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EROSION IN SECOND STAGE CYCLONES: EFFECTS OF CYCLONE LENGTH AND OUTLET GAS VELOCITY

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ABSTRACT

Severe erosion in the lower cone and in the upper dipleg of second stage cyclones have been observed in commercial cyclones. The main objective of this study is to shed light on the mechanism by which this erosion takes place, and how different design and operating parameters affect the erosion. Experimental data on how parameters such as the cyclone length-to diameter ratio (L/D), inlet solids loading and gas outlet velocity affect second stage cyclone erosion are presented. The outlet gas velocity was varied by changing the size of the vortex tube diameter. The effect of a vortex stabilizer on cyclone cone erosion is also discussed.

INTRODUCTION

Petroleum refineries have increased their focus on improving unit reliability, and reducing operational and maintenance costs. Because their cyclones have high efficiencies, fluidized catalytic cracking unit (FCCU) process operators are now concerned with longer campaign durations, and would like to improve cyclone reliability. The 2008 NPRA survey and other surveys (1,2) revealed that FCCU cyclone reliability (3,4) was a major concern for refineries. The most pervasive problem is erosion in secondary cyclones in the lower cone and upper dipleg, which is the focus of this study.

There is a fundamental difference between first and second stage FCC cyclones in regard to erosion patterns. Highly-loaded first stage cyclones normally experience no cone erosion, whereas lightly-loaded second stage cyclones can have severe cone erosion. This seems to be counter-intuitive, but can be explained by the differences in the solids flow patterns and vortex lengths, as shown in Figure 1.

Due to the high solids loading and the low gas inlet velocity in a typical FCCU primary cyclone, gravitational force plays a key role. As a result, the solids appear to fall rapidly down into the cyclone cone and dipleg, as shown in Fig. 1, taking only one to two full turns before exiting the cyclone. The vortex length in a highly-loaded

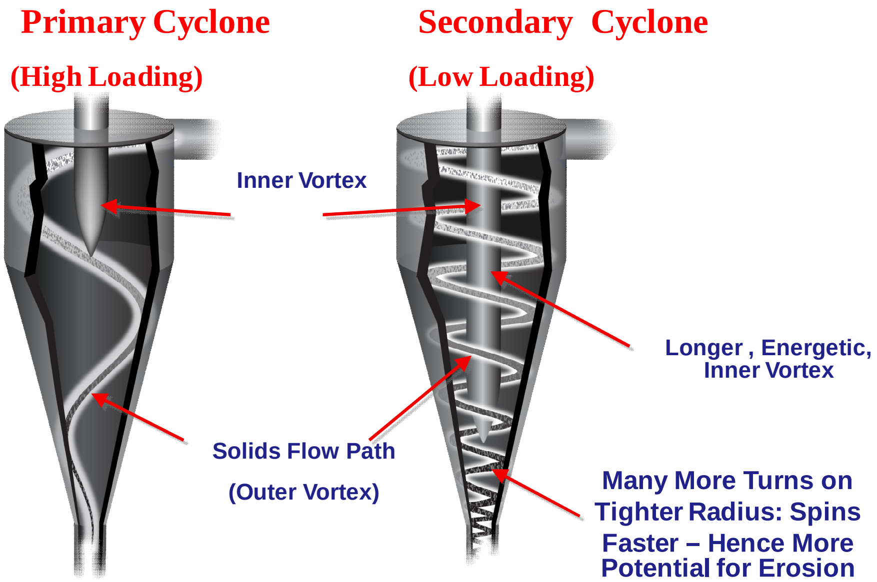


Figure 1. Schematic Depiction of First and Second-Stage Cyclone Operation

primary cyclone is much shorter, because the high solids loading dampens the formation of a long vortex. Therefore, the vortex does not “whip” the solids at a high velocity around the cone as in a primary cyclone.

In a typical second stage cyclone, the solids loading is approximately 1/1000 to 1/10,000 of the loading in the first stage cyclone. Due to the light solids loading and high gas velocity, the inner vortex is relatively long and energetic. As the swirling solids in the outer vortex approach the cone in a second stage cyclone, the long, rapidly-rotating vortex accelerates the solids stream and causes it to intensify its rotation because of the conservation of angular momentum. The solids in a second-stage cyclone typically take four to seven turns before exiting the bottom cone, and the spinning continues into the top portion of the dipleg below the cone. Most of those spins are located in the lower part of the cone and in the upper dipleg where the small diameters result in high angular velocities. The rapidly-rotating solids stream coupled with the unstable, continuous movement of the vortex causes significant erosion in the cone and at the top of the dipleg of second-stage cyclones.

