reaction tubes may have the same diameter or cross-sectional area. In at least one embodiment, the R2 reaction tubes may have a cross-sectional area at least 25% greater than the cross-sectional area of the R1 reaction tubes. In a further embodiment, the R2 reaction tubes may have a cross-sectional area at least 50% greater than the cross-sectional area of the R1 reaction tubes.

In at least one embodiment, the R1 reaction tubes may have a diameter of 22.3 mm (0.878 in) or less. In other embodiments, the R1 reaction tubes may have a diameter greater than 22.3 mm (0.878 in), such as, for example, 25.4 mm (1 in) or more.

In at least one embodiment, the internal diameter of the tubes of second reaction stage within the SSOI reactor can be greater than 22.3 mm. In at least one embodiment, the R1 and R2 reaction tubes have a diameter greater than 22.3 mm (0.878 in). In a further embodiment the internal diameter of the tubes of second reaction stage within the SSOI reactor range from 23.6 mm to 50 mm. In at least one embodiment, the internal diameter of the tubes of second reaction stage within the SSOI reactor is at least 25.4 mm (1 in). In accordance with an embodiment of the present disclosure, the tubes of the second reaction stage are not more than 4,500 mm (177 in) in length.

The negative impact on heat removal of larger diameter tubes may be compensated for with appropriate adjustments in one or more of the other design variables, such as for example, the number of shellside baffles, the baffle geometry and placement, the tubesheet layout and spacing between tubes (also known as tube pitch), the circulation rate of the cooling salt, and the supply temperature of the cooling salt. For example, in one embodiment, low salt circulation rates through the reactor shell are employed, thereby minimizing power requirements for the salt circulation pumps; such a design philosophy may generally result in a temperature rise of the salt through the shell of the reactor (salt temperature out relative to salt temperature in) of as ~~much as~~ much as 14 to 17 °C (25 to 30 °F). In an alternative embodiment, high salt circulation rates are utilized and the temperature increase of the salt through the shell of the reactor is constrained to the range of just 1 to 3 °C (2 - 5 °F).

Such design adjustments can be made by one of ordinary skill in the art of heat exchanger design, using commercially available design software from HTRI or the like; alternatively, cooling system design services may be outsourced to established

Major sections of the reactor include the inlet head 100, the first reaction stage 110 ("R1"), the interstage heat exchanger 130 ("ISHX"), the open interstage region 150, the second reaction stage 160 ("R2"), and the outlet head 180. Unless otherwise specified, all reactor components can be constructed of carbon steel, such as for example ASME SA-516 grade 70 carbon steel.

The interface between adjacent sections, identified in the figures as 105, 125, 145, 155, and 175, may comprise permanent (e.g., welded) connections or may optionally comprise separable connections, such as flanged connections secured with a plurality of fasteners, such as for example bolts or clamps. In the embodiment of Figure 1a, interface 105 and 175 are separable connections, allowing inlet head 100 and outlet head 180 to be easily removed for catalyst replacement, while interfaces 125, 145 and 155 are welded connections.

In this embodiment, reactor inlet head 100 is constructed of 316 stainless steel for added corrosion resistance. Both reactor inlet head 100 and outlet head 180 also incorporate optional temperature control components (not shown), such as for example electric tracing, steam heating jackets, and circulating-salt heat transfer coils, for use in maintaining internal surface temperatures above the dewpoint temperature of the process gas stream. External insulation can also be employed on the reactor heads as well as elsewhere on the reactor shell and associated piping systems.

Reactor inlet head 100 and outlet head 180 may be further outfitted with one or more optional emergency pressure relief devices (not shown), such as, for example, pressure safety valves (PSVs) or rupture discs. In some embodiments, such emergency pressure relief devices may instead be installed on the inlet and/or outlet piping connected to the reactor.

