

Performance Testing of a Russian Mir Space Station Trace Contaminant Control Assembly

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ABSTRACT

A filter assembly which is incorporated into the Russian Trace Contaminant Control Assembly was tested for removal of airborne trace chemical contaminants in a closed loop 9 m³ system. Given contaminant loading rates and maximum allowable atmospheric concentrations, the Russian system was able to maintain system air concentrations below maximum allowable limits. This was achieved for both a new filter system and for a system where a part of it was pre-loaded to emulate 3 years of system age.

INTRODUCTION

RUSSIAN TCCA DESCRIPTION - The Trace Contaminant Control Assembly (TCCA) used onboard the Mir Space Station has been in operation since April, 1987. The TCCA, shown in Figure 1 is composed of six primary components: a blower, a non-regenerable charcoal Pre-filter, two regenerable charcoal filters, an ambient temperature catalyst canister, and a valve assembly. The TCCA processes 15-25 m³/hr of cabin air, nominally 20 m³/hr.

The non-regenerable charcoal pre-filter weighs 6 kg., is 22.5 cm. long and 20 cm. in diameter. Air flows radially through approximately 1.3 kg. of activated charcoal and is designed to remove organic contaminants with molecular weight greater than about 80. It serves to protect the regenerable filters from fouling with contaminants that are difficult to desorb from the charcoal.

The total TCCA air flow from the Pre-filter is then split equally between the 2 regenerable filters. These axial-flow filters are designed to remove contaminants of lower molecular weight (<80). These filters each weigh approximately 16 kg each, have a length of 29.5 cm, and a diameter of 25 cm. Each filter contains about 1.4 kg of activated charcoal. Each of these canisters also contain

4 heater elements and 3 RTDs (resistive temperature devices) for thermal-vacuum regeneration every 20 operational days.

Downstream of the regenerable filters the air streams recombine and flow through a radial flow ambient temperature catalyst filter. This filter is designed to oxidize carbon monoxide and hydrogen. It has a length of 23.5 cm and a diameter of 12 cm. The catalyst filter's overall weight is 2.5 kg of which 0.5 kg is accounted for by the catalyst.

The Russian TCCA was designed to remove trace chemical contaminants from the Mir Space station

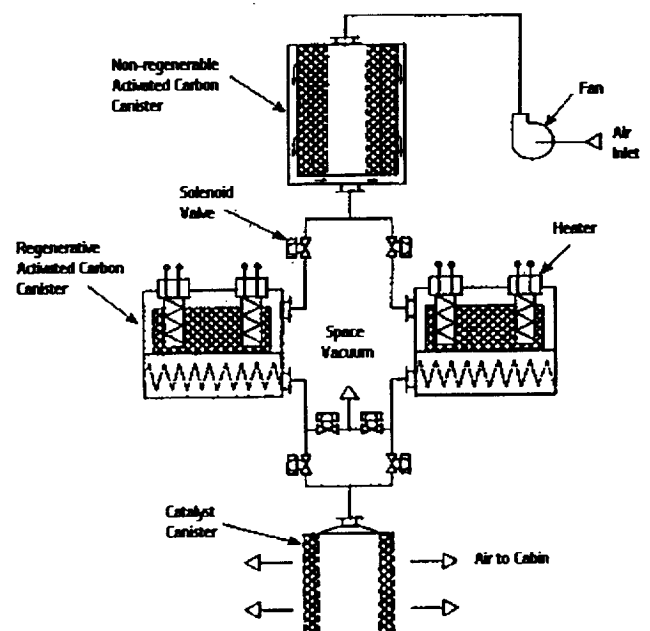


Figure 1. Mir Trace Contaminant Control Assembly

atmosphere at the rates specified in Table 1. At these rates, the Maximum Allowable Concentrations (MACs) also listed by Table 1 were not to be exceeded [1,2,3].