EXPERIMENTAL

The testing was structured to benchmark three possible solutions to mitigate the erosion occurring in second-stage cyclones: 1) increasing cyclone length-to-diameter ratio (L/D), 2) increasing the angle of the cone, and 3) adding a vortex stabilizer.

The cyclone test facility used in the study is shown in Fig. 2. It consisted of a 0.91-m-diameter fluidized bed, a 0.2-m-diameter standpipe approximately 17 m in length; a slide valve to control the solids flow rate around the unit; a 0.2-m-diameter riser approximately 21 m tall; a 0.48-m-diameter first stage cyclone; and the 0.43-m-diameter second stage cyclone.

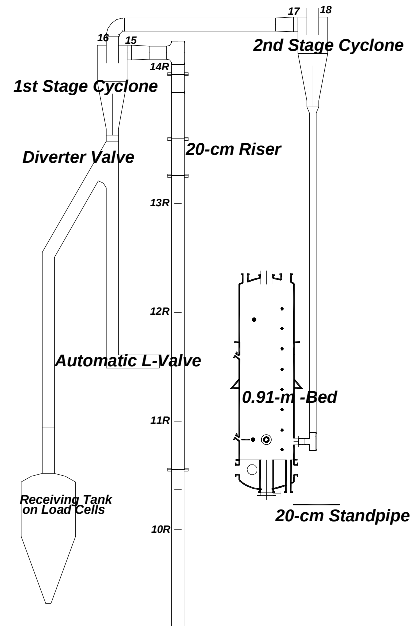
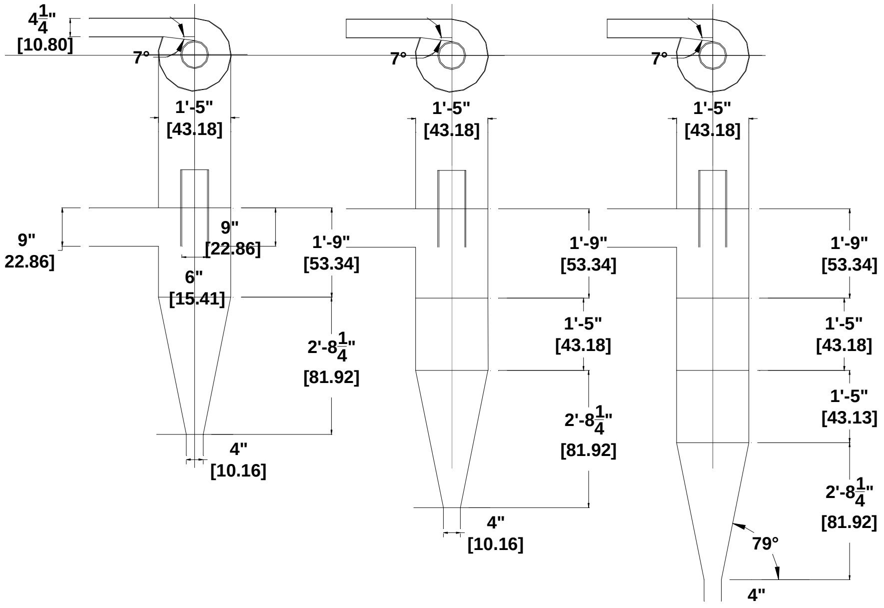


Figure 2. Schematic Drawing of Cyclone Erosion Test Unit

Air was used as the conveying gas in the test unit. The solids used were equilibrium FCC catalyst with a median ($d_{p,50}$) particle size of 75 μm. The fines (material < 44 microns) concentration in the catalyst was approximately 8 wt.%. The particle density of the catalyst was 1490 kg/m^3. Loadings to the second stage cyclone were varied between 0.001 to 0.21 kg/m^3. The secondary cyclone was constructed modularly for easy change of dimensions. A schematic drawing of the second stage cyclone is shown in Fig. 3 for several different barrel lengths. Multiple coatings of drywall joint compound were added to the inside of the cyclone before each test. The amount of erosion occurring in the cyclone was measured by the weight loss of the drywall compound occurring over a certain period of time.



