

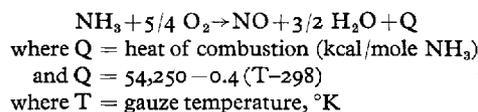
The Manufacture of Nitric Acid

THE ROLE OF PLATINUM ALLOY GAUZES IN THE AMMONIA OXIDATION PROCESS

By H. Connor, B.Sc.

In the second part of this article, concluded from the January issue of Platinum Metals Review, the author deals principally with the problem of platinum losses from gauzes during operation, with the catalytic reduction of tail gases and with the production and handling of gauzes for use in ammonia converters.

A great deal of heat is liberated by the reaction. This heat is equivalent to 8.73×10^5 kcal per theoretical ton of 100 per cent HNO_3 formed, and if only 20 per cent of this energy is recovered it would be equivalent to a power output of about 2,580 h.p. for a 250 ton/day plant. A more accurate assessment of the liberated heat may be made from the following equation (16)



To recover as much as possible of the heat of combustion to raise steam for power production, the gauze pad is usually situated immediately above the waste heat boiler.

Catalyst Loading

It is possible to calculate with some precision the platinum surface area, and hence the weight, of gauze required to achieve a given output under specified conditions (11, 24). Such calculations are complex, and involve aerodynamic analyses of the gas flows within the converter and around individual gauze wires. An empirical approach indicates that in a modern atmospheric pressure converter 1 oz troy of platinum burns about 140 lb ammonia per day (17) (1 kg platinum per 2050 kg ammonia per day). This is a substantially higher platinum investment per unit of output than is required for high

pressure converters, where 1 oz platinum burns 250 to 300 lb ammonia per day (1 kg platinum per 3660 to 4400 kg ammonia per day), and accounts in part for the higher initial cost of the lower pressure plants.

Gauze Deterioration and Platinum Losses

The ammonia oxidation reaction is started by feeding the cold gas mixture at a low rate to the gauze pad. A small area of the top gauze is heated by means of a hydrogen-oxygen flame or an electrically heated nickel-chromium wire, and the ammonia combustion reaction starts when this hot zone reaches about 600°C. The heat of combustion raises the temperature of the rest of the gauze, and the reaction progressively spreads over the whole surface. Full operation is reached when the feed mixture attains its designed pre-heat temperature.

New gauzes, with their smooth rounded wires, are difficult to ignite and show a very low initial activity. Pure platinum is rather better in this respect than 5 or 10 per cent rhodium-platinum, but the phenomenon is perfectly general. After the reaction has been in progress for some time the surface of the platinum or rhodium-platinum alloy is seen to alter. The surface roughens greatly, and cauliflower-like growths form that increase the effective diameter of each wire almost by a factor of 2. This metal transport at the

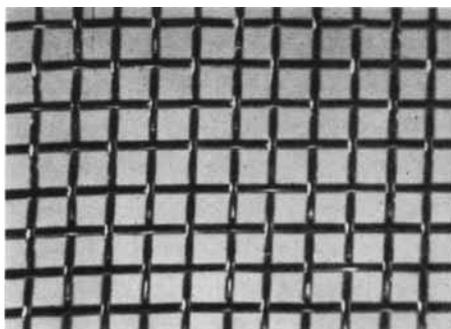


Fig. 4a New 10 per cent rhodium-platinum alloy gauze, showing smooth rounded wire surface ($\times 50$)

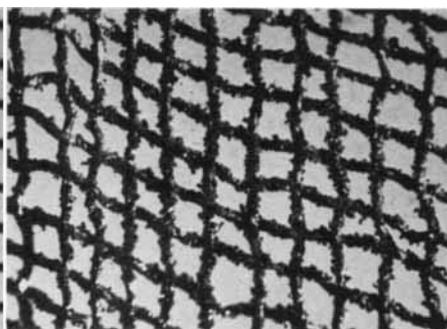


Fig. 4b A rhodium-platinum alloy gauze after a period in operation. The growths on the wire surface are clearly seen ($\times 50$)

surface is carried out at the expense of the wire interior, and the mechanical strength of the wire is thus considerably reduced. Figs 4a and 4b illustrate these surface changes and Figs 5a and 5b illustrate the accompanying metallurgical changes that take place in the gauze wires.

