 to complete the cycle. A solid reactant vessel may be used to hold the regenerated solid reactant 468 from the regeneration reactor 464 before being transported to the HBr capture reactor. A heat exchanger 471 may be used to heat or cool the regenerated solid reactant to a desired temperature at which the HBr capture reaction may occur.

In the embodiment shown in Figure 25, a process gas stream may be used pneumatically to transport a catalyst or solid reactant stream if a moving bed or fluidized bed reactor design is used. For example, the process gas stream may be a portion of the hydrocarbon stream used as the input into the process. In another embodiment, an inert gas such as nitrogen may be used to transport the catalyst or solid reactant. After the material is transported to the desired location, the process gas stream may be recycled within the process, used as a feed to the process, used as a fuel stream, vented, or any combination thereof.

As shown in Figure 26, the HBr to Br_2 conversion process using copper bromides may be applied to a process for the conversion of alkanes to higher liquid hydrocarbons. In an embodiment, natural gas or another hydrocarbon feedstock may be carried by line 501 into a heated bromine generation reactor 503. Solid CuBr_2 may be carried by line 502 into the bromine generation reactor 503 where it may be heated to about 275 °C or higher to release elemental bromine, resulting in the conversion of the CuBr_2 to CuBr . The bromine generation reactor products may include a vapor stream 504 comprising the entering hydrocarbon feedstock and the elemental bromine and a solids stream 506 comprising CuBr and any unconverted CuBr_2 . The solids stream may pass to a HBr capture reactor, as discussed in more detail below. In an embodiment, the bromine generation reactor 503 may be, without limitation, a moving bed reactor or a fluidized bed reactor.

The vapor stream 504 may pass to a bromination reactor 508 where the hydrocarbon feedstock may be allowed to react with the elemental bromine to form various bromination products including, but are not limited to, HBr, alkyl bromides, olefins, and possibly unreacted hydrocarbons. In an embodiment, a reproporationation scheme may be used with the bromination reactor as described in more detail herein. In this embodiment, The bromination products may exit the reactor and be enter a separation unit where monobrominated hydrocarbons and HBr may be separated from polybrominated hydrocarbons. In some embodiments, the polybromides may be carried back to the bromination reactor, where they may undergo reproporationation with methane, other light hydrocarbons, or a combination thereof, which may be present in the natural gas and/or introduced to the bromination reactor. In another embodiment, a separate reactor may be utilized for bromination of any C_2 or heavier hydrocarbons. In some embodiments, the

bromine generation reactor and the bromination reactor may take place in the same vessel, which may be operated as a moving bed or fluidized bed reactor.

In the embodiment shown in Figure 26, any unreacted hydrocarbon feedstock, HBr, monobromides, and any olefins formed in the bromination reactor may be carried by a line 510 to coupling reactor 512, where the monobromides, olefins, or any combination thereof may react in the presence of a coupling catalyst to form higher hydrocarbons. In an embodiment, a heat exchanger may be used to adjust the temperature of the brominated products stream 510 to a desired inlet temperature to the coupling reactor 512. The coupling reactor products may include HBr, higher hydrocarbons, unreacted hydrocarbons, alkyl bromides, or any combination thereof. The coupling reactor products may exit the coupling reactor 512 and be carried by a line 514 to an HBr separation unit 516. The coupling reactor products may pass through another heat exchanger as necessary to adjust the temperature of the coupling products stream to a desired inlet temperature to the HBr separation unit 516.

HBr may be separated from the hydrocarbons using any suitable separation techniques.

In an embodiment, the HBr may be separated from the HBr coupling reactor products using aqueous absorption. In this embodiment, the HBr coupling reactor products may be contacted with an aqueous solution to absorb any HBr in the vapor stream. The resulting substantially HBr-free products stream may pass by line 518 to a products recovery unit, numerous embodiments of which are disclosed herein. In general, any light hydrocarbons contained in the product stream may be separated and directed through line 522. Any recovered methane may be returned to the bromination reactor and other light hydrocarbons may be returned to a lights bromination reactor if present. Alternately, the light gases may be added to the downstream zone of the bromination reactor where they may repropionate with polybromides to form the corresponding alkyl bromides. In still another embodiment, the light hydrocarbons may be directed to a fuel line for use in generating any desired energy for the process. A final products stream may be directed through line 524 to pass out of the process.

The aqueous HBr stream leaving the absorber may be carried by a line 526 to an HBr capture reactor. Air or oxygen may be fed into the unit through line 532 and a solid CuBr stream may be fed into the unit through line 506 from the bromine generation reactor 503. HBr may be captured through the reaction of HBr and oxygen with the CuBr to yield CuBr₂ and water. Any inert gases contained in the feed streams, such as N₂ if air is used as the oxygen source, may exit the reactor through vent line 530. The vent line may pass through a scrubbing unit to remove any trace HBr prior to being released from the process. In another embodiment, an aqueous solution of CuBr/CuBr₂ may be utilized as the absorbent in the absorption step. Alternatively, a

slurry consisting of CuBr and CuBr₂ crystals in solution saturated with respect to CuBr and CuBr₂ may be used as the absorbent.

The resulting slurry generated in the HBr Capture Reactor 530 may contain CuBr₂, any unreacted CuBr, water, and potentially trace amounts of HBr. The slurry may be subjected to
5 evaporative crystallization or other suitable technique to remove excess water formed in the reaction and to form additional CuBr₂ crystals. Separation of CuBr₂ crystals from the slurry may be accomplished by filtration, centrifugation, or any other suitable solids/liquids separation technique. The evaporated water may pass through line 538 to be used as a contact absorbent in the absorber 516, to pass out of the system, or any combination thereof.

10 The slurry containing the solid phase crystals may pass through line 546 to a dewatering unit to further remove any excess water from the solid phase CuBr and CuBr₂ crystals. The dewater unit may be any type of process capable of removing additional water from the CuBr and CuBr₂ crystals. For example, the dewatering unit may be a filtration unit, a centrifugal separator, or a heating unit capable of thermally driving off the water. The aqueous stream
15 leaving the dewatering unit 544 may be saturated with respect to both CuBr and CuBr₂ and may contain small amounts of solid crystals suspended in the fluid. The aqueous stream 542 may pass back to the crystallizer 536 through line 542. Alternatively the aqueous stream 542 may go to the absorber/stripper 516 and serve as the HBr absorbent.

The CuBr₂ and CuBr crystals, which may still contain water, may be dried in a drying
20 unit 550 at a temperature low enough to avoid bromine release. In an embodiment, the drying temperature may be below about 200 °C. Any remaining water in the CuBr and CuBr₂ crystals may be driven off and leave the system through line 552. The water vapor may pass through a scavenging unit to capture any bromine generated during drying. The dried CuBr₂ crystals may then be sent to a bromine generation unit through line 502.

25 As shown in Figure 27, an aqueous HBr to Br₂ conversion process may be applied to a process for the conversion of alkanes to higher liquid hydrocarbons. In an embodiment, natural gas (or another hydrocarbon feedstock) and molecular bromine may be carried by separate lines 601, 602 into a heated bromination reactor 603 and allowed to react. Bromination products may include, but are not limited to, HBr, alkyl bromides, olefins, and possibly unreacted
30 hydrocarbons. The bromination products may exit the reactor and be carried by a line 604 into a first separation unit 605, where monobrominated hydrocarbons and HBr may be separated from polybrominated hydrocarbons. In some embodiments, the polybromides may be carried by a line 606 back to the bromination reactor, where they may undergo reproporationation with methane and/or other light hydrocarbons, which may be present in the natural gas and/or introduced to the
35 bromination reactor. Light gases such as ethane, propane and butane may be carried by line 621

and may be allowed react with bromine in a light hydrocarbon bromination reactor 615 to produce alkyl halides and HBr.

In the embodiment shown in Figure 27, any unreacted hydrocarbon feedstock, HBr, monobromides, and any olefins formed in the bromination reactor may be carried by a line 607 to coupling reactor 609, where the monobromides, olefins, or any combination thereof may react in the presence of a coupling catalyst to form higher hydrocarbons. In an embodiment, a heat exchanger 608 may be used to adjust the temperature of the brominated products stream 607 to a desired inlet temperature to the coupling reactor 609. The coupling reactor products may include HBr, higher hydrocarbons, unreacted hydrocarbons, alkyl bromides, or any combination thereof. The coupling reactor products may exit the coupling reactor 609 and be carried by a line 610 to an HBr separation unit 612. The coupling reactor products may pass through another heat exchanger 611 as necessary to adjust the temperature of the coupling products stream to a desired inlet temperature to the HBr separation unit 612. HBr can be separated from the hydrocarbons using a number of different methods as previously described herein. For example, HBr may be separate using pressure-swing absorption, temperature-swing absorption, temperature-swing adsorption, membrane-based separation, distillation, or any combination of separation techniques, or another suitable separation technology. Specific descriptions of these technologies are included herein.

The liquid hydrocarbon products may then be carried by a line 16 to a product clean-up unit 613, to yield final hydrocarbon products 617. After HBr is separated from the hydrocarbon products and any light hydrocarbons that may be present in the HBr separation unit 612, the light hydrocarbons may be carried by a line 618 into a second separation unit 619, which may employ pressure- or temperature-swing adsorption, membrane-based separation, cryogenic distillation or any other suitable separation technology. Methane may be returned to the bromination reactor 604 via one or more line 620 and other light hydrocarbons may be returned to the lights bromination reactor 615 via line 621. Alternately, the light gases may be added to the downstream zone of the bromination reactor where they may repropionate with polybromides to form the corresponding alkyl bromides.

The HBr stream that evolves from the HBr separation unit 612 may be carried by a line 622 to a bromine generation unit 623. Air or oxygen may be fed into the unit through line 624. Bromine may be regenerated by reacting HBr with oxygen in the presence of a suitable catalyst such as an aqueous solution of selenium bromide or oxybromides (SeOBr_2 , Se_2Br_2 , etc.), as described above.

The resulting stream 625 from bromine generation reactor 623 may contain water, molecular bromine, oxygen, nitrogen, and possibly other gases if air was used as the source of

oxygen. This product stream 625 may be carried through a heat exchanger system 626 into a flash vaporization unit 627, which may separate most of the molecular bromine from water, oxygen, nitrogen, and other gases that are present. Molecular bromine containing no more than a trace of H_2O , either as a liquid or vapor, may be carried by a line 628 to a heat exchanger 629, and then returned to the bromination reactor 603, the lights bromination reactor 615, or both.