L/D$_b$ = 3.1 **L/D$_b$ = 4.1** **L/D$_b$ = 5.1**

Figure 3. Schematic Drawing of Different Cyclone L/D's [cm]

RESULTS AND DISCUSSION

Effect of Increased Cyclone L/D

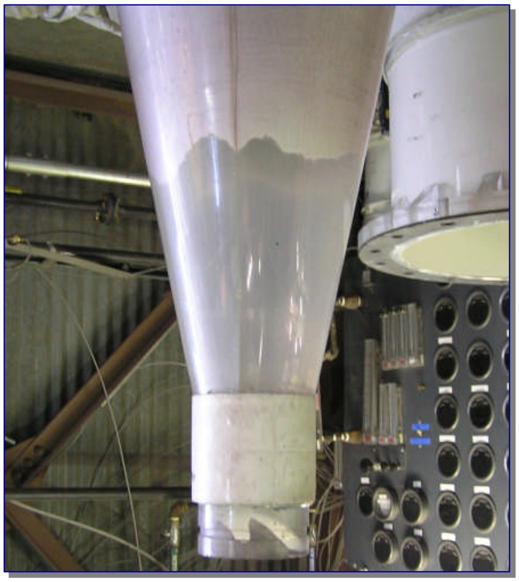


Figure 4. Photograph of Erosion of Drywall Joint Compound in the Cone of a Second-Stage Cyclone

The study found that the erosion took place primarily in the bottom 1/3 of the cone of the secondary cyclone". A photograph illustrating this effect is shown in Fig. 4. This figure shows that the drywall coating was completely eroded from the bottom 1/3 of the cone, whereas the remaining drywall was mostly intact.

Cyclone lengths were increased by increasing the length of the cyclone barrel to give length-to-diameter (L/D) ratios of 3.1, 4.1 and 5.1. In these tests, the inlet gas velocity to the cyclone was 19.8 m/s and the outlet gas velocity was 27 m/s. The results of the testing to determine the effect of cyclone L/D is shown in Fig. 5. As can be seen, the erosion rate decreased with increasing cyclone L/D. The measured erosion rate at an L/D of 5.1 was about 70% of the erosion rate of the cyclone with an L/D of 3.1.

Barrel erosion rates were also measured in the tests and were found to be much lower than the erosion rates in the cone (Fig. 5). Measured barrel erosion rates ranged between 85 to 105 g/h, which was about 15% of the cone erosion rate for the cyclone with an L/D of 3.1, and about 20% for a cyclone with an L/D of 5.1.

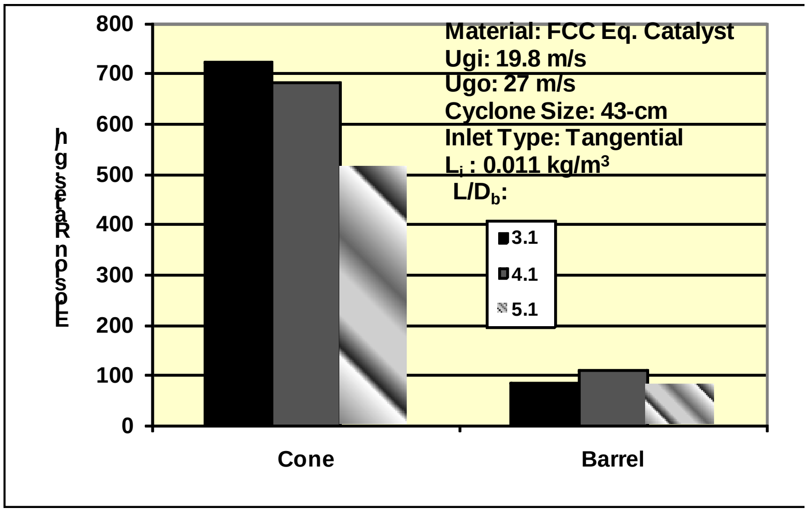


Figure 5. The Effect of Second-Stage Cyclone L/D on Cone Erosion and Barrel Erosion

Effect of Cone Length

The effect of cone length on cyclone cone erosion was tested by adding a longer cone so that the cone angle from the horizontal increased from 79 to 84º. This increased the cone length from 0.82 to 1.68 m. When comparing the two cone configurations, the overall length of the cyclone was held constant.