It is very probable that this observed surface mobility results from very high local temperatures due to the heat liberated by the catalytic reaction—perhaps temperatures very close to the melting point of the metal are produced in the surface atomic layers (18). This view is supported by the fact that no such change in the metal surface is observed when it is heated in pure ammonia, oxygen or nitric oxide separately. A very similar change occurs, moreover, when platinum is heated in oxygen-hydrogen mixtures, and the reaction

proceeds catalytically on its surface. It is likely that the oxygen plays a part in activating the platinum mobility under these conditions (19). Perhaps the rise of catalytic activity of the gauze with increasing formation of growths on the wire surface is related to the recrystallisation of the pure metal or alloy, since platinum, with its lower recrystallisation temperature than rhodium-platinum alloys, exhibits a higher initial activity (20). New nitric acid plants whose converters have not operated previously are usually fitted with gauze pads of which the upper gauze has been “activated” by operating within a gauze pad in an existing, working plant. This treatment greatly facilitates the start-up for the new plant.

When the gauzes are fully operative at their working temperature they lose metal from

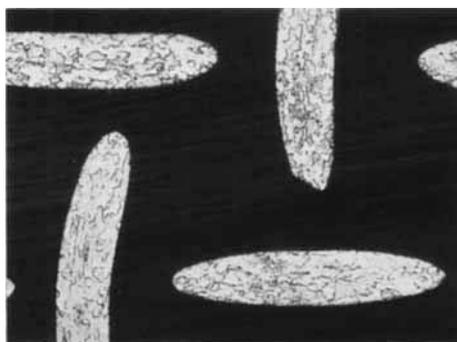


Fig. 5a Section through a new gauze after etching, showing a uniform small grain size in the rhodium-platinum alloy wire ($\times 150$)

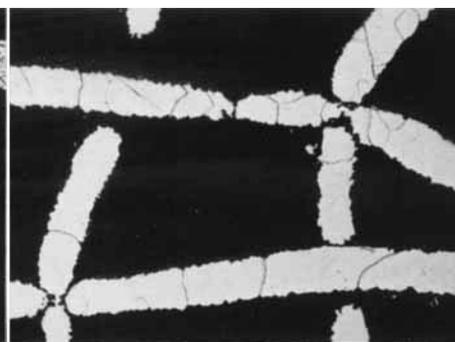


Fig. 5b Section through a gauze after a period in operation. Most of the surface growths were dissolved during etching but the enlarged grain size is clearly seen ($\times 150$)

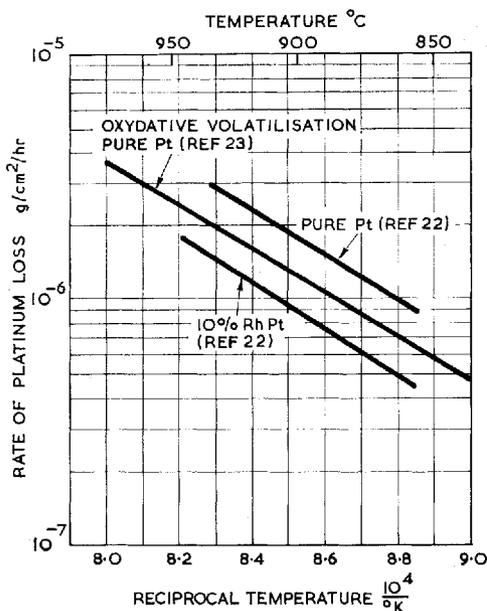


Fig. 6 Arrhenius plots of platinum weight losses at gauze operating temperatures, comparing results obtained by oxidative volatilisation of platinum (ref. 23) with metal losses from gauzes under plant conditions (ref. 22). Good agreement is observed, indicating that oxygen plays a large part in causing metal loss from gauzes (Nowak)

the wire surface at a fairly constant rate. This metal loss rate contributes significantly to the plant operating costs, and is highly dependent on the gauze temperature. A tenfold increase in the metal loss rate occurs when the operating temperature rises from about 820 to 920°C.