Water from the flash vaporization unit (containing up to about 3 % by weight of molecular bromine) may be sent by a line 630 to a distillation unit 631, which may yields water as the bottoms stream and bromine or bromine-water azeotrope as a distillate. The distillate may be returned through a line 632 back to the flash vaporization unit. An embodiment of this invention may utilize pH control in the distillation column 631 to prevent the hydrolysis reaction between water and bromine. The hydrolysis reaction may produce HBr , which may be lost in the bottoms stream of the distillation column in the absence of pH control. A pH of lower than about 3 may be desired to reduce or eliminate the hydrolysis reaction. Conventional acids such as sulfuric acid, hydrochloric acid, or phosphoric acid may be used for pH control.

The gaseous products of the flash vaporization unit may contain no more than a minor or trace amount of bromine and may carried by a line 633 to a bromine scavenging unit 634, which may separate molecular bromine from the other gases. As described above, adsorbents or reactants capable of capturing bromine may be used for bromine scavenging.

Another embodiment of the process for converting gaseous alkanes into liquid hydrocarbons utilizing the conversion of HBr into elemental bromine in the presence of selenium or tellurium is shown in Figure 28. In this process configuration, the operating pressure of the Br_2 generation unit 623 may be greater than the pressure in the bromination reactor 603. As in the previous case, stream 625 from bromine generation reactor 623 may contain water, molecular bromine, oxygen, nitrogen, and possibly other gases if air was used as the source of oxygen. This product stream 625 may be carried through a heat exchanger system 626 into a flash vaporization unit 627, which may separate most of the molecular bromine from water, oxygen, nitrogen, and any other gases that may be present. Liquid molecular bromine, containing no more than a trace of H_2O , may be carried by a line 628 to a heat exchanger 629, and then returned to the bromination reactor. Water from the flash vaporization unit, which may contain up to about 3% by weight of molecular bromine, may be sent by a line 630 to a distillation unit 631, which may yield water as the bottoms stream and bromine or bromine-water azeotrope as a distillate. The distillate may be returned through a line 632 back to the flash vaporization unit.

The gaseous products of the flash vaporization unit may be returned to the bromination reactor 603, the lights bromination reactor 615, or both. In this embodiment, the bromination reactor 603, the polybromide separation unit 605, the lights bromination reactor 615, and the

coupling reactor 609 may be the same as in the previous embodiment, except that all product and feed streams, with the exception of stream 606, may also contain N_2 .

The coupling product stream 610, which may contain hydrocarbons, HBr, and N_2 , may be cooled in heat exchanger 611, and then go to the HBr separation unit 612. The HBr separation unit 612 may selectively separate HBr from the other components and transport the HBr via line 622 to the bromine generation unit 623. A number of different methods may be used to achieve the desired separation (*e.g.*, distillation, adsorption, etc.). In some embodiments, temperature swing absorption may be used to separate the HBr from the coupling products stream, as described above.

Stream 718, which may contain only hydrocarbons and N_2 , may be transported to a product recovery unit 719. The product recovery unit 719 may produce a liquid hydrocarbon product stream 616, which may be sent to a product cleanup unit 613 to yield the final hydrocarbon products 617; a light gases stream 621 containing primarily C_3 and C_4 hydrocarbons, which may be further refined to product LPG product or sent to lights bromination unit 615; and a gas stream 736, which may contain N_2 , unconverted CH_4 , and possibly some C_2 and C_3 hydrocarbons. The gas stream 736 may be used as fuel for generating any energy (*e.g.*, heat, electricity, etc.) that may be required for the process.

A number of different methods may be used to achieve the desired separation in the product recovery unit 719. In some embodiments, a heavy organic solvent (either a pure component (*e.g.*, $C_{12}H_{26}$) or a mixture (*e.g.*, diesel)) may be used to absorb all the C_5 and heavier hydrocarbons, along with significant amounts of C_4 and C_3 hydrocarbons present in stream 718. A distillation sequence may then be used to recover the liquid hydrocarbon product and light gases (*e.g.*, C_4 and C_3 hydrocarbons) from the solvent, which may then be recycled to the absorber. Any C_4 and lighter hydrocarbons may be recovered from the gas stream leaving the absorber using techniques such as cryogenic distillation, expansion cooling, absorption, membrane, pressure/temperature swing adsorption, etc.

This embodiment may allow the bromine scavenging unit to be eliminated and allow cooling water, rather than brine or refrigeration, to be used in the flash separation unit 627. However, due to the presence of N_2 , the bromination reactor 603, the polybromide separation unit 605, the lights bromination reactor 615, and the coupling reactor 609 may be larger. This embodiment may be economically attractive for small scale processes such as those producing less than about 3,000 barrels of liquid hydrocarbons per day. In another embodiment, this embodiment may be attractive for processes producing less than about 2,000 barrels per day.

Another embodiment of the process is shown in FIG. 29. Due to the difficulty in obtaining a high purity HBr stream with a high recovery as a result of the VLE behavior of

ethane-HBr and HBr-propene, a different separation process may be used to remove HBr from the coupling products stream 610. In this embodiment, the cooled coupling product stream 610, which may contain hydrocarbons and HBr, may be separated to yield a vapor stream 822 containing HBr, C₃, and lighter hydrocarbons; a liquid hydrocarbon stream 616; and a C₄ hydrocarbon stream 818, which may also contain some C₃ as well. A number of different methods may be used to achieve the separation including, but not limited to, distillation, a solvent absorption based process, or both. Stream 822 may be transported to the bromine generation unit 623 where HBr may be converted to Br₂ in the presence of selenium or tellurium, as described above. The light hydrocarbons may pass through the process unreacted. Stream 625 from bromine generation reactor 623 may contain water, molecular bromine, oxygen, nitrogen if air was used as the source of oxygen, and any C₃ and lighter hydrocarbons that entered the bromine generation reactor. The product stream 625 may be carried through a heat exchanger system 626 into a flash vaporization unit 627, which may separate most of the molecular bromine from the water, oxygen, nitrogen, and any light hydrocarbons that may be present. Liquid molecular bromine containing no more than a trace of H₂O may be carried by a line 628 to a heat exchanger 629, and then returned to the bromination reactor 603, the lights bromination reactor 615, or both. Water from the flash vaporization unit containing up to about 3% by weight of molecular bromine may be sent by a line 630 to a distillation unit 631, which may yield water as the bottoms stream and bromine or bromine-water azeotrope as a distillate. The distillate may be returned through a line 632 back to the flash vaporization unit.

The gaseous products of the flash vaporization unit (*e.g.*, oxygen, nitrogen, light hydrocarbons, and no more than a minor or trace amount of bromine) may be carried by a line 633 to a bromine scavenging unit 634, which may separate molecular bromine from any other gases present. Any of the techniques described above may be used for bromine scavenging. The recovered bromine may be carried by a line 365 through a heat exchanger 629 and reintroduced into the bromination reactor 603, the lights bromination reactor 615, or both. The remaining gases, which may include oxygen, nitrogen, and light hydrocarbons, may be transported via line 837 to a separation unit 819, where any hydrocarbons including, but not limited to, C₂, C₃, and heavier hydrocarbons, may be recovered and sent, along with stream 818, to lights bromination reactor 615. The remaining gases including, but not limited to oxygen, nitrogen, methane and some light hydrocarbons, may be used as fuel for generating energy for the process. Any standard separation technology including, but not limited to, distillation, expansion cooling, absorption, membrane, and pressure/temperature swing adsorption, may be used to achieve the desired separation.

Continuous Flow Zone Reactor Configurations (CFZR)

In an embodiment that utilizes a solid reactant to capture hydrogen halide, a continuous flow zone reactor (hereinafter CFZR) may be used to carry out the method of converting hydrocarbon feedstocks into useful products. The CFZR comprises of two or more zones in which the solid catalyst particulates (*e.g.*, comprising cataloreactants) may be transported between the zones by gravity, pneumatic conveyance, or any other direct transport means as are known in the art for fluidized or moving bed reactor designs, or any combination thereof. An embodiment of the CFZR is shown in Figure 30 with a plurality of reactor zones. The solid reactant particles may react with hydrogen halide (*e.g.*, HBr) in the hydrogen halide neutralization zone 910 to make water and metal bromide, which may pass along with the products and any inert gases in the outlet stream 912 to a products separation sub-process 914, as described in more detail above. The catalytic solids may leave the neutralization zone as a metal bromide stream 916. In order to prevent hydrogen halide breakthrough in the neutralization zone, the solids flowrate may contain a metal oxide in an amount exceeding the stoichiometric requirement to neutralize the entering hydrogen halide. As a result, the metal bromide stream 916 leaving the hydrogen halide neutralization zone 910 may comprise metal bromide and metal oxide.

As shown in Fig. 30, the metal bromide stream 916 may be heated in a heating zone 918 using any known method for heating a solid particulate. Non-limiting examples may include heat transfer through direct contact with inert gases or by indirect contact through heat transfer tubes in a fluidized bed. The resulting heated metal bromide stream 920 may leave the heating zone 918 and pass into a bromine generation reactor 922. The metal bromide, which may contain some metal oxide, may be contacted with an air or oxygen stream 936 to generate elemental bromine in the bromine generation reactor 922. Any residual hydrocarbons or brominated hydrocarbons adsorbed on the solid catalyst may also be oxidized by contact with air. The combustion products may include CO₂, N₂, and potentially some trace hydrogen halide. These products may pass out of the bromine generation reactor 922 as a bromine stream 924, which may pass to a bromination reactor 926 for use in the formation of alkyl bromides, as described in more detail above. Upon contact with the air or oxygen source, the metal bromide may be converted to a metal oxide for reuse in the process. Depending on the reaction conditions, the metal oxide stream 930 may comprise some solid catalyst as a metal bromide in order to avoid oxygen breakthrough into the bromine stream 924.

The metal oxide stream 930 leaving the bromine generation reactor may be conveyed to a cooling zone 928, where the catalyst may be cooled using any known method for cooling a solid particulate. Non-limiting examples may include heat transfer through direct contact with inert

gases or by indirect contact through heat transfer tubes in a fluidized bed. The cooled metal oxide stream 932 may then pass out of the cooling zone 928 and into the hydrogen halide neutralization zone 910 to complete the solid catalyst recycle loop. An optional metal oxide storage vessel 934 may be utilized before or after the cooling zone to store the metal oxide solid reactant prior to metering a desired amount back into the process. In an embodiment utilizing a storage vessel, the storage vessel may be capable of storing the entire amount of metal oxide in the event of a process shutdown.

In the embodiment shown in Fig. 30, both bromine generation reactor 922 and the hydrogen halide neutralization zone 910 may be adiabatic reactors. The HBr neutralization zone 910 may be a dense moving bed or a fluidized bed reactor, or a combination of both. The Bromine regeneration reactor may be either a dense moving bed reactor, a fluidized bed reactor, or a combination of both. The moving bed reactors may be configured with gas flowing upward against the flow of solids, or downward, parallel to the flow of solids. Solid flow from each reactor may be regulated by a looping seal valve, a rotary valve, or by other mechanical means. Although Fig. 30 shows a particular vertical alignment of the zone reactor, other configurations are feasible.