PERFORMANCE CONFIRMATION TESTING - In 1996 Boeing conducted a system level test with a filter assembly which is currently used on the MIR space station. This assembly includes the following components:

- A Pre-filter element containing activated charcoal for removal of high molecular weight organics (>80)
- Two regenerable Fine Filter canisters containing activated charcoal for lower molecular weight organic removal, heater elements and RTDs

- An ambient temperature Catalytic Filter element for primarily removing Carbon Monoxide and Hydrogen.

These filter components were incorporated into a nominal 9 m³ closed air loop ground test facility which emulated the MIR filter assembly operation. The filters were configured as shown in Figure 2. The filters were then tested with a multi-contaminant load from January 29 to April 25, 1996, under contract to NASA's Marshall Space Flight Center (NASA/MSFC) in Huntsville, Alabama. The goal of the test was to verify that the filter assembly would remove airborne chemical contaminants at specified daily loading rates and maintain concentrations to below Russian Maximum Allowable Concentrations.

TRACE CONTAMINANT	RUSSIAN MAC (mg/m ³)	MINIMUM DAILY LOADING (mg/day)	COMMENTS
Isopropyl Benzene	0.5	50	
Toluene	2.0	66	
Cyclohexane	3.0	200	
Ethylacetate	4.0	250	
Benzene	2.0	0.45	
Butanol	0.8	80	
Acetone	1.0	27	
Ethanol	10.0	250	Total of 300 mg/day added
Ethylene Glycol	(100.0)	(50)	NOT ADDED Ethanol added instead
Methanol	1.0	3.0	
Formaldehyde	0.3	10	
Acetaldehyde	1.0	24	
Nitrogen Dioxide	0.3	13.5	
Ammonia	1.0	20	
Carbon Monoxide	5.0	390	
Methane	0.5 vol %	30	
Hydrogen	0.5 vol %	1200 l/day*	

* The hydrogen loading was adjusted for the volume of the test system (approximately 9 m³) not to exceed the MAC.

Table 1 Russian Normal Contaminant Load, Maximum Allowable Concentration

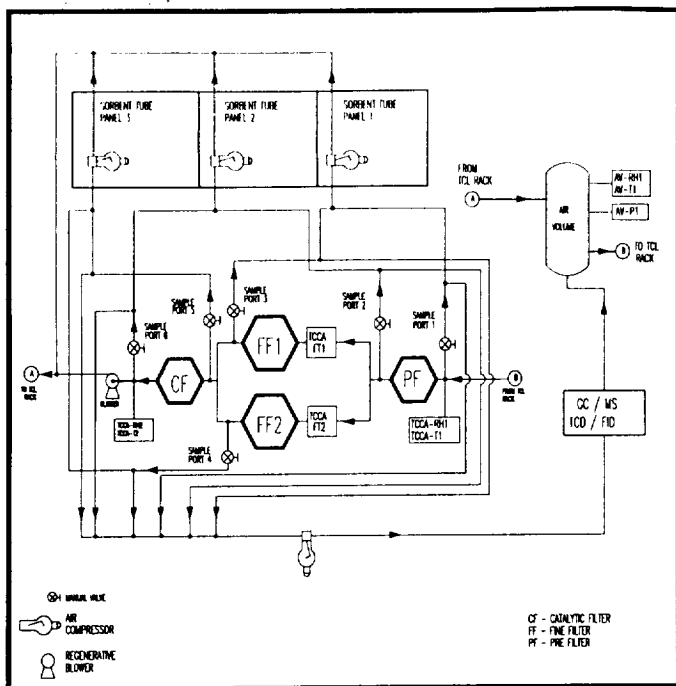


Figure 2 Trace Contaminant Control Assembly (TCCA) and Sampling Port Schematic

TEST REQUIREMENTS AND SPECIFICATIONS -

The Russian Maximum Allowable Concentrations (MAC) and contaminant injection rates used for this test are given in Table 1. All contaminants were injected continuously to create a multi-contaminant system air loading which would simulate an on-orbit cabin air environment. Ethylene glycol was not injected for this test due to technical difficulties in obtaining a gas phase concentration of 100 mg/m³ of ethylene glycol at ambient temperatures. The amount of ethanol injected daily was increased by the amount expected for ethylene glycol. All contaminants, except hydrogen, were injected continuously for the duration of each test phase. Hydrogen removal was tested separately in the final phase of testing. Its presence and removal is considered to represent an off-nominal operational situation, such as leakage from the oxygen generator assembly. Methane was injected as part of the normal continuous contaminant load.