As shown in Fig. 6, the cyclone with the longer cone had a higher erosion rate at low outlet gas velocities than the cyclone with the shorter cone but longer barrel. However, the erosion rate became approximately equal to the erosion rate of the shorter cone at the highest outlet gas velocity. The trend of the two curves was exactly opposite. For the cyclone with the shorter cone, the erosion rate increased with gas velocity, whereas for the longer cone the erosion rate decreased with gas velocity. For an outlet gas velocity of approximately 27 m/s, the erosion rate for the short cone cyclone was approximately 800 g/h, while the erosion rate for the long cone cyclone was approximately 1800 g/h, a factor of 2.25. However, even at the highest outlet gas velocities, which were outside typical operating outlet velocities of secondary cyclones, the longer cone did not have a significant advantage over the shorter cone in regard to cone erosion

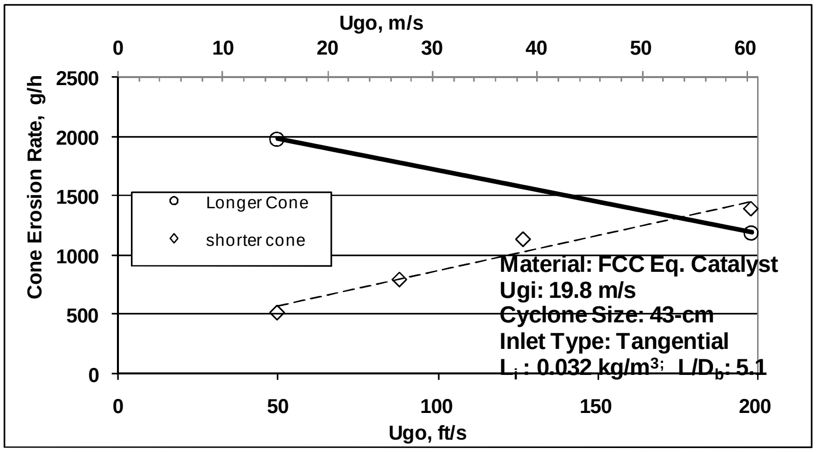


Figure 6. The Effect of Cone Length on Second-Stage Cyclone Cone Erosion

Vortex Stabilizers

To determine the effect of adding a vortex stabilizer on cone erosion, a flat-disk vortex stabilizer was added in the cyclone cone, approximately 1/3 of the cone length from its bottom, at the top of the region in which the cone erosion was most significant. A photograph of the disk is shown in Fig. 7.

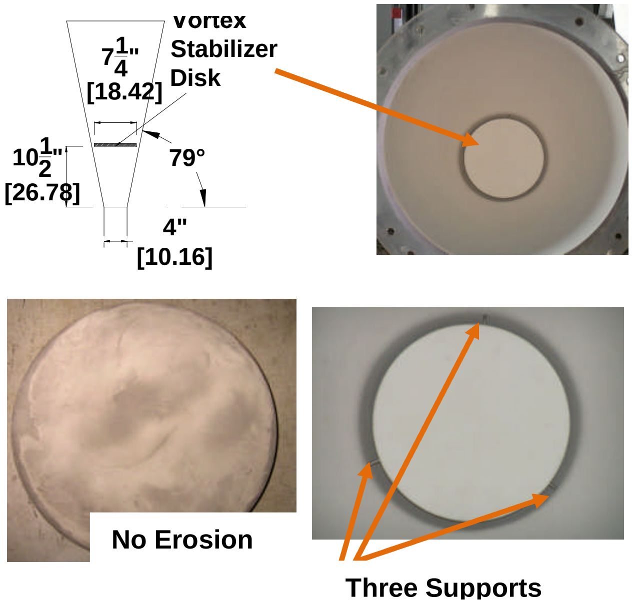


Figure 7. Photographs and Schematic Drawing of the Vortex Stabilizer and Supports

The location of the vortex stabilizer was selected to be at the top of the high-erosion section of the cone. It was thought that adding the vortex stabilizer 1/3 of the cone height from the bottom of the cone would prevent high-velocity spinning solids in that region and reduce erosion. The purpose of the flat plate (or the vortex stabilizer) was to stabilize the central vortex. It was expected that the influence of the vortex would end at the plate, and the number and intensity of the solids spirals below the plate would be reduced.