In another embodiment of the CFZR, an additional gas stream (not shown in FIG. 30) may also be added to the neutralization zone 910. This stream may be substantially hydrogen halide free, and may be primarily composed of light gases such as N_2 , methane and other light hydrocarbons (*e.g.*, C_2 , C_3 , and C_4). In addition it may also include water and small amounts of higher hydrocarbons (C_5+). The purpose of this stream is to reduce the temperature rise in the neutralization zone, and this stream may be either added directly to the neutralization zone, or mixed with the feed stream to the neutralization zone. This stream may be external to the system, or it may be an appropriate stream from another part of the system (*e.g.*, an appropriate gas stream in the separation sub-process). This embodiment may improve the economics of the entire process by reducing or eliminating the cooling load in cooling section of the CFZR and transferring it to the product recovery system. This may result in a process with a lower capital cost as the materials of construction used for the heat transfer surfaces in the CFZR may be significantly more expensive than those used in the product recovery system due to the presence of a hydrohalic acid. In addition, this embodiment also decreases the change in the temperature of the catalytic solids as it passes through the different zones of the CFZR, which may in turn increase the overall life of the catalytic solid.

Other embodiments may also be possible. For example, the solid catalytic reactant may remain stationary, while moving the zone from one location to the next, in a continuous loop, in the configuration of a simulated moving bed. In this embodiment, a series of control valves may

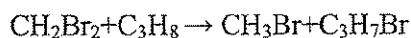
be used to sequentially direct flow from one zone to the next. This has the advantage of near continuous operation without the additional complexity of moving the solids between zones. In a similar manner, the zone reactor may be configured as rotating wheel, in which case the solids may be moved in a dense plug from one location to another in tangential movement. The gases in each zone are fed continuously, while solids are pushed from one zone to the next in a circular pathway around the wheel.

To facilitate a better understanding of the present invention, the following examples of certain aspects of some embodiments are given. In no way should the following examples be read to limit, or define, the scope of the invention.

EXAMPLE 1

Reproportionation of Dibromomethane with Propane

Methane (11 sccm, 1 atm) was combined with nitrogen (15 sccm, 1 atm) at room temperature via a mixing tee and passed through a room temperature bubbler full of bromine. The $\text{CH}_4/\text{N}_2/\text{Br}_2$ mixture was plumbed into a preheated glass tube at 500 °C, and bromination of the methane took place with a residence time (" t_{res} ") of 60 seconds, producing primarily bromomethane, dibromomethane, and HBr. The stream of nitrogen, HBr, and partially brominated hydrocarbon was combined with propane (0.75 sccm, 1 atm) in a mixing tee and passed into a second glass reactor tube at 525 °C with a residence time (" t_{res} ") of 60 s. In the second reactor tube, polybrominated hydrocarbons (*e.g.*, CH_2Br_2 , CHBr_3) react with the propane to produce bromopropanes. The reproportionation is idealized by the following reaction:



As products left the second reactor, they were collected by a series of traps containing 4 M NaOH (which neutralized the HBr) and hexadecane (containing octadecane as an internal standard) to dissolve as much of the hydrocarbon products as possible. Volatile components like methane and propane were collected in a gas bag after the HBr/hydrocarbon traps. All products were quantified by gas chromatography. The results ("Ex. 1") are summarized in Table 1. For comparison, the reactions were also run with two reactors, but without reproportionation with propane ("Control A"), and with only the first reactor and without propane ("Control B").

TABLE 1

<u>Reproportionation of Dibromomethane</u>			
	Ex. 1 (bromination/ reproportionation)	Control A (bromination)	Control B (bromination)
Bromination t_{res}	60	60	60
Reproportionation t_{res}	60	60	0
CH ₄ conversion	40%	47%	45%
CH ₃ Br/(CH ₃ Br +CH ₂ Br ₂)	93%	84%	74%
C ₃ H ₈ conversion	85%	N/A	N/A
Carbon balance	96%	97%	96%

EXAMPLE 2

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Separation of Anhydrous HBr

20 ml stock HBr aqueous solution were added to 20 g CaBr₂·H₂O followed by heating to 70 °C. A significant evolution of HBr gas was observed (determined by AgNO₃ precipitation and the NH₃ fuming test). The released HBr was not quantified as the reaction was carried out in an open vessel.

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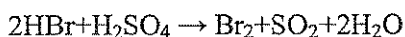
EXAMPLE 3

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Separation of Anhydrous HBr

Dehydration with H₂SO₄ was attempted by adding a concentrated solution of H₂SO₄ to HBr. Qualitative tests were conducted in which different concentration of H₂SO₄ were added to HBr for determination of the threshold concentration where oxidation of HBr no longer occurs:

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It was determined that the H_2SO_4 concentration below which no oxidation is apparent is about 70 wt. %. 30 ml 70% H_2SO_4 was added to 30 ml stock HBr azeotrope (48 wt. %) and the mixture was heated to boiling. The HBr content was determined quantitatively by AgNO_3 precipitation and gravimetric determination of AgBr from a solution aliquot at the moment of mixing, after 15 min and after 30 min boiling.

EXAMPLE 4

Metathesis of Brominated Methane Over Selected Catalysts

A series of experiments were conducted in which methane was brominated in a manner substantially the same as or similar to that described in Example 1 (10 sccm methane bubbled through room temperature bromine, followed by passage of the mixture through a reactor tube heated to 500 °C), and the bromination products were then passed over various metal-ion exchanged or impregnated zeolite catalysts, at atmospheric pressure (total pressure), at a temperature of from 350 °C to 450 °C, with a residence time of 40 seconds. Table 2 summarizes the distribution of metathesis products. Catalysts are denoted by metal ion (e.g., Ba, Co, Mn, etc.) and by type of Zeolyst Int'l. zeolite (e.g., 5524, 58, 8014, etc.). The mass (mg) of each product, as well as the total mass of products is given for each run. The abbreviations, B, PhBr, T, X, and M refer to benzene, phenyl bromide, toluene, xylene, and mesitylene, respectively.

TABLE 2

Metathesis of Brominated Methane Over Selected Catalysts							
T (C)	Catalyst	B	PhBr	T	X	M	Total (mg)
350	Ba 5524	0.25	0	0.96	2.58	3.14	6.93
350	Ba 58	0.31	0	1.48	3.2	3.11	8.11
350	Ba 8014	0.3	0	1.3	2.87	3.15	7.6
350	Ca 58	0.2	0	0.81	2.44	3.09	6.53

<u>Metathesis of Brominated Methane Over Selected Catalysts</u>							
T (C)	Catalyst	B	PhBr	T	X	M	Total (mg)
350	Co 2314	1.22	0.02	3.05	2.18	0.56	7.04
350	Co 3024	0.36	0	2.06	4.21	3.47	10.1
350	Co 58	0.2	0	1.05	2.91	3.34	7.5
350	Mg 3024	0.31	0	1.53	3.59	3.89	9.32
350	Mg 58	0.28	0	1.41	3.3	3.43	8.42
350	Mn 2314	1.07	0.03	2.86	2.26	0.65	6.86
350	Mn 3024	0.53	0	2.92	4.8	3.02	11.27
350	Mn 58	0.17	0	0.88	2.7	3.62	7.37
350	Ni 2314	1.12	0.05	2.94	2.44	0.74	7.29
350	Ni 3024	0.61	0	2.82	3.85	2.13	9.41
375	Ba 5524	0.32	0	1.32	2.82	2.57	7.04
375	Ba 58	0.4	0	1.84	2.93	2.4	7.57
375	Ba 8014	0.32	0	1.23	2.84	2.95	7.34
375	Ca 58	0.2	0	0.96	2.55	2.93	6.64
375	Co 3024	0.47	0	2.3	3.52	2.18	8.48
375	Co 58	0.3	0	1.54	2.83	2.42	7.1
375	Mg 3024	0.37	0	1.81	3.26	2.78	8.22
375	Mg 58	0.34	0	1.67	3.04	2.74	7.8
375	Mn 3024	0.62	0	2.91	3.9	2.17	9.59
375	Mn 58	0.22	0	1.18	2.71	2.83	6.94
375	Pd 2314	1.54	0	3.1	1.83	0.37	6.85
400	Ba 5524	0.46	0	2.37	4.16	2.95	9.94
400	Ba 58	0.7	0	3.15	3.91	2.7	10.47
400	Ba 8014	0.38	0	1.57	3.81	3.77	9.53

Metathesis of Brominated Methane Over Selected Catalysts							
T (C)	Catalyst	B	PhBr	T	X	M	Total (mg)
400	Ca 58	0.41	0	1.89	3.43	2.81	8.54
400	Co 3024	0.78	0	3.42	4.14	2.26	10.6
400	Co 58	0.62	0	2.71	3.36	2.31	8.99
400	Mg 3024	0.76	0	3.26	4.11	2.64	10.76
400	Mg 58	0.71	0	3.04	3.74	2.59	10.08
400	Mn 3024	0.98	0	4.1	4.38	2.06	11.52
400	Mn 58	0.48	0	2.26	3.44	2.64	8.82
400	Ni 3024	0.81	0	3.15	3.35	1.72	9.04
400	Pb 2314	1.2	0.03	3.25	3.27	1.2	8.94
400	Pb 3024	1.07	0.04	2.77	3.63	1.66	9.17
400	Pd 2314	2.44	0	3.16	1.22	0.18	7.01
400	Sr 2314	2.13	0.01	4.05	2.29	0.46	8.94
400	Sr 3024	1.93	0.05	4.03	2.67	0.65	9.32
425	Ag 3024	2.79	0.02	4.16	1.78	0.29	9.04
425	Ag 8014	3.09	0.02	3.52	1.09	0.16	7.88
425	Ba 5524	0.54	0	2.67	3.67	2.33	9.22
425	Ba 58	0.79	0	3	2.94	1.75	8.48
425	Bi 2314	3.13	0.03	4.47	1.61	0.23	9.48
425	Co 2314	3.39	0.03	4.34	1.59	0.25	9.6
425	Co 3024	1.07	0	3.42	2.79	1.09	8.38
425	Cu 2314	2.89	0.02	4.74	2.13	0.37	10.15
425	Li 5524	1.51	0.04	3.31	3.27	1.12	9.24
425	Mg 3024	0.99	0	3.28	2.85	1.37	8.48
425	Mg 58	0.81	0	2.62	2.16	1.11	6.7