Referring again to Figure 1a, the first reaction stage 110 has a length of 4,600 mm (15 feet) and contains a plurality of seamless carbon steel tubes, represented generally in the figure as 115a, 115b, 115c. The entrance end of each tube in the first reaction stage can be attached, for example by welding or rolling, to the R1 inlet tubesheet (not shown per se, but located at the same position in the figure as separable connection 105). Each tube within the first reaction stage 110 extends through interstage baffle 126 (see Figure 1b) and passes completely through the interstage heat exchanger 130, which has a length of 2,100 mm (6.9 feet). This means that tube segment 135a is the lower end of tube 115a, tube segment 135b is the lower end of tube 115b, tube segment 135c is the lower end of tube 115c, and so on. As a result,

include but are not limited to ACS, ACS-2, ACS-6, ACS-7, and ACS-8, commercially available from Nippon Shokubai of Japan and T-202, commercially available from Nippon Kayaku of Japan. Some of these catalysts are also available in more than one size, for example ACS-7 catalyst is available as spheres in both large and small diameters, designated herein as ACS-7L (large) and ACS-7S (small), and may be used individually or in combination. Portions of the R2 tubes may also contain inert materials, such as for example 5 mm (~~5~~3/16 in) diameter Silica-alumina support spheres (designated as "SA-5218" and available from Norton Chemical Process Products Corp, Akron OH, USA), to create preheating or cool-down zones at specified locations within each tube. Selection and installation of appropriate R2 catalysts and inerts in the tubes of the second reaction stage are within the ability of one of ordinary skill in the art.

In this embodiment, the twistee inserts within the interstage heat exchanger as well as the second reaction stage (R2) catalyst are both retained in the reactor tubes using catalyst support grid panels comprising wire mesh. The use of catalyst support grid panels comprising wire mesh may provide significant manpower and time savings during catalyst installation and removal as compared to the use of traditional catalyst clips or other in-tube retaining means. In this specific embodiment, the catalyst support grid panels comprise segments of 2.7 mm wire mesh formed from 0.6 mm diameter wire. The wire mesh segments are welded to a 15 mm thick (0.6 in) support plate, comprising a plurality of 22.3mm diameter holes in a pattern that matches the specific geometry of the R2 outlet tubesheet; this results in a set of generally rectangular catalyst support grid panels, with a nominal rectangular dimensioning of about 918 mm x 471 mm (36 in x 18.5 in); panels to be fit along the circumference of the reactor tubesheet must of course deviate from a true rectangular shape due to the presence of one or more arcs, and therefore delineate a somewhat smaller area than the full-size rectangular panels.

In this embodiment, a total of 60 catalyst support grid panels are employed to retain the R2 catalyst within the tubes of the second reaction stage. Prior to the introduction of catalyst into the reactor tubes, each catalyst support grid panel can be placed with the wire mesh in direct contact with the bottom surface of the R2 outlet tubesheet and the panel can be secured with bolts that pass through solid regions of the panel and are anchored directly in the tubesheet. In at least one embodiment, the bolts can be permanently attached to the R2 outlet tubesheet and have sufficient

triangular pattern, with a 33.73 mm (1.328 in) tubesheet pitch, resulting in a distance between the tubes of about 6.5 mm (0.254 in).

To retain catalyst within these continuous tubes, a plurality of the previously-described catalyst support grid panels comprising wire mesh can be directly attached to the ISHX outlet tubesheet 345. Each of the continuous tubes may then be loaded as follows, beginning with the upstream (entrance) end of the tube:

- 282 mm (11 in) of 3/16 inch diameter (4.75 mm) SA-5218 silica-alumina support spheres (available from Norton Chemical Process Products Corp, Akron OH, USA)
- 905 mm (36 in) of ACF7-L (large cylinder) catalyst
- 3,413 mm (134 in) of ACF7-S (small cylinder) catalyst
- 51 mm (2 in) of 5/16 inch diameter silicon carbide rings (available from Norton Chemical Process Products Corp, Akron OH, USA)
- a 1,905 mm (75 in) long Twistee turbulence inducing insert, fitted with optional 8x8 wire mesh on the upstream end

This loading schedule results in a charge of 1.273 kg of total ACF7 catalyst (large + small size cylinders) in each first reaction stage tube.

