Claims

1. A method of regenerating a spent catalyst comprising a transition metal and a catalyst support in a metal reactor, the method comprising:

   (1) contacting the spent catalyst with a chlorine-containing stream comprising a chlorine-containing compound to produce a chlorinated spent catalyst;

   (2) contacting the chlorinated spent catalyst with a decoking gas stream comprising oxygen to produce a de-coked catalyst; and

   (3) contacting the de-coked catalyst with a fluorine-containing stream comprising a fluorine-containing compound to form a regenerated catalyst containing less than about 1 wt. % of carbon; wherein:

   the transition metal comprises a Group 8-11 transition metal;

   the catalyst support comprises a large pore zeolite having an average pore diameter in a range of from about 7 Å to about 12 Å; and

   the spent catalyst further comprises chlorine and/or fluorine.

2. The method of claim 1, wherein step (1) is conducted at a chlorination temperature in a range from about 20° C. to about 300° C.

3. The method of claim 1, wherein an amount of the chlorine-containing compound in the chlorine-containing stream is controlled to give a concentration of chlorine (Cl) in the chlorine-containing stream in a range from about 5,000 to about 50,000 ppm by volume.

4. The method of claim 3, wherein the chlorine-containing stream is substantially free of an oxygen-containing compound.

5. The method of claim 1, wherein the chlorine-containing stream comprises Cl_2 and nitrogen.

6. The method of claim 1, further comprising a chlorine purging step prior to step (2), the chlorine purging step comprising contacting the chlorinated spent catalyst with a chlorine purging stream consisting essentially of an inert gas.

7. The method of claim 1, wherein:

   step (2) is conducted at a peak decoking temperature in a range from about 300° C. to about 500° C.;

   the decoking gas stream comprises nitrogen and oxygen; and

   the decoking gas stream is substantially free of halogen-containing compounds.

8. The method of claim 1, wherein step (3) is conducted at a fluorination temperature in a range from about 20° C. to about 250° C.

9. The method of claim 1, wherein an amount of the fluorine-containing compound in the fluorine-containing stream is controlled to give a concentration of fluorine (F) in the fluorine-containing stream is in a range from about 5,000 to about 100,000 ppm by volume.

10. The method of claim 9, wherein the fluorine-containing stream is substantially free of oxygen-containing compounds.

11. The method of claim 1, wherein the fluorine-containing stream comprises F_2 and nitrogen.

12. The method of claim 1, further comprising a fluorine purging step after step (3), the fluorine purging step comprising contacting the regenerated catalyst with a fluorine purging stream consisting essentially of an inert gas.

13. The method of claim 1, wherein the spent catalyst comprises:

    platinum on the catalyst support, wherein the catalyst support comprises a KL-zeolite and a binder comprising alumina, silica, a mixed oxide thereof, or a mixture thereof;

    from about 0.01 wt. % to about 5 wt. % chlorine; and

    from about 0.01 wt. % to about 5 wt. % fluorine.

14. The method of claim 1, further comprising a reducing step after step (3), the reducing step comprising contacting the regenerated catalyst with a reducing gas stream comprising molecular hydrogen.

15. The method of claim 1, wherein the metal reactor comprises a stainless steel, and the regenerated catalyst contains less than about 250 ppmw of iron and less than about 0.5 wt. % of carbon.

16. The method of claim 15, wherein the regenerated catalyst is characterized by:

a TEOR (end of run temperature) within about 40° F. of the TEOR of a fresh reference catalyst;

a FR (fouling rate) in a range from about 0.02° F./hr to about 0.2° F./hr; and

a benzene+toluene selectivity in a range from about 0.88 to about 0.95.

17. A method of regenerating a spent catalyst comprising a transition metal and a catalyst support in a metal reactor, the method comprising:

(i) contacting the spent catalyst with a chlorine-containing stream comprising a chlorine-containing compound to produce a chlorinated spent catalyst;

(ii) contacting the chlorinated spent catalyst with a chlorine purging stream comprising an inert gas;

(iii) contacting the chlorinated spent catalyst with a decoking gas stream comprising oxygen to produce a de-coked catalyst;

(iv) contacting the de-coked catalyst with a fluorine-containing stream comprising a fluorine-containing compound to produce a de-coked and fluorinated catalyst; and

(v) contacting the de-coked and fluorinated catalyst with a fluorine purging stream comprising an inert gas to form a regenerated catalyst containing less than about 1 wt. % of carbon; wherein:

the transition metal comprises a Group 8-11 transition metal;

the catalyst support comprises a large pore zeolite having an average pore diameter in a range of from about 7 Å to about 12 Å; and

the spent catalyst further comprises chlorine and/or fluorine.

18. The method of claim 17, wherein:

the chlorine-containing stream comprises Cl_2 and nitrogen;

the chlorine purging stream consists essentially of nitrogen;

the decoking gas stream comprises nitrogen and oxygen;

the fluorine-containing stream comprises F_2 and nitrogen; and

the fluorine purging stream consists essentially of nitrogen.

19. The method of claim 17, further comprising an oxygen purging step after step (iii) and before step (iv), the oxygen purging step comprising contacting the de-coked catalyst with an oxygen purging stream consisting essentially of an inert gas.

20. The method of claim 17, further comprising a reducing step after step (v), the reducing step comprising contacting the regenerated catalyst with a reducing gas stream comprising molecular hydrogen to produce a reactivated catalyst.

21. The method of claim 20, wherein the reactivated catalyst contains less than about 300 ppmw of iron and less than about 0.5 wt. % of carbon, and is characterized by:

a TEOR (end of run temperature) within about 40° F. of the TEOR of a fresh reference catalyst;

a FR (fouling rate) in a range from about 0.02° F./hr to about 0.2° F./hr; and

a benzene +toluene selectivity in a range from about 0.88 to about 0.95.

22. A reforming process comprising:

(A) contacting a hydrocarbon feed with an aromatization catalyst comprising a transition metal and a catalyst support under reforming conditions in a metal reactor system to produce an aromatic product;

(B) performing step (A) for a time period sufficient to form a spent catalyst;

(C) contacting the spent catalyst with a chlorine-containing stream comprising a chlorine-containing compound to produce a chlorinated spent catalyst;

(D) contacting the chlorinated spent catalyst with a decoking gas stream comprising oxygen to produce a de-coked catalyst; and

(E) contacting the de-coked catalyst with a fluorine-containing stream comprising a fluorine-containing compound to form a regenerated catalyst containing less than about 1 wt. % of carbon; wherein:

the transition metal comprises a Group 8-11 transition metal;

the catalyst support comprises a large pore zeolite having an average pore diameter in a range of from about 7 Å to about 12 Å;

the aromatization catalyst further comprises chlorine and/or fluorine, and wherein steps (C)-(E) are performed in a metal reactor.

23. The process of claim 22, wherein the reforming process is an in situ process.

24. The process of claim 22, wherein steps (C)-(E) are performed in a metal reactor external to the metal reactor system.