During this test, air flow rate was controlled to 21-22 m³/hr (12.4-12.9 scfm), system air temperature to 21-24 °C (70-75 °F), system air relative humidity to 38-42 %, and system air pressure to 750-850 mmHg (14.57-16.51 psia). At these operating conditions, all Russian operating requirements were met.

TEST SYSTEM DESCRIPTION

The Trace Contaminant Control Test Facility incorporated a rack which housed the Trace Contaminant Control Assembly (TCCA Rack); a rack to control system air temperature, humidity, and to inject trace contaminants (TCL Rack); a 9 m³ stainless steel tank; and an in-line GC/MS. These major components were interconnected by 2-inch stainless steel tubing to create a closed air loop. The components were configured as shown in Figure 3.

The TCCA Rack receives air from the Thermal Control and Contamination Control Loop (TCL) Rack, which has been conditioned for temperature, humidity, and contaminant load. In the TCCA Rack, the air is directed to the filters or shunted around them. After exiting the TCCA Rack, the air is directed back to the TCL rack in a closed loop.

The TCCA system air is monitored for flow, temperature, humidity, and contaminant load. This monitoring point is in the TCCA Rack just prior to the Pre-filter inlet. The chemical makeup of the test atmosphere is monitored at sample port 1, which is collocated with the instrumentation. As shown in Figure 2, the TCCA Rack contains 6 sample ports which were used to sample around individual filter elements.

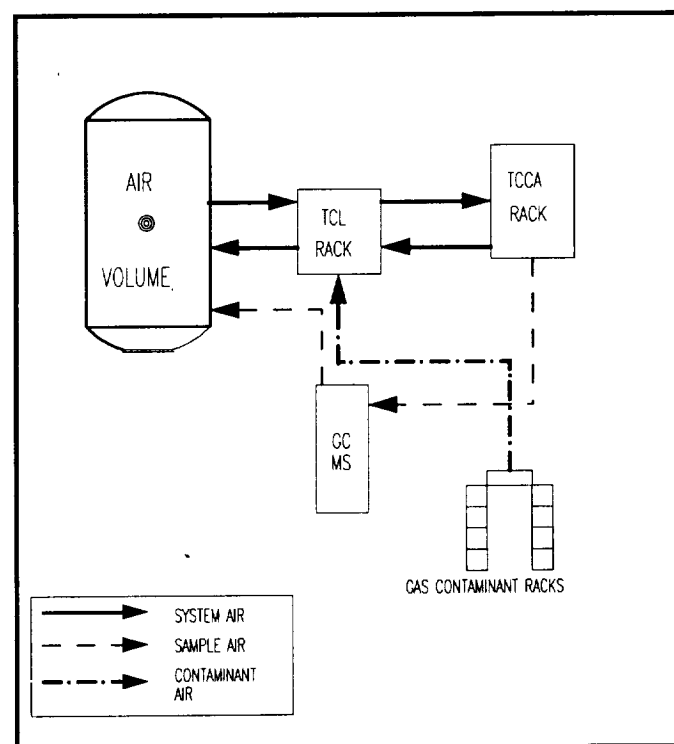


Figure 3 Test Facility Layout

CONTAMINANT INJECTION - The Gaseous Contaminant Injection Assembly provided pressure regulation and mass flow control of the gas-phase contaminants used for contaminant loading during filter performance testing. During nominal performance testing, gas-phase contaminants were injected into the air volume tank. As a follow-on to nominal testing, hydrogen was injected to 0.5 vol. % as an off-nominal condition. The gases were supplied from pressurized bottles containing a certified percentage of the contaminant in air as listed below:

- 0.295% +/- 0.004 Ammonia/Balance Air
- 4.0% +/- 0.080 Carbon Monoxide/Balance Air
- 0.515% +/- 0.010 Methane/Balance Air
- 0.145% +/- 0.003 Nitrogen Dioxide/Balance Air
- 0.199% +/- 0.004 Acetaldehyde/Balance N₂

The gases were injected continuously at varying rates into the system air at the TCL Rack to achieve the required daily system mass loading specified in Table 1.