The mechanism of this metal loss is not fully understood, although oxygen is firmly believed to play a role in its origin since the losses increase with increasing oxygen partial pressure (25). It is partly due, of course, to mechanical losses of the surface growths exposed to a high velocity gas stream at high temperatures, in particular while subjected to the vibrations normally present in industrial plants. This, however, does not account for much of the metal that is lost. When rhodium-platinum alloy gauzes are used—as is almost universally the case—the platinum has a tendency to volatilise preferentially. Gauzes that commence life with a 10 per cent rhodium

content contain 11 to 13 per cent of this metal when they are finally discarded. This has been confirmed experimentally using non-catalytic conditions (21).

When loss rates from platinum and rhodium-platinum alloys were compared and the latter were shown to have substantially lower losses as well as slightly higher catalytic activity, the industry changed over to the use of the alloy (22). These early workers' metal loss rates have recently been compared with losses resulting purely from oxidative volatilisation (23), and when presented as an Arrhenius plot in Fig. 6 show very good agreement (24). It is very likely, therefore, that the transient formation of volatile oxides of platinum and rhodium play a role in the loss of metal under operating conditions. This is supported by independent evidence which points to the probability that the metal surface is in any event almost completely covered by oxygen atoms during the reaction, making the formation of volatile oxides at the very high local surface temperatures both feasible and probable.

The gauzes continue in operation with a more or less constant metal loss rate until they become too brittle and fragile to handle, or holes and tears appear that are too extensive to repair. Since the top gauze of a pad experiences the most arduous conditions and is responsible for most of the catalytic conversion, replacement of gauzes is effected by removal of the damaged gauze from the top and its replacement by a new one placed at the bottom of the pad. In this manner gauzes work their way progressively up the pad. By the time they are discarded they will have lost about 15 per cent of their initial weight.

Deactivation by Poisons

All catalysts may become deactivated by certain substances that chemi-sorb on to their active sites more strongly than the molecules that are intended to react there. In such an event, or when the catalytic surface is chemically attacked by contaminants present in the reactants, the rate and yield of the reaction

will decline or even diminish to zero. Platinum alloy gauzes are no exception to this generalisation, although catastrophic loss of activity due to poisoning is rare. It is very important, therefore, to exclude most carefully from the reactants any potentially harmful contaminants.

Synthetic ammonia, fortunately, is very pure and generally contains no gauze poisons. The lubricant oils in the compressors used to liquefy the ammonia, frequently, however, contain sulphur and other additives, and oil droplets that find their way into the ammonia may thus prove to be very harmful to the gauze pad. Even when—as is usual—the oil content of the ammonia used in modern nitric acid plants is specified to be no more than 5 ppm, the cumulative effect of this contaminant on the gauze may be quite considerable in view of the great quantities of ammonia that reach it continuously over an extended period. Oil mist filters are, therefore, normally fitted to most ammonia lines in practice.

Ammonia derived from non-synthetic sources, e.g. coke oven liquors, is usually high in sulphur, arsenic and other base metal impurities; these must be removed to very low levels if economically acceptable gauze lives are to be achieved. (The total of sulphur, arsenic and other impurities should not exceed 1 or 2 ppm.)

The air used for the ammonia oxidation is generally carefully filtered to exclude dust and contaminants before pre-heating. Gaseous impurities, for example SO_2 from other nearby plants, must be absorbed to prevent them from reaching the gauze pad.

Iron oxide, in the form of plant scale blown on to the gauze pad by the rapidly flowing gases, has also been shown to be responsible for a decline in nitric oxide yield. This may be less due to true gauze poisoning by the iron oxide than its action in promoting the decomposition of ammonia into hydrogen and nitrogen before reaction on the platinum surface. Iron oxide formation is minimised by using as much non-rusting material in

plant construction as possible. Its accumulation on the gauze pad may be avoided by periodic pickling of the pad as described in a later paragraph.

Cutting the Losses

The losses of platinum alloy from the gauze in operation may contribute significantly to the overall cost of nitric acid production. This is particularly the case for gauzes in converters operating at medium or high pressure, and filters or other means to catch the platinum particles in the gas downstream from the gauzes are usually incorporated in such plants. The disadvantage of such platinum filters is that they generally provide a significant pressure drop in the gas system which results in increased power consumption. This pressure drop, moreover, rises with compaction of the filter medium during operation and as a result of the platinum and plant corrosion scale dusts that it retains.