<u>Metathesis of Brominated Methane Over Selected Catalysts</u>							
T (C)	Catalyst	B	PhBr	T	X	M	Total (mg)
425	Mn 3024	1.22	0	3.9	3.01	1.14	9.27
425	Mo 2314	3.06	0.04	4.02	1.46	0.24	8.82
425	Ni 3024	0.97	0	3.38	2.85	1.32	8.51
425	Sr 3024	2.53	0.02	4.36	2.22	0.43	9.56
450	Ag 3024	3.84	0.02	4.27	1.36	0.18	9.67
450	Bi 2314	3.9	0.01	3.59	0.67	0.06	8.23
450	Ca 2314	3.64	0.02	4.1	1	0.16	8.92
450	Co 2314	4.12	0.01	3.77	0.77	0.08	8.75
450	Cu 2314	3.65	0	4.3	1.1	0.14	9.19
450	Fe 2314	4.42	0.02	3.43	0.74	0.09	8.69
450	Fe 3024	3.61	0.01	2.96	0.63	0.08	7.28
450	Fe 5524	3.99	0.03	3.63	0.85	0.11	8.6
450	La 2314	3.48	0.01	3.81	0.87	0.12	8.29
450	Li 8014	1.74	0.02	2.61	2.67	0.84	7.89
450	Mg 2314	4.2	0.02	3.84	0.76	0.1	8.92
450	Mn 2314	3.78	0.02	3.9	0.88	0.12	8.7
450	Mo 2314	3.88	0.01	3.26	0.58	0.06	7.79
450	Ni 2314	4.39	0.01	3.12	0.44	0.03	8
450	Pb 2314	2.58	0.01	4.68	2.31	0.45	10.02
450	Pb 3024	2.08	0.01	4.44	2.87	0.7	10.1
450	Pb 5524	1.89	0.02	3.58	2.71	0.73	8.93
450	Pd 2314	4.03	0	1.58	0.14	0	5.76
450	Sr 2314	3.71	0	4.78	1.68	0.21	10.39
450	Sr 3024	2.51	0.01	3.76	1.61	0.26	8.14

EXAMPLE 5

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Hydrodehalogenation Of Bromobenzene, And Catalyst Regeneration

A test solution (1.5 ml/hr), which includes 1.9 wt % bromobenzene (PhBr) dissolved in dodecane, diluted by N₂ (1.1 ml/min) was fed into a tubular quartz reactor in which 3.6 g of highly dispersed precious metal catalyst (Pd/Al₂O₃, 0.5 wt %) was loaded. The reaction was carried out at 325 °C with a residence time of 15 s. The reaction effluent was trapped in a bubbler with 8 ml 4M NaOH solution pre-added. The carrier gas as well as the gaseous product were collected in a gas bag. All of the carbon-based products in the gas phase and oil phase in the liquid product were subjected to GC analysis. For the base trap solution, the HBr concentration was measured with an ion-selective electrode. Based on all of these measurements, carbon and bromine balances were calculated.

The experiment was continuously run for over 300 hours until the conversion of PhBr dropped from 100% in the initial 70 hrs to below 30% (FIG. 31). Hydrodebromination of PhBr took place over the catalyst bed with the formation of benzene ("BZ") and HBr as the major products, accompanied with some light hydrocarbons (C₃-C₇) being detected as byproducts, which originated from solvent decomposition. Carbon deposition was recognized as the primary reason for deactivation of the catalyst. The catalyst proved to be re-generable via decoking at 500 °C with O₂ oxidation (5 ml/min) for 10 hrs, followed by H₂ reduction (20 ml/min) at 400 °C for 3 hrs. The regenerated catalyst was identified to be as effective as the fresh catalyst, as confirmed by its ability to catalyze the same hydrodebromination reaction without activity loss in the first 70 hours (FIG. 32).

EXAMPLE 6

The gas flow rate inlet to the HBr absorption process is 700,000 m³/h at a temperature of 50 °C and includes HBr and hydrocarbons. The molar concentration of HBr is more than 70% of the feed mixture. The gas is fed to an absorption column that is cooled externally with liquid recirculation through a heat exchanger. The liquid inlet to the absorption column is an aqueous HBr stream also at a temperature of 50 °C and has a flowrate of 7,600,000 kg/h, with the HBr concentration of 50% by weight. The liquid outlet stream from the HBr absorption column has a flow rate of 10,800,000 Kg/h with a HBr concentration of 65% by weight. The liquid outlet is

then sent to the evaporation section where 3,200,000 kg/h of HBr is recovered by heating the liquid stream to a temperature of 120 °C. The liquid outlet from the evaporator is returned to the absorption column. Two absorption columns are required in the exemplary embodiment, each with a diameter of 8 meters and a height of 8 meters. Packing material can be used in the column to improve the absorption process.

EXAMPLE 7

The gas flow rate inlet to the HBr absorption process is 700,000 m³/h at a temperature of 100 °C and includes HBr and hydrocarbons. The molar concentration of HBr is more than 70% of the HBr and hydrocarbons feed mixture. A distillation scheme is used to separate HBr from hydrocarbons. The distillation system operates at a pressure between 10 atm and 30 atm. A first distillation column separates methane and C₂ from the rest of the components and requires 24 theoretical stages. The condenser duty for this column is 310 MMkcal/h and the condenser temperature is -35 °C. The reboiler duty is 112 MMkcal/h and the reboiler temperature is -7 °C. A second distillation column separates methane from C₂ and HBr. The bottoms stream consists of C₂ with a small amount of HBr. This column requires 18 theoretical stages. The third distillation column separates HBr from other components heavier than HBr. The distillate is HBr with more than 99% purity. This column requires 37 theoretical stages. The condenser duty for the column is 290 MMkcal/h and the condenser temperature is -9 °C. The reboiler duty is 440 MMkcal/h and the reboiler temperature is -36 °C. The fourth distillation column separates light gases from the rest of the components and requires 10 theoretical stages. The condenser duty for this column is 30 MMkcal/h and the condenser temperature is -28 °C. The reboiler duty is 65 MMkcal/h and the reboiler temperature is 233 °C.

EXAMPLE 8

The gas outlet from the coupling reactor has HBr weight fraction of 72%. This stream is cooled down to 29 °C, and vapor-liquid flash separation is used to remove heavy hydrocarbons. The vapor outlet from the flash is at a pressure of 3 atm and a flow rate of 26870 m³/hr. The aq. HBr inlet to the absorption column has 52% HBr by weight and a flow rate of 339512 kg/hr. The concentrated HBr at the bottom of the absorption column has 65% HBr by weight and a flow rate of 471950 kg/hr. Eight stages are required for the absorption column. The concentrated HBr stream is sent to a stripper where the column with six stages operates at a pressure of 15 atm.

The reboiler temperature is 187 °C. Dehydrated HBr leaves the top of the stripping column with 99% HBr by weight with 1% water by weight and the bottoms stream of the stripper consists of Aq. HBr with 52% HBr by weight and is returned back to the absorption column.

5

EXAMPLE 9

Bromine Recovery Using Chilled Brine

The test setup consisted of three test vessels that were connected in series. The first contained liquid bromine at 15 °C and atmospheric pressure. The second contained a brine solution consisting of 100 ml of 24.7% by weight NaCl in water. The third vessel contained 30 ml of 4 M NaOH as a bromine trap to capture any bromine passing through the chilled brine vessel. A nitrogen carrier stream was introduced into the bottom of the bromine vessel at 10 sccm and allowed to bubble through the liquid bromine. The bromine partial pressure at this temperature was 0.18 atm. The nitrogen and bromine then passed in series to the bottom of the chilled brine and sodium hydroxide solutions in order to ensure proper gas to liquid contact.

Three tests were conducted using the test setup. The first test was conducted using a chilled brine at a temperature of -5 °C with a bromine flow for 3 hours. The second test used a chilled brine at -10 °C and was conducted for 2.5 hours. The results of the first two absorption tests are shown in Table 3. The last test measured the absorption characteristics of the system over time. This test measured the absorption amounts at six times over a 12 hour absorption run. The results of the 12 hour absorption test are shown in Table 4a. Bromine breakthrough to the NaOH trap increases with time on stream as shown in Table 4b. This is a result of saturating the brine solution with bromine, thereby, reducing the capture capacity of the chilled brine.

25

Table 3

Br₂ Recovery Using Chilled Brine

	Br ₂ Absorbed (g/hr-L)	Br ₂ Distribution (%)
Brine at -5 °C (Trapping for 3 hr)		
Brine	7.6	95.1
NaOH	0.4	4.9
Br Balance (%)		94.5

Brine at -10 °C (Trapping for 2.5 hr)		
Brine	7.9	98.5
NaOH	0.1	1.5
Br Balance (%)		92.2

Table 4a

Average Br₂ Recovery Using Chilled Brine

	Br ₂ Absorbed (g/hr-L)	Br ₂ Distribution (%)
Brine at -5 °C (Trapping for 12 hr)		
Brine	7.8	88.1
NaOH	1.1	11.9
Br Balance (%)		101.3

5

Table 4b

Time Dependence of Bromine Breakthrough in Base Trap

Time	Bromine breakthrough Percentage in base Trap
0-2	2.5
2-4	7.5
4-6	9.3
6-8	13.9
8-10	19.6
10-12	19.6

EXAMPLE 10

In this example, 0.5 g SeO_2 was loaded into two bubbler containers. A 3.06 ml 48 wt. % aqueous HBr solution (2.187 g HBr, 4.56 g soln.) was added in the first container, and a 4.08 ml of the same solution (2.917 g HBr, 6.08 g soln.) was added in the second container at room temperature. The samples were submerged in a preheated oil bath at 100 °C. A 3 ml/min. oxygen stream was passed over the containers with the gas leaving the containers passed through 15 ml 4 M NaOH solution that captured all bromine vapors. The NaOH traps were changed every hour and the bromine content was determined by iodometric titration with standard 0.1000 M $\text{Na}_2\text{S}_2\text{O}_3$. The results are shown in Table 5 below.

10

TABLE 5

Time, h	Sample 1	Sample 2	mol Br/hour(1)	mol Br/hour(2)	mmol $\text{Br}_2/\text{ml} \cdot \text{min}(1)$	mmol $\text{Br}_2/\text{ml} \cdot \text{min}(2)$
1	7.6	6.97	0.00076	0.000697	0.002069717	0.001424
2	7.82	5.4	0.000782	0.00054	0.00212963	0.001103
3	4.35	2.78	0.000435	0.000278	0.001184641	0.000568
4	3.92	7	0.000392	0.0007	0.001067538	0.00143
5	4.3	5.5	0.00043	0.00055	0.001171024	0.001123
6	3.28	4.58	0.000328	0.000458	0.000893246	0.000935
7	3.7	5.09	0.00037	0.000509	0.001007625	0.00104

15

EXAMPLE 11

In this example, 1 g SeO_2 was loaded into two bubbler containers. A 3.06 ml, 62 wt. % aqueous HBr solution was added to the first one (2.915.6 g HBr, 4.7 g soln.), and 3.67 ml of the same solution to the second one (3.645 g HBr, 5.88 g soln.) at room temperature. The samples were submerged in a preheated oil bath at 100 °C. A 3 ml/min. oxygen stream was passed over

the containers with the gas leaving the containers passed through 15 ml 4 M NaOH solution that captured all bromine vapors. The NaOH traps were changed every hour and the bromine content was determined by iodometric titration with standard 0.1000 M Na₂S₂O₃. The results are shown in Table 6 below.