Liquid contaminants were injected as two different mixtures at the TCL Rack. The first was an aqueous mixture containing formaldehyde, methanol, ethanol, 1-butanol, and acetone. The second was an organic mixture containing isopropyl benzene, toluene, cyclohexane, ethylacetate, and benzene. Syringe pumps were programmed to inject the liquid mixtures into heated bypass tubes where the system air swept the evaporated contaminants to the air mixing volume. The air from the mixing volume was then directed to the TCCA rack for filtration. Liquid contaminants were injected once every 4 hours, and the concentration pulses monitored hourly by automated in-line GC/MS.

ANALYTICAL METHODS - Sampling methods used during the test are the following:

- Automated in-line sample acquisition
- Sorbent tube collection
- Sample collection into pressurized cylinders.

In-line detection was performed with GC/MS for most organic trace contaminants, Flame Ionization Detection, Thermal Conductivity Detection (TCD) for hydrogen analysis. Sorbent tubes were used primarily to analyze off-line for butanol, methanol, formaldehyde, and ammonia. Carbon monoxide samples were collected in pressurized cylinders for off-line analysis by GC/TCD. All other contaminants were primarily analyzed by GC/MS automatically on an hourly basis.

FILTER REGENERATION

Fine Filters regeneration was conducted during the system test similar to the regeneration schedule used on space station Mir, where one of the Fine Filters is regenerated every 20 days while the full TCCA air flow is directed to the Fine Filter not undergoing regeneration. During regeneration, the filter is continually exposed to space vacuum. After the filter is exposed to space vacuum for 60 minutes, power is applied to internal filter heater elements to raise the filter temperature to 180-200°C. Temperature is controlled to 175-200°C for 1.5 hours. The filters continue to be exposed to space vacuum for 2 additional hours. Vacuum is then disconnected and the filter is allowed to cool down to <45°C. A bleed valve then opens, allowing the filter to be repressurized to cabin air pressure, and the filter is brought back on-line.

During this test both Fine Filters were regenerated simultaneously prior to the start of the testing and then at the end of the first performance test period. The initial regeneration was to establish a test baseline prior to the start of test. The second regeneration was to baseline the Fine Filters for testing of the assembly after accelerated aging of the Pre-filter, as discussed below.

TEST CONDUCT

Nominal performance testing was conducted in two phases. The first phase was a 20-day performance test period where system air contaminants were injected at the rates in Table 1 and the filter elements were new. This data provided a "new filter assembly" performance baseline.

Prior to the start of the second 20-day performance period, the age of the Pre-filter was accelerated to approximately 80% of its expected 3-year design life. This was accomplished by loading the Pre-filter over a 15-day period with isopropylbenzene, toluene, cyclohexane, and benzene with the amounts indicated in Table 2. During this period air flow did not go through the Fine Filters or Catalytic Filter. These contaminants were chosen since the Pre-filter preferentially adsorbs them over the other test contaminants. The filter was then allowed to equilibrate by circulating system air over the next 5 days without contaminant injections.

The second performance period was conducted identically to the first after re-installing the Fine Filters and Catalytic Filter.

RESULTS

Table 2 summarizes the masses of contaminants which were loaded during the two performance and interim pre-load phases of testing. The four gas-phase contaminants listed were injected at a steady rate, and the liquid-phase contaminants by pulse injection every four hours. Nitrogen dioxide was also injected, 639.7 mg during Phase 1 and 73.4 mg during Phase 2. Due to some difficulty with the analytical method, results for removing NO₂ from the system air are not discussed in this paper. However, it is important to note that NO₂ was a part of the multi-contaminant background. Methane injection is shown in Table 2. No significant adsorption of methane was detected during either test phase which could not largely be accounted for through test rig leakage. Some temporary adsorption (1%) was detected early in Phase 1 while the filters were largely unloaded, as shown in Figure 4. Methane was displaced, however, by other contaminants which had greater thermodynamic potential for adsorption.