Various filtration systems have been reviewed (26). The most widely used system incorporates filters made of special glass wool or rock wool formed into hollow cylinders through which the gas flows outwards. The filter pad is retained within coarse mesh stainless steel gauzes, and the assembly is usually situated in the gas stream just behind the waste heat boiler. It operates at the full plant pressure and up to about 450°C .

Such filters are marketed as proprietary plant accessory systems by various firms, for example, Monsanto Chemicals Inc. and Hercules Powder Company, and when newly installed are claimed to have pressure drops across them as low as 0.5 p.s.i. (0.034 atm.). After a period of operation, usually in the range four to nine months depending on the type of process, the filter medium is removed for platinum recovery. By this time the pressure drop across the filter unit has risen to 3 to 4 p.s.i. (0.2 to 0.27 atm.). Such filters are claimed by their suppliers to reduce platinum losses by up to 60 per cent.

A novel method for platinum recovery that operates on the "getter" system has recently

been developed by the Deutsche Gold-und Silber-Scheideanstalt (Degussa) and is currently being evaluated in several nitric acid plants. This system makes use of a pad of two or more gauzes of a gold-palladium alloy installed immediately downstream from the rhodium-platinum oxidation gauzes. The gap separating the two pads is less than 10 mm, and the palladium alloy gauzes are at about the same temperature as the converter gauzes. Platinum that is volatilised from the latter—and to a lesser extent also the rhodium—impinges on the hot gold-palladium gauze pad and immediately alloys with it, diffusing away from the surface into the interior of the palladium alloy wire, giving a solid solution. The palladium alloy has a considerable capacity for thus “gettering” platinum from the hot gas stream, and the platinum is recovered by refining the “getter” gauze pad. Considerable economies in platinum metal recovery are claimed for this system.

Other platinum retention systems have been developed, such as a layer of Raschig rings or calcium oxide lumps placed below the platinum gauzes (27). These, however, have not yet found widespread application.

The efficiencies of various platinum dust filters can be determined by a radioactive tracer technique (28). A tracer gauze made of 2 per cent iridium-platinum alloy and irradiated to form Ir^{192} is incorporated in the gauze pad. Losses from this gauze can be traced throughout the plant using a scintillation counter.

Tail Gas Reduction

Even in the most efficient system the absorption of dinitrogen tetroxide by water to produce the required nitric acid is never 100 per cent complete. The tail gas that escapes from the process to the atmosphere generally contains from 0.1 to 0.5 volume per cent total nitrogen oxides, 2.5 to 5 per cent oxygen, some water vapour and the balance of nitrogen. If the ratio $\text{NO}_2 : \text{NO}$ is high, a gas of such composition produces a brown plume at the tail stack. Such a gas is toxic and highly corrosive.

Table V
Tail Gas Stack Heights
for Nitric Acid Plants (29)

<i>Plant Output</i> (Tons 100% HNO_3 per day)	<i>Recommended</i> <i>Stack Height</i>
175	180 ft (55 m)
350	250 ft (76.5 m)
530	300 ft (91.5 m)
700	350 ft (107 m)

In the United Kingdom, the Alkali Inspectorate permits a maximum of 0.26 volume per cent total nitrogen oxides expressed as NO_2 at the stack exit, and the stack must be sufficiently high to reduce this contaminant to a concentration of less than 0.16 ppm (NO_2) at ground level. This may be achieved by using one or more of the following methods:

- 1 Diluting the stack gas with additional air, prior to its release to atmosphere
- 2 Using a very high stack
- 3 Catalytically reducing the nitrogen oxides to nitrogen using an appropriate fuel.

Method 1 is simple, and most widely employed, particularly in conjunction with Method 2. Recommended stack heights for nitric acid plants of various outputs are shown in Table V (29).