5

TABLE 6

Time, h	Sample 1	Sample 2	mol	mol	mmol	mmol
			Br/hour(1)	Br/hour(2)	Br ₂ /ml*min(1)	Br ₂ /ml*min(2)
1	16.8	20	0.00168	0.002	0.004667	0.004505
2	16.24	17.58	0.001624	0.001758	0.004511	0.003959
3	12.65	15	0.001265	0.0015	0.003514	0.003378
5	15.89	16.7	0.001589	0.00167	0.004414	0.003761

EXAMPLE 12

10 In this example, 1 g SeO₂ was loaded into two bubbler containers. A 5.12 ml, 68 wt. % aqueous HBr solution was added to the first one (5.83 g HBr, 8.81 g soln.), and 7.16 ml of the same solution to the second one (7.29 g HBr, 12.60 g soln.) at room temperature. The samples were submerged in preheated oil bath at 100 °C. A 3 ml/min. oxygen stream was passed over the containers with the gas leaving the containers passed through 15 ml 4 M NaOH solution that
15 captured all bromine vapors. The NaOH traps were changed every hour and the bromine content determined by iodometric titration with standard 0.1000 M Na₂S₂O₃. The results are shown in Table 7 below.

TABLE 7

Time, h	Sample 1	Sample 2	mol Br/hour(1)	mol Br/hour(2)	mmol Br ₂ /ml*min(1)	mmol Br ₂ /ml*min(2)
1	45.6	53.63	0.00456	0.005363	0.0076	0.006242
2	28.05	55.9	0.002805	0.00559	0.004675	0.006506
3	16.13	33.2	0.001613	0.00332	0.002688	0.003864
4	15.2	22.31	0.00152	0.002231	0.002533	0.002597

EXAMPLE 13

In this example, 1 g SeO₂ was loaded in a bubbler container. A 5 ml, 68 wt. % aqueous HI solution was added to the bubbler container (5.83 g HI, 8.81 g soln.) at room temperature. The sample was submerged in preheated oil bath at 100 °C. A 3 ml/min. oxygen stream was passed over the container with the gas leaving the container passed through 15 ml 4 M NaOH solution that captured all iodine vapors. The NaOH traps were changed every hour and the iodine content determined by titration with standard 0.1000 M Na₂S₂O₃.

EXAMPLE 14

In this example, three samples of 20 grams of H-exchanged zeolite was refluxed at 100 °C with 300 mL 0.1 M, 1 M and saturated H₂C₂O₄ (~ 1.15 M) correspondingly for 2 hours. The zeolite was filtered, washed and dried slowly. The resulted ZSM-5 modified materials were exchanged with 0.1 M Mn(NO₃)₂ for at least eight hours, filtered, washed and dried. The three samples were tested for coupling of methyl bromide at 425 °C with a residence time of 3 seconds. The data is summarized in Table 8 shown below.

TABLE 8

Catalyst	Benzene/BTX, %	BTX, %	Coke, %	C-Bal. [H ₂ C ₂ O ₄], %	[H ₂ C ₂ O ₄], mol/l.
----------	----------------	--------	---------	---	---

Mn3024_0	19.1	39.4	5.4	97.9	N/A
De-Al					
Mn3024_1	25.5	42.4	5.4	94.7	0.1
De-Al					
Mn3024_2	26.7	41.5	5.2	94.6	1.0
De-Al					
Mn3024_3	30.8	40.8	6.5	93.6	1.15

EXAMPLE 15

In this example, the effect of water vapors on the catalytic conversion of methyl bromide
 5 conversion to BTX products using conditions typical for a BTX process (425 °C, 0.5 atm. methyl
 bromide partial pressure, 5 s residence time) were examined. The results are summarized below
 in Table 9, showing the trend of the coke generated as a function of water added. It is important
 to note that the products distribution is relatively unchanged by the water addition to the reaction
 mixture .

10

TABLE 9

T Bubbler (°C)	None	0	10	19	36	58
% H ₂ O	0.0	0.3	0.6	1.0	2.9	8.3
% C Bal	100	98.2	103.4	100.1	107.5	105.9
% MeBr Conv.	99.0	99.3	99.4	99.2	99.3	99.2
% Coke	7.4	6.7	5.5	6.3	4.8	4.5
% BTX	35.8	36.6	34.8	34.3	32.8	32.2
% B/BTX	19.6	21.3	20.8	19.0	18.4	16.1
% C2-C6	41.5	42.3	45.3	45.1	49.8	50.4
% MDN+	13.5	13.2	13.4	13.0	11.4	11.5

15

EXAMPLE 16

In this example, a modified ZSM-5 catalyst was used to produce mesitylene from methylbromide. 1.0 gram of 7% CuO/0.5% ZnO impregnated ZSM-5 catalyst was loaded into a test cell with operating conditions as follows: a reaction temperature of 400°C, a reaction time of 1 hour, a residence time of 0.8 sec, a flow rate of MeBr vapor of 12.28 sccm, and a total gas flow rate of 25 sccm. The main aromatic products were mesitylene, 49.3 wt%, and xylene, 23.1 wt%. Benzene production was suppressed: 2.5 wt%.

EXAMPLE 17

Catalyst Preparation of SAPO-34 based Catalysts

A solution of 12.6g of 85% phosphoric acid, 1.6g of 37% HCl and 20.3 g of de-ionized water was added to 27.2 of aluminum isopropoxide in a PE bottle. The bottle was shaken for 1 min, after which 4.0 g of Ludox SM-30 (manufacturer) colloidal silica was added, and the bottle was shaken again for 1 min. Then 56.2 g 35% TEAOH (tetraethylamine hydroxide) and 9.1g water were added and the bottle was shaken for 1 min. The mixture was then transferred to a Teflon- lined autoclave, and left for 48 h under constant agitation at room temperature. The composition of the resulting gel, expressed in terms of the molar ratios, was TEAOH : Al₂O₃ : 0.89 P₂O₅ : 0.3 SiO₂ : 0.2 HCl : 64H₂O. The temperature was then increased to 215°C, and the mixture was heated for 100 h at this temperature. After washing the precipitate with de-ionized water followed by drying at 120°C and calcination at 600°C for 6 h, a powder sample was obtained. The pure SAPO-34 phase (CHA) was identified from XRD measurements. Partial framework substitution with metals such as Co, Ni, Fe, Mn or Ga was conducted by mixing the individual nitrate salt into the starting mixture solution with a molar ratio of metal/Al₂O₃ ~ 0.02.

EXAMPLE 18

Catalyst Preparation of ZSM-5 based catalysts

Commercially available HZSM-5 materials with different SiO₂/Al₂O₃ ratios purchased from ZEOLYST International were used as the initial materials in this work. A representative example is CBV 8014, abbreviated here as 8014. 8014 is an H-exchanged type ZSM-5 with a SiO₂ / Al₂O₃ ratio of 80. The materials were modified by loading various metals via wet impregnation starting from their salt solutions. The doped or exchanged metals involves Mg, Ca,

Sr, Ba, K, Ag, P, La, or Zn and the loading amounts varied in the range of 0.1 to 10% by weight. The metal doped catalysts were further activated by calcination in the temperature range of 500 to 800°C for 6 h prior to use. XRD patterns for the initial material and the ones with metal doped were obtained to verify the compositions. The loading of Mg or Ca slightly affected the peak strengths but did not change the zeolite structures.

EXAMPLES 19

Some non ZSM-5 and non SAPO-34 materials such as ferrierite structure zeolite and a aluminophosphate (AlPO-5) can also be applied in the conversion of CH₃Br to light olefin. These materials are either commercial available or were synthesized in our lab. AlPO-5 was synthesized following the procedure described in IZA website with small modifications. The synthesis procedure is as follows.

- (1) Mix 7g water with 3.84 g 85% phosphoric acid
- (2) Add 2.07 g triethylamine (TEA) drop wise to (1)
- (3) Add 5.23g aluminum isopropoxide to (2) in small amounts at 0°C with intense stirring then stir the mixture at room temperature for 2 h
- (4) Add 0.83g 40% HF (in water) and 89.2 g water to (3), stir for 2 h
- (5) Hydrothermal synthesis at 180°C (preheated oven) for 23 h
- (6) Wash the precipitate with DI water
- (7) Dry the precipitate at 120°C for 10 h
- (8) Calcine the powder at 600°C for 6 h

The XRD measurement confirmed that a pure AFI phase that belongs to AlPO-5 was obtained.

EXAMPLE 20

High Ethylene Mode

High light olefin yields as well as high ethylene/propylene ratios can be achieved by using narrow pore zeolite materials and conducting the reactions at elevated temperature. Two typical results were obtained over SAPO-34 or CoSAPO-34 at 500°C with 2.0 sec residence time and 0.2 atm. partial pressure of CH₃Br. The CH₃Br conversion, combined C₂+C₃ yield (C base), combined ethylene + propylene yield (C base) and ethylene/propylene (weight ratio.) reached

91.4%, 61.9%, 58.7% and 1.7 for SAPO-34 with 8.1% coke formation (C base) and 97.9%, 65.6%, 60.2%, 1.7 for CoSAPO-34 with 11.7% coke.

A typical product selectivity and C mole yield for different products obtained from SAPO-34 at 500 °C, 0.2 sec and 0.2 atm CH₃Br are shown in Table 10.

5

TABLE 10
CH₃Br Coupling over SAPO-34 at 500°C, 0.2 sec and 0.2 atm CH₃Br

Catalyst, SAPO-34			
Condition, 500°C, 0.2sec, 0.2 atm CH ₃ Br			
C mol Selectivity, %		C mol Breakdown, %	
CH ₄	8.2		
C ₂ H ₄	40.2		
C ₂ H ₆	1.0		
C ₃ H ₆	24.1	C ₂ ⁼ + C ₃ ⁼	58.7
C ₃ H ₈	2.4	other C ₁ -C ₆	16.5
C ₄₋₆	6.5	BTXM+	3.4
BTXM+	3.7	CH ₃ Br	8.6
RBr	5.1	RBr	4.7
Coke	8.9	coke	8.1
CH ₃ Br conversion, %		91.4	
C ₂ ⁼ /C ₃ ⁼ (wt)		1.67	
C Balance, %		100.3	

10

EXAMPLE 20

High Propylene Mode

High combined light olefin yield and high propylene selectivity was obtained from ZSM-5 based catalyst at relative lower temperature, 400 °C and short residence time, <1 sec. The

catalysts modified by loading alkaline earth metals (*e.g.* Mg, Ca, Sr or Ba) show excellent performance.