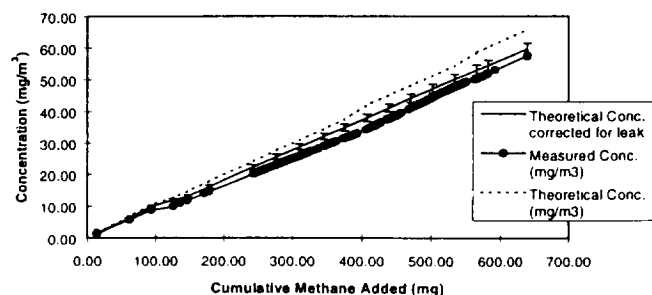


Figure 4. Methane Concentration during Phase 1

CONTAMINANT	CONTAMINANT LOADING			
	20-day Phase 1 (gm)	20-day Preload* (gm)	20-day Phase 2 (gm)	20-day Target (gm)
Acetaldehyde**	0.57		0.47	0.48
Ammonia**	0.47		0.42	0.40
Acetone	0.55		0.54	0.54
Benzene	0.03	0.40	0.009	0.009
Butanol	1.61		1.59	1.60
Isopropylbenzene	1.02	43.3	0.998	1.00
Toluene	1.35	57.3	1.32	1.32
Cyclohexane	4.00	137.3	3.91	4.00
Ethanol	6.03		5.89	6.00
Methanol	0.075		0.057	0.060
Ethylacetate	4.99		4.91	5.00
Formaldehyde	0.20		0.20	0.20
Carbon monoxide	8.35		7.91	7.80
Methane	0.64		31.0	0.60

* The Pre-load phase was designed to accelerate the age of the pre-filter to about 80% of its 3-year design life with selected compounds.

** The gas-phase contaminants were injected in a steady rate manner but with varying levels.

Table 2. Summary of Trace Contaminant Loading during Test

	Russian MAC (mg/m ³)	Phase	Injection Rate* (mg/min)	System Concentration* (mg/m ³)	Error	Detection Limit (mg/m ³)
Acetaldehyde	1.0	1	0.02	0.06-0.08	+/-0.01	0.028
Acetaldehyde	1.0	1	0.13	0.36-0.42	+/-0.03	0.028
Acetaldehyde	1.0	2	0.02	0.05-0.14	+/-0.01	0.006
Ammonia	1.0	1/2	0.02-0.08	0.12	+/-0.04	0.01-0.03
Carbon Monoxide	5.0	1/2	1.14-1.55	2.4	+/-0.8	1.0

* Gas phase contaminant injection rate.

* Sample collection by sorbent tube/ analysis by GC/MS.

** Milligrams per liquid contaminant pulse injection every 4 hours.

Table 3. Gas Phase Contaminant Removal Performance

In all of the test phases, contaminant concentrations did not exceed the Russian Maximum Allowable Concentrations in Table 1. Table 3 summarizes the removal performance results for the gas phase contaminants acetaldehyde, ammonia, and carbon monoxide. Acetaldehyde was injected at two different rates during the 20-day Phase 1 test period. The 0.02 mg/min rate was a nominal 24-hour/day continuous rate. During this rate of injection in Phase 1, acetaldehyde concentration in the tank was 0.06-0.08 mg/m³, which is 10 times less than MAC. An acetaldehyde injection rate 8 times greater than

that specified in Table 1 (0.13 mg/min) was employed for three days, resulting in a small increase in system concentration. However, the acetaldehyde tank concentration remained at one half the MAC. During the 20-day Phase 2 test period only the 0.02 mg/min acetaldehyde continuous injection rate was used. Some breakthrough was observed (0.05 to 0.14 mg/m³); however, the concentration remained well below the acetaldehyde maximum allowable concentration of 1 mg/m³.