When the catalytic method is employed, the tail gas is mixed with a fuel gas to give a slight excess over that which is stoichiometrically required for the total reduction of the free oxygen and the nitrogen oxides present. Among the fuels that may be used are ammonia, carbon monoxide, hydrogen, kerosene, coke oven gas and natural gas (30). The mixture is passed through a catalyst bed consisting of platinum or palladium supported on alumina pellets or spheres or on a crimped nickel-chromium alloy ribbon (31). Palladium is the preferred metal if methane is used as fuel, platinum if the other hydrocarbons or ammonia are employed. Ammonia is able to reduce the nitric oxide and dioxide without first reducing the free oxygen, and

this enables a lower catalyst operating temperature to be used. The disadvantages of using ammonia, however, are its high cost and the lower power recovery that can be made from the hot combustion products. For the other fuels which first reduce the free oxygen, there is a gas temperature rise of about 130°C for every per cent oxygen in the gas mixture (free oxygen plus combined oxygen as nitrogen oxides). The catalyst bed usually operates at about 800°C, and the sensible heat of combustion is recovered in heat exchangers, or turbines. The principal features of the available methods are summarised in Table VI (30).

A practical difficulty frequently encountered by users of the catalytic tail gas reduc-

tion process is that nitrogen dioxide, NO₂, is relatively easily reduced to the nitric oxide, NO. The latter, however, is much more difficult to reduce and some may pass unchanged through the catalyst bed only to re-oxidise in the atmosphere after release from the stack. This re-oxidation is a slow reaction, however, and the gas is usually well dispersed before it takes place.

Platinum Gauze Production

Platinum and the two main rhodium-platinum alloys used in catalyst gauzes are malleable and ductile; they are readily drawn to fine wires, and these may be woven into gauzes by conventional textile weaving techniques using specially designed looms.

Table VI
Catalytic Tail Gas Reduction Processes (30)

Process conditions	Removal of NO and NO ₂	Heat (power) production	Heat (power) production and removal of NO and NO ₂		
Possible fuels	Ammonia	Natural gas, hydrogen, carbon monoxide, hydrocarbons, kerosene, coke oven gas			
Fuel used	Ammonia	Natural gas	Natural gas		
Free oxygen in tail gas, per cent	2 to 5	3 to 5	2 to 3	3 to 5	
Number of stages ..	1*	1	1	2	
				First stage	Second stage
Preferred metal for catalyst	Platinum	Palladium	Palladium	Palladium	Palladium
Hourly space velocity ..	30,000	20,000 to 40,000	60,000	20,000 to 40,000	60,000
Minimum temperature of gas at entry to catalyst bed	180°C	440 to 500°C	460°C	440 to 500°C	460°C
Fuel used, as volume per cent of tail gas ..	0.3	0.5 to 1.4	1.1 to 1.7	0.8 to 1.3	0.9 to 1.4
Approximate temperature rise	20 to 40°C	130°C per % oxygen reduced			

* If a higher temperature is desired a second stage should be employed using hydrogen as fuel



Fig. 7 One of the looms in the Johnson Matthey gauze shop, showing a rhodium-platinum gauze 140 inches (3.56 metres) wide being woven from 0.003 inch diameter wire

The platinum and rhodium sponges used for fabrication into gauzes are carefully selected for their exceptional freedom from impurities. Catalysts of all types are sensitive to poisoning, and the rigorous limitation of trace impurities in the platinum or rhodium-platinum alloy to very low levels is vital to the successful operation of gauzes in ammonia oxidation. After pickling to remove surface iron picked up during weaving, the finished gauzes produced by Johnson Matthey have a total content of base metal impurities of less than 50 p.p.m.

Gauzes may be woven to any required dimension, and the looms in the Johnson Matthey shops illustrated in Fig. 7 are sufficiently wide to weave without any seams the largest circular gauzes required by the nitric acid industry—about 12 ft (3.66 metres) diameter for the largest atmospheric pressure converters. After cutting to size, the edge of

each gauze is generally turned over for about 5 mm and hammer-welded to provide a firm perimeter that will not give rise to loose wires by fraying.

Most modern plants require circular gauzes, but hexagonal, oblong or square ones are also produced, generally for the smaller high pressure converters. Where only a small number of gauzes are required per converter (from 3 to 5 for atmospheric and medium pressure units) these are generally laid singly on top of each other before clamping down. It is helpful for separating them again for pickling, after the unit has been in operation for a period, if the gauzes are installed so that the warp or weft of one gauze makes an angle of 45° with its counterpart adjacent to it.