Using a ZSM-5 based catalyst with 5% Mg loading, 5%Mg/8014-750, 98.3% CH₃Br conversion, 54.3% LO yield with ethylene/propylene weight ratio 0.10 were achieved at 400°C with 0.5 sec residence time and 0.1 atm CH₃Br. Much lower coke formation (0.6%) was measured compared with SAPO-34 based materials. The catalyst also showed excellent reproducibility during the test of over 20 cycles. The product selectivity and C mole yield for different products obtained using this catalyst are shown in Table 11.

10

Table 11

CH₃Br Coupling over 5%Mg/8014-750 at 400°C, 0.5 sec and 0.1 atm. CH₃Br

Catalyst, 5%Mg/8014-750			
Condition, 400°C, 0.5sec, 0.1 atm CH ₃ Br			
C mol Selectivity, %		C mol Breakdown, %	
CH ₄	0.0		
C ₂ H ₄	4.8		
C ₂ H ₆	0.0		
C ₃ H ₆	50.5	C ₂ ⁼ + C ₃ ⁼	54.3
C ₃ H ₈	0.0	other C ₁ -C ₆	16.5
C ₄₋₆	29.3	BTXM+	3.4
BTXM+	7.7	CH ₃ Br	1.8
RBr	6.9	RBr	6.8
Coke	0.6	coke	0.6
CH ₃ Br conversion, %	98.3		
C ₂ ⁼ /C ₃ ⁼ (wt)	0.1		
C Balance, %	92.1		

EXAMPLE 21

Moderate ethylene mode

High light olefin yield, >50%, flexible ethylene and propylene fractions (ethylene/propylene weight ratio, 0.3 to 1.3) can be achieved either by using SAPO-34 and ZSM-5 based catalysts independently at a wide temperature condition or by using the two types of materials sequentially. Initially, the feed was allowed to contact SAPO-34, where high ethylene/propylene ratio and incomplete CH₃Br conversion (70 - 80%) were achieved, and then let the product gasses pass through the second catalyst bed where highly active ZSM-5 based catalyst was loaded, which substantially consumed all unconverted CH₃Br and produce more propylene than ethylene as a compromise. As a results, a high CH₃Br conversion and acceptable ethylene/propylene fraction can be achieved from this mixed catalyst system. It is expected that this combinational method still has large room for further improvement through optimizing the conditions for the two catalyst beds.

From a sequential mixed catalyst system SAPO-34 B + 5%Sr/8014-750, the CH₃Br conversion, light olefin yield and ethylene/propylene ratios reached 93.3%, 51.7% and 0.7 respectively at 475°C, with 2.1 sec residence time (2.0 sec over SAPO 34-B and 0.1sec over 5%Sr/8014-750) and 0.2 atm CH₃Br.

One typical result obtained from SAPO-34 B + 5%Sr/ZSM-5 are shown in Table 12.

Table 12

CH₃Br Coupling over SAPO-34B + 5%Sr/8014-750 at 475°C, 2.1 sec and 0.2 atm. CH₃Br

Catalyst, SAPO-34B + 5%Sr/8014-750			
Condition, 475°C, 2.1sec, 0.2 atm CH ₃ Br			
C mol Selectivity, %		C mol Breakdown, %	
CH ₄	7.3		
C ₂ H ₄	22.8		
C ₂ H ₆	0.7		
C ₃ H ₆	32.1	C ₂ = + C ₃ =	51.3
C ₃ H ₈	3.0	other C ₁ -C ₆	20.4

C ₄₋₆	10.7	BTXM+	8.6
BTXM+	9.2	CH ₃ Br	6.6
RBr	6.3	RBr	5.9
Coke	7.8	coke	7.3
CH ₃ Br conversion, %	93.3		
C ₂ ⁼ /C ₃ ⁼ (wt)	0.71		
C Balance, %	100.9		

Table 13 summarizes more results on the three operation modes.

5

Table 13

Summary of the Results for Three Modes of Operation: (1) High ethylene, (2) High Propylene, and (3) Moderate Ethylene

Mode	Catalyst	Temp/ C	(sec) [†]	PCH ₃ Br	Conv. %	LO Yield, %	C ₂ ⁼ /C ₃ ⁼ (wt)	Coke, %	C-Balance, %
High C ₂ ⁼	SAPO-34	500	2.0	0.2	91.4	58.7	1.7	8.1	100.3
	CoSAPO-34	500	2.0	0.2	97.9	60.2	1.7	11.7	100.4
High C ₃ ⁼	5%Mg/ZSM-5	400	0.5	0.1	98.3	54.2	0.1	0.6	95.6
Moderate C ₂ ⁼	SAPO-34	475	2.0	0.2	88.1	54.2	1.3	7.6	99.9
	Co-SAPO-34	450	2.0	0.2	96.2	50.6	1.0	10.8	98.3
	CoSAPO-34	475	2.0	0.2	96.8	58.4	1.3	9.9	99.8
	Mixed	475	2.1	0.2	93.3	51.7	0.7	7.3	100.9
	Catalyst*								

10 * SAPO-34-B + 5%Sr/8014-750 (1.55g + 0.1g)

EXAMPLE 22

Ferrierite

A non ZSM-5, non-SAPO-34 materials, with 2-dimensional and 10-ring ferrierite structure was tested under the conditions for coupling reactions. A commercial available ferrierite, CP914 (Zeolyst) with SiO₂/Al₂O₃ ratio of 55 was tested at 475°C, 0.2 atm CH₃Br with a residence time 15 of 1.0 sec. The catalyst exhibited moderate activity towards the reaction and moderate ethylene selectivity. The CH₃Br conversion, light olefin yield and ethylene/propylene ratio reached 49.8%, 14.8% and 0.89% respectively. The results are shown in Table 14.

10

Table 14

CH₃Br Coupling over Ferrierite at 475°C, 1.0 sec and 0.2 atm. CH₃Br

Catalyst, ferrierite (CP914)			
Condition, 475°C, 1.0sec, 0.2 atm CH ₃ Br			
C mol Selectivity, %		C mol Breakdown, %	
CH ₄	10.9		
C ₂ H ₄	13.9		
C ₂ H ₆	1.1		
C ₃ H ₆	15.8	C ₂ ⁼ + C ₃ ⁼	14.8
C ₃ H ₈	3.4	other C ₁ -C ₆	18.0
C ₄₋₆	20.7	BTXM+	3.9
BTXM+	7.9	CH ₃ Br	50.2
RBr	14.9	RBr	7.4
Coke	11.4	coke	5.7
CH ₃ Br conversion, %		49.8	
C ₂ ⁼ /C ₃ ⁼ (wt)		0.89	

C Balance, % 99.9

EXAMPLE 23

AlPO-5

5 Another non-ZSM-5 and non-SAPO-34 type zeolite, AlPO-5 was synthesized in the lab following a procedure described on IZA website. XRD measurement confirmed the existence of one dimensional AFI structure in our sample. The coupling reaction was conducted at 400°C, 0.2 atm CH₃Br with a residence time of 2 sec. The catalyst gave 8.8% CH₃Br conversion with light olefin yield of 1.2% and ethylene/propylene weight ratio of 0.62. The results are shown in
10 Table 15.

Table 15

CH₃Br Coupling over AlPO-5 at 400°C, 2.0 sec and 0.2 atm CH₃Br

Catalyst, C-H-5			
Condition, 400°C, 2sec, 0.2 atm CH ₃ Br			
C mol Selectivity, %		C mol Breakdown, %	
CH ₄	13.7		
C ₂ H ₄	7.9		
C ₂ H ₆	0.0		
C ₃ H ₆	12.8	C ₂ = + C ₃ =	1.2
C ₃ H ₈	0.0	other C ₁ -C ₆	1.1
C ₄₋₆	5.9	BTXM+	0.9
BTXM+	15.4	CH ₃ Br	94.3
RBr	1.2	RBr	0.1

Coke	43.0	coke	2.5
CH ₃ Br conversion, %		8.8	
C ₂ [≡] /C ₃ [≡] (wt)		0.62	
C Balance, %		96.8	

EXAMPLE 24

Effect of Reaction Temperature over SAPO-34

- 5 The coupling of bromomethane was conducted over SAPO-34 in a temperature range from 400 to 500 °C. It was found that high temperature favors the formation of ethylene and propylene. It was observed that increasing the reaction temperature significantly enhanced CH₃Br conversion, light olefin yield and the ethylene/propylene weight ratio. Coke amount also increased from 4.0% at 400°C to 8.1% at 500°C. At the temperature higher than 475 °C, CH₃Br
- 10 conversion exceeded 88%, light olefin yield reached 55% or higher and the ethylene/propylene weight ratios were higher than 1. Examining the product selectivity, it was found that high temperature may promote C₄ decomposition, suppresses C₃H₈ and RBr formation and as a result, produces more ethylene and methane while with less C₄ product formation. The results are shown in FIG 33 and Table 16.

15

Table 16

Effect of Reaction Temperature on Product Selectivity over SAPO-34

Catalyst, SAPO-34					
Condition, 2.0sec, 0.2 atm CH ₃ Br					
C mol Selectivity, %					
	400°C	425°C	450°C	475°C	500°C
CH ₄	1.3	2.1	3.2	4.8	8.2
C ₂ H ₄	19.4	24.3	29.7	34.4	40.2

C ₂ H ₆	0.3	0.4	0.6	0.8	1.0
C ₃ H ₆	39.3	35.9	32.5	27.1	24.1
C ₃ H ₈	7.0	5.2	4.8	3.6	2.4
C ₄₋₆	14.0	13.3	10.4	9.6	6.5
BTXM+	2.8	4.4	3.7	3.1	3.7
RBr	8.9	9.1	9.2	7.9	5.1
Coke	7.0	5.3	5.9	8.6	8.9

EXAMPLE 25

Catalyst stability and reproducibility

5 The stability of the catalyst system for at least 10 cycles including reactions has been demonstrated with SAPO-34 catalyst. Reactions were run at 475 °C with 0.2 sec residence time and 0.2 atm. partial pressure CH₃Br. Catalyst regeneration (decoking) was done at 500°C overnight with 5 sccm air. The catalyst showed excellent stability and reproducibility in terms of CH₃Br conversions, light olefin yields, ethylene/propylene ratios, coke amounts etc. The results, as a function of cycle number, are displayed in FIG. 34. No noticeable catalyst decay was observed under these conditions and no structure changes were observed in XRD measurements.

EXAMPLE 26

15 Effect of Residence Time on Product Distribution over 5%Mg/8014

Using the catalyst of 5%Mg/8014 we investigated the effect of residence time by changing the residence time from 0.1 sec to 5 sec. The data, displayed in FIG. 35 show that short residence time (<1 sec) favors the formation of light olefin while longer residence time lead to more BTX and light alkanes (propane and butanes), which contribute to the major component of "other C₁ - C₆".