	Injection Mass* (mg)	Injection Concentration** (mg/m ³)	Russian MAC (mg/m ³)	40 min.* (Phase 1)	1 hour**(Phase 2)	2 hour** (Phase 2)	3 hour** (Phase 2)	4 hour** (Phase 2)
Isopropylbenzene	8.49	0.91	0.5	0.31	0.29	0.18	0.13	0.09
Toluene	11.2	1.2	2.0	0.41	0.36	0.22	0.16	0.12
Benzene	0.08	0.008	2.0	<0.024	<0.02	<0.01	<0.007	<0.005
1-Butanol	13.48	1.45	0.8	0.52	0.48	0.29	0.20	0.14
Ethanol	49.88	5.35	10.0	1.96	2.49	1.81	1.53	1.24
Methanol	0.5	0.05	1.0	0.20	0.11	0.04	<0.018	0.014
Ethylacetate	41.8	4.48	4.0	1.66	1.58	0.99	0.74	0.54
Acetone	4.58	0.49	1.0	0.21	0.18	0.14	0.10	0.09
Formaldehyde	1.69	0.18	0.3	0.06		0.03		0.010
Cyclohexane***	33.3	3.57	3.0	2.100	1.92	1.22	0.87	0.700

* Milligrams of liquid contaminant injected every 4 hours.

** Calculated concentration expected in the system (@ STP) after injection, with no removal by filtration.

* Contaminant concentration on day 20 of Phase 1; sample collection for 40 minutes following injection.

** Contaminant concentrations for day 20 of phase 2:

- 1 hour continuous sorbent tube collection after injection
- 2 hours continuous sorbent tube collection after injection
- 3 hours continuous sorbent tube collection after injection
- 4 hours continuous sorbent tube collection after injection

*** Sample analyses by on-line GC/MS, values are integrated average concentrations over the respective sample periods of 1, 2, 3, and 4 hours.

Table 4. Liquid Contaminant Removal Performance

Ammonia was injected at various rates (0.02-0.08 mg/min) during both Phases 1 and 2. There was little sensitivity of system concentration to injection rate; therefore, the analytical results were treated as a single group. Based on samples taken before and after each filter element, ammonia removal efficiency was generally shown to be 100%, maintaining system concentration of ammonia at about 0.12 mg/m³.

The results for removing carbon monoxide from air were also treated as a single group. Some variation in injection rate was used, as indicated in Table 3. Carbon monoxide concentration in the system air was maintained at approximately 2.4 mg/m³ by oxidation in the Catalytic Filter.

Liquid-phase contaminant removal results are summarized in Table 4. These contaminants were pulse-injected every four hours. Table 4 shows the mass of each pulse and the system concentration after each pulse which would be expected without any removal by filtration. In the cases of isopropylbenzene, butanol, ethylacetate, and cyclohexane, the system concentration of these contaminants, without any removal by filtration after a single pulse, would exceed MACs. The results in Table 4 are from continuous sorbent tube collection, with sample collection periods ranging from 40 minutes to 4 hours. These samples were collected at sample port 1 (see Figure 1) which represented tank (system) concentrations.

During phase 1, samples were collected for the 40 minute period immediately following the injection. These results provided a good indication of contaminant removal. As shown in Table 4, all 40 minute sample results were less than MAC. However, a 40 minute sample collection time did not provide complete monitoring of the system

concentration between injections. Therefore, during phase 2, system air samples were continuously collected for 1, 2, 3, and 4 hours following injection. The 4-hour sample normalizes the system air concentration following the injection over a 4 hour period. This effectively provides a system level steady state concentration for each contaminant. In summary, none of the 4-hour liquid phase contaminant concentrations exceeded the Russian MACs.

The system air concentrations were monitored by GC/MS during each 4 hour injection cycle over the 20 days of each test phase. There were 4 in-line GC/MS samples taken after each injection. The fourth sample of each cycle represented the system air concentration just prior to the next injection, and therefore, the residual mass in the system. This residual mass indicated less than 100% removal efficiency in the operation of the filter assembly. Figure 5 shows the residual mass for test phases 1 and 2 for some of the liquid phase contaminants.