For some medium pressure and almost all high pressure converters the number of individual gauzes per converter may be considerable—up to about 40. In such cases

it is convenient to use multi-ply gauze pads, comprising two, three or five individual gauzes hammer-welded together at their peripheries and across one or two diameters. Such multi-ply pads are easier to separate for pickling after a period in operation than their equivalent number of single gauzes.

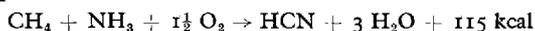
The gauzes used by Kaiser in 1909 were woven of wires 0.06 mm diameter, and had 1050 apertures per cm². Since that date their pattern has not changed appreciably, and the principal features of gauzes used throughout the world today are illustrated in Table VII. The 5 per cent rhodium-platinum alloy is more generally used in Continental Europe, whereas 10 per cent rhodium-platinum is favoured in the United Kingdom and the U.S.A., especially for high pressure converters where operating conditions are much more arduous.

Of the design variables for gauzes, the wire diameter and mesh or apertures per unit area are not as important to a plant operator as the surface area of the gauze. Since this is not easily measured directly, it is inferred from the weight of a gauze when its wire diameter and mesh are kept constant. In order, therefore, to ensure that the platinum alloy catalyst charge has the correct weight, which is much more easily measured, and that it thus operates with the designed ammonia loading, it is important that each gauze should be woven to a specified weight per unit area. That this weaving density be kept within closely controlled limits

Platinum Gauzes for Hydrogen Cyanide Production

The same type of rhodium-platinum alloy gauzes that are used in ammonia oxidation to produce nitric acid are also employed, in a closely analogous manner, in the Andrussov process for making hydrogen cyanide (33). This is an industrially important product, used as a basic raw material in the production of acrylic plastics, adiponitrile for nylon, nitrile rubbers and other materials made on a large scale.

In the Andrussov process, methane, ammonia and oxygen are reacted by passing the gas mixture through a platinum alloy gauze pad. The reaction, which is believed to proceed via the formation of an NH radical, takes place at about 1000°C, and the heat liberated enables it to be self-sustaining (34). The overall reaction is represented by the following equation:



The mixed gases are pre-heated to about 500°C, and the methane:ammonia ratio is in the range 0.8 to 1.2:1. Sufficient air is added to provide 25 to 40 per cent of the theoretical requirement to oxidise the methane and ammonia (35).

A very short contact time, about 3×10^{-4} seconds, is employed and the products of reaction are rapidly cooled to obtain maximum yields. Reactors are similar to ammonia oxidation converters, although usually smaller in diameter. Since the gauze operates at about 1000°C, its radiant heat causes the converter walls to be hotter than in the ammonia oxidation, and some ammonia is lost from the reaction by pre-decomposition. Some carbon monoxide and nitrogen are also formed by undesirable side reactions.

The gauzes are generally woven of 10 per cent rhodium-platinum alloy, and to the same mesh and wire diameter specifications as for ammonia oxidation. The mobility of the platinum alloy surface is also observed in this reaction, and growths form on the gauze wires exactly as in the oxidation of ammonia. Since they run hotter, there is a substantially higher platinum loss—around 500 mgm/ton HCN.

is much more relevant to a plant operator than the very slight departures from the nominal wire diameter or apertures per unit area that may be required to achieve the specified density.

By controlling most carefully the degree of annealing of the wires used during weaving and their tensions on the looms, together with

Table VII
Standard Platinum and Rhodium-Platinum Alloy Gauzes

Composition	Mesh		Nominal Wire Diameter		Approximate Weight per Unit Area	
	Mesh per linear inch	Apertures sq. cm	inch	mm	oz. troy per sq. ft	Kg per sq. m
Platinum	80	—	0.003	—	1.84	—
	80	—	0.0026	—	1.40	—
	—	1024	—	0.06	—	0.415
5% Rhodium-Platinum	80	—	0.003	—	1.78	—
	—	1024	—	0.06	—	0.400
10% Rhodium-Platinum	80	—	0.003	—	1.72	—
	—	1024	—	0.06	—	0.386

their diameters and mesh, the workshops of Johnson Matthey are able to produce gauzes that deviate by less than 2 per cent from any specified weight per unit area.