EXAMPLE 27

Methanol to Light Olefin Comparison

Methanol coupling to light olefin (MTO) experiments were also conducted with two GRT catalysts, 5%Mg/8014, and 5%Ca/8014 and a commercially available MTO catalyst (Grace Davison olefin Oultra). Reactions were run at 400°C, 0.1 atm. partial pressure MeOH and a residence time of 0.5 sec. The results are summarized in Table 17. The GRT catalysts have higher combined ethylene+propylene yield.

Table 17

Comparison of GRT catalysts and Grace Davison C.A.O.C for Conversion of MeOH to Light Olefins at 400 °C, 0.1 atm. MeOH and 0.5sec

Catalyst	Utilization	$C_2 = + C_3 =$	$C_2 = / C_2$	$C_3 = / C_3$
5%Mg/8014	93%	47% (7/40)	100%	97%
5%Ca/8014	87%	51% (3/48)	100%	100%
Olefin Oultra	95%	37% (12/25)	100%	85%

EXAMPLE 28

In order to demonstrate the above expected results, a lab scale setup was used for bromination reaction. Typical bromination reaction conditions of about 500 °C, 60 sec residence time, 70 % CH₄ conversion, 1.5 sccm O₂ was run for about 2 hours. The product gasses passed through the Ba(OH)₂ solution to precipitate CO₂ generated during bromination. After the first reaction cycle, the inlet portion of the reactor appears clean, while the portion disposed downstream of the NiBr₂ bed appears to have accumulated coke. The coke deposited downstream of NiBr₂ was decoked in the second cycle by switching feed directions. Here the coke from the bottom portion (the downstream portion in the first run) was collected after removal of the NiBr₂ from the reactor. The measurements of the amount of coke are shown in

FIG. 36. The results indicate that most of the coke oxidized in the first cycle during bromination. The total coke measured in this configuration appears to be greater than an empty tube bromination (based case), which may be due to CH_2Br_2 conversion into CO_2 during bromination in the presence of oxygen.

5 The invention has been described with references to various examples and preferred embodiments, but is not limited thereto. Other modifications and equivalent arrangements, apparent to a skilled person upon consideration of this disclosure, are also included within the scope of the invention. With reference to FIG. 1 and FIG. 2, in an alternate embodiment of the invention, the products 25 from the bromine generation reactor are fed directly into the
10 bromination reactor 3. The advantage of such a configuration is in eliminating the bromine holdup needed in the flash unit 27, thereby reducing the handling of liquid bromine. Also, by eliminating the bromine scavenging section including units 26, 27, 31 and 34, the capital cost for the process can be reduced significantly. For energy efficiency, it is desirable to have the outlet of bromine generation be equal to the bromination temperature. For bromine generation, cerium-
15 based catalysts are therefore preferred over copper-based catalysts in this embodiment, since cerium bromide has a higher melting point (722 °C) than copper (I) bromide (504 °C). The presence of oxygen in bromination and coupling reduces the selectivity to the desired products; therefore, the bromine generation reactor must consume all of the oxygen in the feed. In this embodiment, the monobromide separation 5 must be modified to remove water using a liquid-
20 liquid split on the bottoms stream of the distillation column 51. The water removed in the liquid-liquid split contains HBr , which can be removed from water using extractive distillation (see, *e.g.*, FIG. 9), and then recycled back to the bromine generation section.

Therefore, the present invention is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed
25 above are illustrative only, as the present invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered or modified and all such variations are
30 considered within the scope and spirit of the present invention. While compositions and methods are described in terms of "comprising," "containing," or "including" various components or steps, the compositions and methods can also "consist essentially of" or "consist of" the various components and steps. All numbers and ranges disclosed above may vary by some amount. Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and
35 any included range falling within the range is specifically disclosed. In particular, every range of

values (of the form, "from about a to about b," or, equivalently, "from approximately a to b," or, equivalently, "from approximately a-b") disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the

5 patentee. Moreover, the indefinite articles "a" or "an", as used in the claims, are defined herein to mean one or more than one of the element that it introduces. If there is any conflict in the usages of a word or term in this specification and one or more patent or other documents that may be incorporated herein by reference, the definitions that are consistent with this specification should be adopted.

What is claimed is:

1. A method comprising:

providing a first halogen stream;

providing a first alkane stream;

5 reacting at least a portion of the first halogen stream with at least a portion of the first alkane stream in a first reaction vessel to form a first halogenated stream;

providing a second alkane stream comprising C₂ and higher hydrocarbons;

providing a second halogen stream; and

10 reacting at least a portion of the second halogen stream with at least a portion of the second alkane stream in a second reaction vessel to form a second halogenated stream.

2. The method of claim 1 wherein the first halogenated stream, the second halogenated stream, or both comprise alkyl monohalides and alkyl polyhalides and further comprising reacting at least a portion of the alkyl polyhalides with an additional alkane stream to create at least some additional alkyl monohalides.

15 3. The method of claim 1 further comprising:

contacting at least a portion of the first halogenated stream, the second halogenated stream, or both with a catalyst to form a product stream that comprises higher hydrocarbons and hydrogen halide.

4. The method of claim 3 further comprising:

20 separating the hydrogen halide from the product stream; and

reacting the hydrogen halide with a source of oxygen to regenerate a halogen stream.

5. The method of claim 1 where the first reaction vessel, the second reaction vessel, or both comprise a halogenation catalyst.

25 6. The method of claim 5 wherein the halogenation catalyst comprises at least one catalyst selected from the group consisting of: a zeolite, an amorphous alumino-silicate, an acidic

zirconia, a tungstate, a solid phosphoric acid, a metal oxide, a mixed metal oxide, a metal halide, and a mixed metal halide.

7. A method comprising:

providing a halogen stream;

5 providing a first alkane stream;

reacting at least a portion of the halogen stream with at least a portion of the first alkane stream to form a halogenated stream, wherein the halogenated stream comprises alkyl monohalides, alkyl polyhalides, and hydrogen halide; and

10 contacting at least some of the alkyl monohalides with a coupling catalyst to form a product stream that comprises higher hydrocarbons and hydrogen halide.

8. The method of claim 7 further comprising:

providing a second alkane stream;

reacting at least a portion of the second alkane stream with at least a portion of the higher alkyl halides to create at least some additional alkyl monohalides; and

15 contacting at least some of the additional alkyl monohalides with the catalyst to form at least some higher hydrocarbons and hydrogen halide.

9. The method of claim 7 further comprising:

separating the hydrogen halide from the product stream; and

20 reacting the hydrogen halide with a source of oxygen to regenerate the halogen stream.

10. The method of claim 7 wherein the coupling catalyst comprises a reduced aluminum content ZSM-5 zeolite.

11. The method of claim 10 further comprising forming the reduced aluminum content ZSM-5 zeolite by contacting a zeolite with a dealumination agent, wherein the
25 dealumination agent comprises at least one material selected from the group consisting of: a mineral acid, hydrochloric acid, hydrofluoric acid, a chelating agent, ethylenediaminetetraacetic

acid, oxalic acid, malonic acid; steam, an exchange reagent, SiCl_4 , $\text{NH}_4[\text{SiF}_6]$, NH_4HF_2 , AlF_3 , a trialkyl phosphates, an organic phosphites, and a combination thereof.

12. The method of claim 7 wherein the catalyst comprises a plurality of catalytic materials wherein each catalytic material is disposed in a different reaction vessel.

5 13. The method of claim 8 wherein the higher hydrocarbons comprise light olefins.

14. The method of claim 13 wherein the catalyst comprises at least one material selected from the group consisting of: a crystalline silico-alumino-phosphate; an alumino silicate; SAPO-34; a silico-alumino-phosphate substituted with Co, Ni, Mn, Ga, or Fe; a ZSM-5, a ZSM doped with Mg, Ca, Sr, Ba, K, Ag, P, La, or Zn; erionite; ferrierite; ALPO-5; MAPO-36;
10 ZSM-12; ZSM-57; ZSM-23; ZSM-22; MCM-22; and a combination thereof.

15. The method of claim 7 wherein the catalyst comprises a ZSM-5 catalyst modified with mixture comprising copper oxide and zinc oxide, wherein the higher hydrocarbons comprise mesitylene.

16. The method of claim 7 further comprising:
15 providing a Lewis base molecule; and
contacting the Lewis base molecule with the catalyst contemporaneously with the contacting of at least some of the alkyl monohalides with the coupling catalyst to form the product stream.

17. The method of claim 16 wherein the Lewis base molecule is present in an amount
20 less than about 15% by weight of the total feed to the coupling catalyst.

18. A method comprising:
providing an alkyl halide stream;
contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide;
25 contacting the product stream with an aqueous solution comprising a metal halide to remove at least a portion of the hydrogen halide from the product stream;
separating at least some of the metal halide from the aqueous solution; and

heating the separated metal halide to generate a corresponding halogen.

19. The method of claim 18 wherein the metal halide comprises a metal with multiple stable oxidation states.

20. The method of claim 18 wherein the metal halide comprises CuBr or CuBr₂.

5 21. The method of claim 18 wherein the separating the metal halide from the aqueous solution comprises at least one process selected from the group consisting of: crystallization, evaporation, evaporative crystallization, filtration, and centrifugation.

22. The method of claim 18 wherein the metal halide is separated from the aqueous solution at a temperature below about 200 °C.

10 23. The method of claim 18 wherein the separated metal halide is heated to a temperature above about 275 °C.

24. The method of claim 18 further comprising:

combining the heated metal halide with an aqueous solution to form the aqueous solution comprising a metal halide.

15 25. The method of claim 18 further comprising:

providing an alkane stream; and

contacting the alkane stream and the corresponding halogen to generate the alkyl halide stream.

26. A method comprising:

20 providing an alkyl halide stream;

contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide;

contacting the product stream with a solid reactant to remove at least a portion of the hydrogen halide from the product stream; and

25 reacting the solid reactant with a source of oxygen to generate a corresponding halogen.

27. The method of claim 26 wherein contacting the product stream with a solid reactant and reacting the solid reactant with a source of oxygen occur at different temperatures.

28. The method of claim 26 wherein the solid reactant comprises a calcium silicate.

29. The method of claim 28 wherein the calcium silicate is doped with an alkali metal.

30. The method of claim 26 wherein the solid reactant comprises at least one material selected from the group consisting of: a nickel oxide, a cobalt oxide, a copper oxide, a calcium oxide, an iron oxide, and a combination thereof.

31. The method of claim 30 wherein the solid reactant is synthesized using a sol-gel method, a sol-gel method coupled with oil-drop method, a co-precipitation based method, or a combination thereof.