In this embodiment, the residence time of process gas through the Interstage Heat Exchanger is found to be 0.96 seconds.

The open interstage region 350 of this embodiment has a total length of 2,134 mm (7 ft). Its shell comprises two 610 mm (24 in) diameter lower manways (not shown in Figure 3a), on opposite sides of the reactor (180 degrees apart), placed such that the lower manway centerline is located at a distance of about 356 mm (14 in) from the R2 inlet tubesheet 355. Additionally, the shell of open interstage region 350 comprises two 610 mm (24 in) diameter upper manways (not shown), on opposite sides of the reactor (180 degrees apart), placed such that the manway centerline is located at a distance of about 356 mm (14 in) from the ISHX tubesheet 345. These manways can provide personnel access to the interior of open interstage region 350 for catalyst replacements and other maintenance work. The upper manways may also be beneficially employed for transferring particulate materials - such as loose-fill spheres, cylinders, tablets, pellets, and granules - into the open interstage region such as by pouring.

such as for example, Syltherm™ heat transfer fluid in the R1 coolant circulation system and the ISHX coolant circulation system, and HITEC® salt in the R2 coolant circulation system.

When operated under the supplemental oxidant addition conditions summarized in Case 2 of Table 7A, the reactor of this embodiment has a nominal acrylic acid capacity of 110 kT per year. Also, the interstage residence time for this embodiment, being the sum total of the residence time through the interstage heat exchanger, the ceramic foam layer, and each section of the venturi-mixer, is determined to be ~~2.85~~2.56 seconds. Example 7 (below) illustrates how the interstage residence time is calculated for SSOI reactors operated with supplemental oxidant addition.

Figure 6 provides a detailed view of one embodiment of a supplemental oxidant mixing assembly, useful in SSOI reactors operated with supplemental oxidant addition. In this embodiment, the supplemental oxidant mixing assembly is a venturi mixer comprising a novel injector ring, and said venturi mixer is shown in a process upflow orientation, wherein process gases enter from the bottom through inlet contracting section 650, pass through intermediate throat section 630, and exit through outlet expanding section 640. Such an orientation may be useful in process upflow reactors, such as for example the reactor embodiment of Figure 4. Although described herein in a process upflow orientation, it should be noted that the venturi mixer apparatus of Figure 6 could also be beneficially employed in a downflow orientation.

In this embodiment, the venturi mixer rests upon a 150 mm thick (6 in) layer of stainless steel open cell foam 660. Inlet contracting section 650 is conical in shape, with a base dimension D1 of 5517 mm (18.1 ft), a height H1 of 379 mm (1.24 ft), and an included angle A1 of 160 degrees. Section 650 further comprises mounting flange 651, which is about 76 mm (3 in) thick. In at least one embodiment, the interior volume of inlet contracting section comprises a particulate inert material having a bulk void fraction of less than 50%. In one embodiment, for example, 50% of the interior volume of inlet contracting section 650 is occupied with 25.4 mm (1 in) diameter Denstone 57 inert spheres (represented in the figure as 655) to reduce residence time in this section of the venturi mixer.

Intermediate throat section 630 is cylindrical, with an internal diameter D0 of 1,219 mm (4 ft). Section 630 has overall height H0 of 457 mm (1.5 ft), which results

exchanger, located immediately downstream of the first reaction stage and referred to herein as an integrated interstage heat exchanger. Thus, the interstage heat exchanger (ISHX) also comprises over 33,000 seamless carbon steel tubes of 25.4 mm internal diameter. The ISHX has a length of 2,100 mm (6.9 ft). The total length of the continuous tubes passing through both the first reaction stage and the interstage heat exchanger is therefore 5,850 mm (19.2 ft). To retain catalyst within these continuous tubes, a plurality of the previously described catalyst support grid panels comprising wire mesh are directly attached to the first stage inlet tubesheet. Each of the continuous tubes is then loaded as follows, beginning with the upstream (entrance) end of the tube:

- 250 mm (10 in) of ¼ in (6 mm) diameter EnviroStone 66 inert ceramic spheres
- 730 mm (~~36~~ 29 in) of ACF7-L (large cyclinder) catalyst
- 2770 mm (~~136~~ 109 in) of ACF7-S (small cylinder) catalyst
- a 2100 mm (83 in) long twistee turbulence inducing insert

This loading schedule results in a charge of 1.042 kg of total ACF7 catalyst (large + small size particles) in each first reaction stage tube. The residence time of the process gas through the interstage heat exchanger is about 0.94 seconds.

The process gases leave the interstage heat exchanger at a temperature of not more than about 280 °C (536 °F) and then pass through the open interstage region. Optional supplemental oxidant 835, such as air or other oxygen-containing gases, may be passed through optional heat exchanger 836 and then added to the open interstage region; in such cases, optional mixing devices, such as for example a venturi mixer of the type previously described herein and further illustrated in Figure 6, may be used to safely homogenize the mixture of process gas and supplemental oxidant. In this specific embodiment, however, supplemental oxidant is not added to the open interstage region.

The open interstage region is 2,100 mm long (6.9 ft) and is loaded with sufficient 38 mm (1.5 in) diameter EnviroStone 66 inert spheres to occupy about 90% of the volume within the open interstage region, thereby providing a bed of ceramic spheres with an average depth of over 1,895 mm (6.2 ft) and more than 4,180 m^2 (more than 45,000 sq ft) of surface area for removal of foulants. Additionally, the interstage residence time (ISHX and open interstage region residence times

combined), as measured at the reference conditions of 240 °C and 30 psia (2 atm), is about 2.2 seconds, i.e., less than 3 seconds residence time.

Process gases then pass into the second reaction stage, located in the upper portion of the reactor. The second reaction stage has a length of 3,405 mm (11.2 feet). The second reaction stage has a tube count, internal tube diameter, and tube layout equal to that of the first reaction stage, thereby also comprising over 33,000 seamless carbon steel tubes of 25.4 mm internal diameter, arranged on a 60-degree triangular pattern. To retain catalyst within these tubes, a plurality of the previously described catalyst support grid panels comprising wire mesh are directly attached to the second stage inlet tubesheet. Each of these tubes is loaded as follows, beginning with the upstream (entrance) end of the tube:

- a modified twistee insert of 305 mm (12 in) overall length, comprising a 25.4 mm (1 in) long conical retaining spring attached to the ~~downstream~~ upstream end of a 280 mm (11 in) long twistee turbulence inducing insert
- 640 mm (~~31.5~~25in) of ACS7-L (large sphere) catalyst
- 2260 mm (~~120.5~~89in) of ACS7-S (small sphere) catalyst
- 200 mm (7.9 in) of ¼ in (6 mm) diameter EnviroStone 66 inert ceramic spheres

This loading schedule results in a charge of 1.417 kg of total ACS7 catalyst (large + small size particles) in each second reaction stage tube, and provides an overall 1.36 Catalyst Mass Ratio for the reactor.

All three primary reactor regions (first reaction stage, interstage heat exchanger, and second reaction stage) may be cooled by their own independent, shell-side coolant circulation systems. One or more of Dowtherm™, Syltherm™, or HITEC® salt may be used as the cooling medium; in this specific embodiment, molten HITEC® cooling salt is employed. Although not specifically shown in the figure, each of these coolant circulation systems comprises other components, such as for example pumps, coolant flow control valves, and steam boilers, and operates in a co-current circulation configuration, meaning that, for each reactor region, a stream of cool salt enters the lower portion of the region and a stream of warm salt exits the upper portion of the region.

Product gas comprising acrylic acid 801 leaves the top of the reactor and is cooled in indirect heat exchanger 832 to a temperature of about 225 °C (437 °F).