After inspection, gauzes are protected from damage by interleaving with layers of tissue paper, and if less than about 3 ft (1 metre) in diameter are packed flat in specially constructed wooden boxes. Larger gauzes are rolled on to rigid tubular plastic formers 4 to 6 in. (10 to 15 cm) diameter, suitably interleaved with protective tissue paper. These rolls are then packed into strong crates for despatch.

Handling Gauzes on a Plant Site

On account of their high intrinsic value the gauzes are normally stored on the works site in a special high-security room adjacent or near to the nitric acid plant. A portable flat foldable wooden table with a clean surface is generally provided and placed next to the converter at gauze level when a gauze change is to be made. The new gauzes are then unrolled and laid flat on this table, the diameter of which is very slightly greater than that of the gauzes. Such an arrangement greatly facilitates handling the gauzes and ensures

that they may be fitted into the converter free from folds or creases.

In any gauze pad for high, medium or atmospheric pressure converters, the gauzes facing the oncoming gas stream sustain the greatest damage, and those that are too badly damaged and beyond repair are removed and replaced by an equivalent number on the downstream side of the pad. The life of individual gauzes depends on numerous factors, but is generally two to three months in a converter operating at 8 atmospheres pressure, rising to eight to twelve months in one operating at atmospheric pressure. In high pressure plants the need for more frequent gauze cleaning and replacement results in a higher proportion of down-time than is usual for low pressure converters.

During operation the gauze pad acts as a filter for atmospheric or plant scale dusts that are present in the ammonia and air streams. These dusts—mainly iron oxide scale—collect on the upper gauze layers and serve to raise the pressure drop across the pad and to decrease the catalytic conversion efficiency of the ammonia oxidation process. It requires very little iron oxide scale to effect a significant reduction in conversion efficiency. At intervals, therefore, the plant is shut down

and the gauze pad removed. Where possible, individual gauzes are separated and pickled in warm (about 60°C) constant boiling-point mixture hydrochloric acid (32). The acid is contained in shallow tanks made of silica, glass fibre, rigid PVC or other suitable material, and the gauzes rest on glass rods placed on the bottom. A silica-sheathed immersion heater may be used to heat the acid, and air blown in by a glass tube to a point below the gauzes agitates the pickling liquor. Pickling thus for about two hours effectively removes the iron oxide scale and most other contaminants, and is followed by successive washes in tap water and distilled water until the washings are free from chloride. It is important to retain any solid residues from the pickle liquor or washings, since these can contain an appreciable amount of platinum lost by attrition from the gauzes during this treatment. Thereafter the gauzes are air-dried, and any metal oxides that may have formed during operation can be reduced by playing a hydrogen flame over the gauzes while the latter are hung from a clean stainless steel "washing line".

Torn or damaged gauzes may be repaired by patching with a piece of clean, pickled gauze. The damaged gauze is also pickled, a patch is cut to size and laid over the damaged area and hammer-welded into place by using a piece of clean stainless steel as an "anvil" and a stainless steel hammer. The hammer-welding operation is carried out while both patch and gauze are held at dull red heat by means of a hydrogen torch.

Platinum Recovery

The economic feasibility of using platinum on an industrial scale always depends on the very high value the metal realises upon its almost complete recovery when spent. This is particularly true of the use of platinum gauzes in nitric acid production, where metal lost from the catalyst pad during operation gives rise to recoverable residues in a number of locations within the plant.

Spent gauzes constitute, of course, a very

high proportion of the total recoverable platinum. In addition, platinum dust may settle out in parts of the waste heat boiler immediately downstream from the gauze pad, as well as being trapped in special glass wool filters. Such filter media contain substantial amounts of recoverable platinum.

Inevitably, some platinum dust passes through the filter (if one is installed) and then may settle out in "dead space" pockets in the nitric oxide oxidation chamber, in pipes and ducts, in the compressor or at the bottom of the absorption towers. Some dust even passes into the nitric acid, and eventually settles out as a fine sludge in the acid storage tanks, to be collected whenever these are drained for maintenance. The Johnson Matthey refineries deal with large volumes of all these residues, and effect almost complete recovery of their noble metal contents.

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