The effect of adding the vortex stabilizer disk on cyclone cone erosion is shown in Figs. 8 and 9 for cyclones with L/Ds of 3.1 and 5.1, respectively. It was found that cone erosion for a cyclone with a vortex stabilizer was significantly lower than that for a cyclone without a vortex stabilizer. Cone erosion was found to increase linearly with increasing gas velocity for a cyclone without a vortex stabilizer. However, cone erosion in a cyclone with a vortex stabilizer decreased slightly with increasing gas outlet velocity. The decrease in erosion is counter-intuitive. However, this can be explained by the fact that the vortex diameter is smaller when the diameter of the outlet tube is decreased. This increases the distance between the vortex and the cone wall, which then reduces the centrifugal force (and, therefore, the solids velocity) on the solids rotating in the cone. The reduction in force on the solids appears to explain the decrease of cone erosion vs. gas outlet velocity for a cyclone with a vortex stabilizer (Figs. 8 and 9).

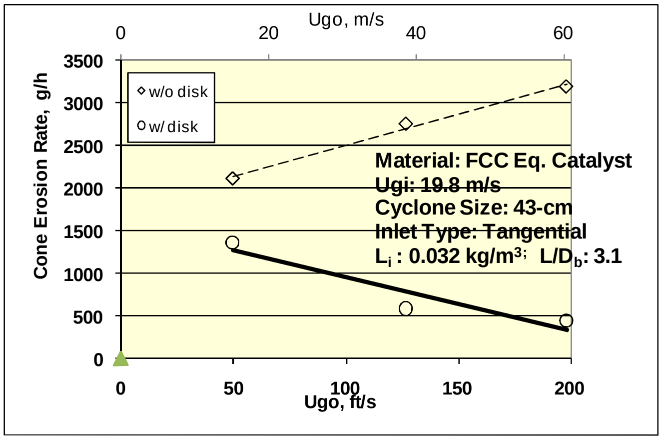


Figure 8. The Effect of Gas Outlet Velocity on Second-Stage Cyclone Cone Erosion for Cyclones With and Without a Flat-Plate Vortex

For the shorter cyclone, the cone erosion rate was approximately 2100 g/h for the cyclone without a vortex stabilizer at an outlet gas velocity of 15.2 m/s. The corresponding cone erosion rate for the cyclone with a vortex stabilizer at the same outlet gas velocity was about 1400 g/h. The cone erosion rate with the vortex stabilizer was about 67% of the cone erosion rate for the cyclone without the vortex stabilizer. However, at an outlet gas velocity (45.7 m/s) closer to actual practice, the cone erosion rate for a cyclone with the vortex stabilizer was only about 600 g/h. The corresponding cone erosion rate for a conventional cyclone without a vortex stabilizer was about 2900 g/h. This was a factor of about 4.8.

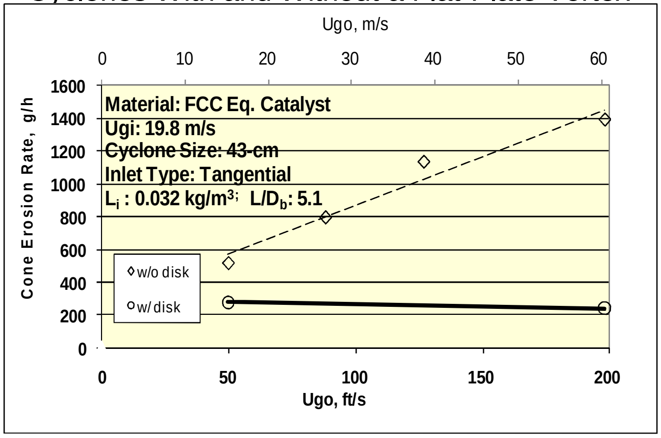


Figure 9. The Effect of Gas Outlet Velocity on Second-Stage Cyclone Cone Erosion Rate for Cyclones With and Without a Flat-Plate Vortex Stabilizer

For the cyclone with an L/D of 5.1, the overall cone erosion rates were lower. This was expected because the tests with the longer cyclone described above gave lower cone erosion rates than shorter cyclones. As with the shorter cyclone, the trendlines of cone erosion rate vs. outlet gas velocity were linear. Similarly, the curve for the conventional cyclone erosion rate without a vortex stabilizer increased with increasing gas velocity, and the curve for the cyclone erosion rate with the vortex stabilizer decreased slightly with increasing gas velocity. However, as with the shorter cyclone, the cyclone with the vortex stabilizer was found to have much lower erosion rates than the conventional cyclone without the vortex stabilizer. Comparing the cone erosion rates at an outlet gas velocity of 45.7 m/s, the conventional cyclone without a vortex stabilizer had a cone erosion rate of approximately 1200 g/h, while the cyclone with the vortex stabilizer had a cone erosion rate of about 240 g/h. This is a factor of approximately 5 - similar to what was found for the shorter cyclone.