32. The method of claim 26 wherein the solid reactant comprises a fluorinated alumina.

33. The method of claim 32 wherein the solid reactant comprises an impregnated metal oxide.

34. The method of claim 32 wherein the solid reactant is doped with an alkali or alkali earth metal.

35. The method of claim 32 wherein the solid reactant is formed by contacting an alumina with a fluorinated agent.

36. The method of 26 further comprising:

combining an aqueous fluid with the product stream in a quench column to lower the temperature of the product stream prior to contacting the product stream with the solid reactant.

37. The method of 36 wherein the aqueous fluid is water.

38. The method of 36 wherein the quench column comprises at least one column type selected from the group consisting of: a packed bed column, and a spray tower.

39. The method of claim 26 further comprising:

contacting the products stream with at least a portion of the hydrogen halide removed with an organic solvent to absorb at least some of the higher hydrocarbons; and

separating the organic solvent comprising at least some of the higher hydrocarbons from the higher hydrocarbons.

5 40. The method of claim 39 wherein the organic solvent is contacted with the products stream in an absorber.

41. The method of claim 39 wherein the organic solvent comprises a non-volatile hydrocarbon.

10 42. The method of claim 41 wherein the non-volatile hydrocarbon comprises at least one hydrocarbon selected from the group consisting of: mesitylene, diesel, a mixture of C₈ and higher hydrocarbons, and a combination thereof.

43. The method of claim 39 wherein the higher hydrocarbons are separated from the organic solvent in a series of separators to produce a plurality of streams with different hydrocarbon fractions.

15 44. The method of claim 26 wherein the alkyl halide stream further comprises light hydrocarbons.

45. The method of claim 44 further comprising:

20 passing the products stream through an expansion valve, wherein the products stream comprises at least some of the light hydrocarbons, wherein the temperature of the products stream drops during expansion.

separating any heavier hydrocarbons that condense from the light hydrocarbons.

46. The method of claim 45 further comprising:

thermally contacting the separated light hydrocarbons with the products stream in a heat exchanger prior to the products stream passing through the expansion valve.

25 47. A method comprising:

providing an alkyl halide stream;

contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide;

separating at least some of the product stream from the hydrogen halide; and

5 contacting the hydrogen halide with oxygen and an aqueous solution comprising a metal capable of forming multiple stable oxidation states to generate a corresponding halogen and water.

48. The method of claim 47 wherein the metal capable of forming multiple oxidation states comprises at least one metal selected from the group consisting of: Cu, Fe, Sb, Mn, V, As,
10 Ru, and a combination thereof.

49. The method of claim 47 wherein the aqueous solution has a pH less than about 7.0.

50. The method of claim 47 wherein the contacting of the hydrogen halide, oxygen, and the aqueous solution takes place at a temperature from about 65 °C to about 300 °C.

15 51. The method of claim 47 wherein the contacting of the hydrogen halide, oxygen, and the aqueous solution takes place at a pressure from about 0.1 atm to about 40 atm.

52. The method of claim 47 further comprising separating the corresponding halogen and the water.

53. The method of claim 52 wherein the steps of contacting the hydrogen halide with
20 oxygen and an aqueous solution and separating the corresponding halogen and the water both take place in a reactive distillation unit.

54. The method of claim 52 further comprising:

providing an alkane stream;

contacting the alkane stream with the separated corresponding halogen to form
25 the alkyl halide stream.

55. A system comprising:

a coupling reactor comprising a coupling catalyst for receiving an alkyl halide stream and contacting at least a portion of the alkyl halide stream with the coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide;

5 a separator unit for separating at least some of the product stream from the hydrogen halide; and

an oxidation reactor comprising an aqueous solution comprising a metal capable of forming multiple stable oxidation states for receiving a source of oxygen and at least a portion of the hydrogen halide from the separator unit and generating a corresponding halogen and water.

10 56. The system of claim 55 wherein the metal capable of forming multiple oxidation states in the oxidation reactor comprises at least one metal selected from the group consisting of: Cu, Fe, Sb, Mn, V, As, Ru, and a combination thereof.

57. The system of claim 55 wherein the aqueous solution in the oxidation reactor has a pH less than about 7.0.

15 58. The system of claim 55 wherein the oxidation reactor is at a temperature from about 65 °C to about 300 °C.

59. The system of claim 55 wherein the oxidation reactor is at a pressure from about 0.1 atm to about 40 atm.

20 60. The system of claim 55 wherein the oxidation reactor comprises at least one reactor type selected from the group consisting of: a continuous stirred tank reactor, a plug flow reactor, a packed column reactor, a fixed bed reactor, and a fluidized bed reactor.

61. The system of claim 55 further comprising a product separator for receiving the products of the oxidation reactor and separating the corresponding halogen and the water.

25 62. The system of claim 55 further comprising a halogenation reactor for receiving a halogen stream and an alkane stream and generating the alkyl halide stream.

63. A method comprising:

providing a halogen stream;

providing an alkane stream;

providing a decoking agent; and

reacting at least a portion of the halogen stream with at least a portion of the alkane stream in the presence of a halogenation catalyst and the decoking agent to form a halogenated stream.

5 64. The method of claim 63 further comprising a metal bromide catalyst downstream of the halogenation catalyst.

65. The method of claim 64 further comprising a metal bromide catalyst disposed between two sections of the halogenation catalyst.

66. The method of claim 63 wherein the decoking agent comprises at least one agent
10 selected from the group consisting of water, oxygen, and a combination thereof.

67. The method of claim 63 further comprising:

contacting at least a portion of the halogenated stream with a catalyst to form a product stream that comprises higher hydrocarbons and hydrogen halide.

68. The method of claim 63 wherein the flow direction of the halogen stream, the
15 alkane stream, and the decoking agent cycles relative to the halogenation catalyst.

69. The method of claim 63 wherein the reacting at least a portion of the halogen stream with at least a portion of the alkane stream in the presence of a halogenation catalyst and the decoking agent to form a halogenated stream occurs in a reactor comprising at least one reactor type selected from the group consisting of: a fixed bed reactor, a vertical fixed bed
20 reactor, and a radial bed reactor.

70. The method of claim 64 wherein the metal halide catalyst comprises at least one material selected from the group consisting of: copper oxide, mangesium oxide, yttrium oxide, nickel oxide, cobalt oxide, iron oxide, calcium oxide, vanadium oxide, molybdenum oxide, chromium oxide, manganese oxide, zinc oxide, lanthanum oxide, tungsten oxide, tin oxide,
25 indium oxide, bismuth oxide, a copper halide, a mangesium halide, a yttrium halide, a nickel halide, a cobalt halide, an iron halide, a calcium halide, a vanadium halide, a molybdenum halide, a chromium halide, a manganese halide, a zinc halide, a lanthanum halide, a tungsten halide, a tin halide, a indium halide, a bismuth halide, and a combination thereof.

71. The method of claim 63 wherein the decoking agent comprises less than about 5% by volume of the feed to the reaction.

72. The method of claim 65 further comprising:

separating the hydrogen halide from the product stream; and

5 reacting the hydrogen halide with a source of oxygen to regenerate a halogen stream.

73. The method of claim 67 wherein the halogenation catalyst comprises at least one catalyst selected from the group consisting of: a zeolite, an amorphous alumino-silicate, an acidic zirconia, a tungstate, a solid phosphoric acid, a metal oxide, a mixed metal oxide, a metal halide,
10 and a mixed metal halide.

74. A method comprising:

providing a gas phase stream comprising an elemental halide;

contacting the gas phase stream with a chilled brine in the liquid phase, wherein the chilled brine comprises an aqueous solution and a salt;

15 separating the elemental halogen along with the chilled brine from the remainder of the gas phase stream that remains in the gas phase; and

separating the elemental halide from the chilled brine.

75. The method of claim 74 wherein the elemental halide comprises at least one halide selected from the group consisting of: bromine, chlorine, fluorine, and iodine.

20 76. The method of claim 74 wherein the chilled brine lowers the temperature of the gas phase stream from about 10 °C to about -30 °C.

77. The method of claim 74 wherein the salt is a halide salt and wherein the halide of the halide salt is the same halide as the elemental halogen.

25 78. The method of claim 74 wherein the chilled brine comprises from about 0.1% to about 60% by weight of the salt.

79. The method of claim 74 wherein the elemental halide is separated from the chilled brine by liquid-liquid phase separation.

80. The method of claim 74 wherein the elemental halide is separated from the chilled brine by heating the chilled brine to vaporize the elemental halide.

81. The method of claim 74 further comprising:

providing a product stream comprising a hydrogen halide; and

5 contacting the product stream with an oxidation catalyst in the presence of oxygen to generate the gas phase stream comprising an elemental halide and water.

82. The method of claim 74 further comprising:

providing a first alkane stream;

10 reacting at least a portion of the halogen stream with at least a portion of the first alkane stream to form a halogenated stream, wherein the halogenated stream comprises alkyl monohalides, higher alkyl halides, and a hydrogen halide;

providing a second alkane stream; and

reacting at least a portion of the second alkane stream with at least a portion of the higher alkyl halides to create at least some additional alkyl monohalides.

15 83. The method of claim 82 further comprising:

contacting at least some of the alkyl monohalides and at least some of the additional alkyl monohalides with a catalyst to form a product stream that comprises higher hydrocarbons and hydrogen halide.

84. A method comprising:

20 providing an alkyl halide stream;

contacting at least some of the alkyl halides with a coupling catalyst to form a product stream comprising higher hydrocarbons and hydrogen halide;

separating the hydrogen halide from the product stream; and

25 reacting the hydrogen halide with a source of oxygen in the presence of an oxidation catalyst to generate a corresponding halogen.

85. The method of claim 84 wherein the hydrogen halide is separated from the product stream using temperature swing absorption.

86. The method of claim 85 further comprising:

providing an aqueous hydrogen halide stream;

5 providing an absorption vessel;

providing a separation vessel;

contacting the product stream with the aqueous hydrogen halide stream in the absorption vessel to absorb at least some of the hydrogen halide in the product stream in the aqueous hydrogen halide stream;

10 transferring the aqueous hydrogen halide stream containing at least some of the hydrogen halide to the separation vessel, wherein at least a portion of the hydrogen halide in the aqueous hydrogen halide stream is removed through heating; and

recycling the aqueous hydrogen halide stream to the absorption vessel.

15 87. The method of claim 86 wherein the aqueous hydrogen halide stream entering the absorption vessel has a hydrogen halide concentration of at least about 48 % by weight.

88. The method of claim 86 wherein the aqueous hydrogen halide stream exiting the absorption vessel has a hydrogen halide concentration from about 50% to about 80% by weight of the aqueous hydrogen halide stream.

20 89. The method of claim 86 wherein the aqueous hydrogen halide stream is heated in the separation vessel to greater than about 125 °C.