An increase in residual concentrations of certain of the liquid phase contaminants was observed between test phases 1 and 2. These results are also shown in Figure 5. Four of the contaminants showed significant increase in residual system air concentration between phases 1 and 2: ethanol, cyclohexane, ethyl acetate, and acetone. These contaminants were displaced from the Pre-filter after the Pre-loading phase, basically reducing the system capacity for these contaminants during phase 2. However, these concentrations are still well below MACs.

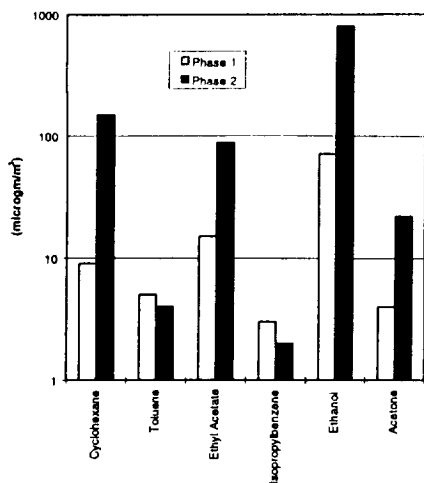


Figure 5. Residual Concentrations 4 Hours after Liquid Injection by Test Phase

HYDROGEN TEST

Hydrogen removal is performed by the catalytic filter. Hydrogen was tested separately at the end of the two 20-day performance periods. After the last contaminant pulse injection, hydrogen was injected into the tank air, raising the system air hydrogen concentration to 0.5%/v. Hydrogen removal represents an on-orbit contingency situation in the event of a leak in the oxygen generation assembly. This test was designed to demonstrate the hydrogen removal efficiency of the catalytic filter. As shown in Figure 6, hydrogen concentration decayed from 450 mg/m³ to approximately 130 mg/m³ in 70 minutes. Ultimately, hydrogen concentration decayed to detection limit (50 mg/m³) within 48 hours.

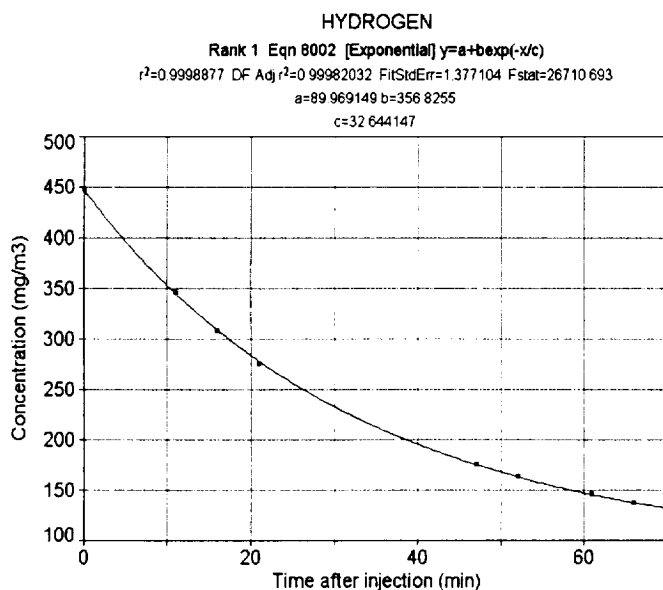


Figure 6. Hydrogen Concentration Decay

CONCLUSIONS

Based on using Table 1 loading rates, the following conclusions can be made:

- The Russian TCCA can maintain contaminant concentrations below Russian MACs when the filters are new.
- The Russian TCCA can maintain contaminant concentrations below Russian MACs after aging the Pre-filter with approximately 80% of a 3-year loading of isopropylbenzene, toluene, cyclohexane, and benzene.
- The assumption that the Pre-filter has a useful life of 3 years is valid based on the loading rates in Table 1 for the high molecular weight organic compounds. No significant increase in test chamber concentration was observed based on the aged Pre-filter.
- The thermal vacuum regeneration of the Fine Filters enabled the filter system to maintain contaminant concentrations to within the limits of Table 1.

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