Why does the vortex stabilizer decrease cone erosion? It appears that the stabilizer prevents the vortex from "whipping" the solids around at high velocities below the stabilizer in the region where high cone erosion rates are experienced for a cyclone without a vortex stabilizer. Below the stabilizer, the high-velocity central vortex does not really exist. Therefore, this reduction in the spinning solids velocity at the wall leads to a significant reduction in erosion. A comparison of the cone erosion rates for various second-stage cyclone configurations is given in Table 2.

Drywall joint compound was also added to the disk to see if the upper surface of the vortex stabilizer would erode. However, essentially no erosion was measured on the upper surface of the disk, and no erosion was found on the supporting rods.

Shell Experience with Vortex Stabilizers

In the 1980's, Shell had over 30 FCC units, mostly with cyclones without vortex stabilizers, which were found to be the number one cause of all FCC unscheduled shutdowns. Shell started using the vortex stabilizer (5) in the early 90's. Fig. 11 shows the result of how the vortex stabilizer reduced overall FCC unscheduled down time.

Table 2. Comparison of cone erosion rates for different cyclone configurations

	L/D (-)	Velocity Inlet, m/s	Velocity Outlet, m/s	Erosion Reduction Factor	Cone Erosion Rate, g/h
Short Cyclone	3.1	19.8	45.7	Base	2850
Long Cyclone	5.1	19.8	45.7	>2	1200
Long Cone	5.1	19.8	45.7	>2	1200
Vortex Stabilizer	3.1	19.8	45.7	>4	650
Vortex Stabilizer	5.1	19.8	45.7	>11	240

Using 1992 data as the base line, Fig. 11 shows that cyclones with the vortex stabilizer reduced the total unit down time of all FCC units in the Shell system by a factor of 10 over a period of 8 years.

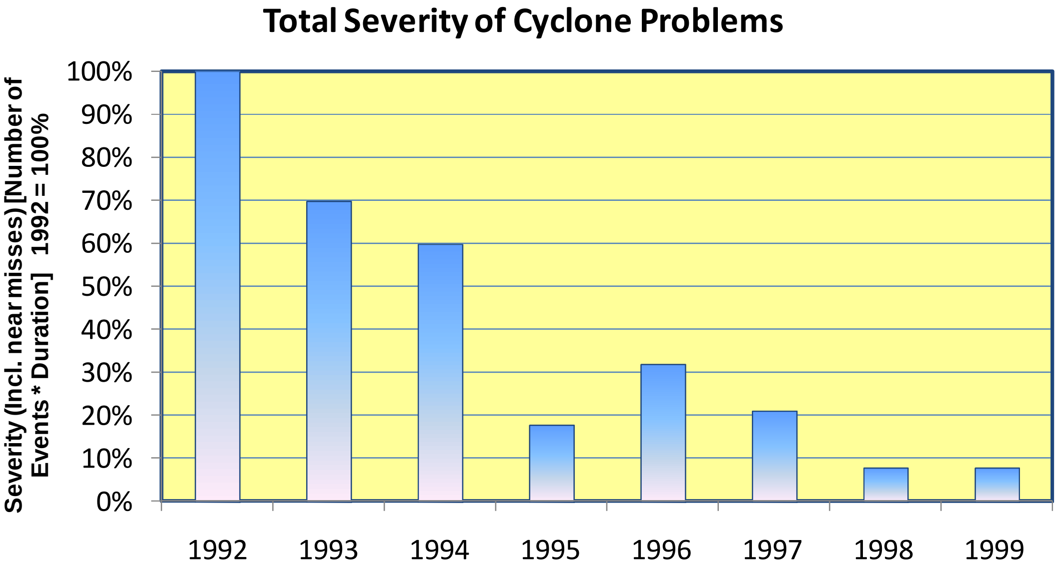


Figure 10. Cyclone Severity vs. Time

CONCLUSIONS

Second stage cyclone cone erosion is a pervasive problem in FCCU operation, which can be significantly improved by incorporating the use of a vortex stabilizer. Vortex stabilizers were more effective in reducing second stage cyclone cone erosion than increasing cyclone barrel or cone length.

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