

A Design Basis for Spacecraft Cabin Trace Contaminant Control

J. L. Perry

National Aeronautics and Space Administration

This is a work of the U.S. Government.

ABSTRACT

Successful trace chemical contamination control is one of the components necessary for achieving good cabin atmospheric quality. While employing seemingly simple process technologies, sizing the active contamination control equipment must employ a reliable design basis for the trace chemical load in the cabin atmosphere. A simplified design basis that draws on experience gained from the International Space Station program is presented. The trace chemical contamination control design load refines generation source magnitudes and includes key chemical functional groups representing both engineering and toxicology challenges.

INTRODUCTION

Cabin atmospheric quality has been a concern for spacecraft cabin designers since the advent of crewed space exploration missions. Trace contaminant control (TCC) design begins early in the spacecraft's development when very little if anything is known about the cabin interior and its materials of construction. In reality, all of the TCC design and performance verification takes place in a seeming absence of data because until the first vehicle is fully assembled, the true equipment offgassing load that the TCC design must accommodate is unknown. This typically leads to highly conservative equipment design.

Selecting the right materials of construction that are strong, durable, and lightweight as well as compatible with the spacecraft cabin environment is a continuing

challenge. The increasing knowledge about the interaction of materials of construction and their offgassed products with the cabin environment as well as how that environment's quality may influence human health adds to that challenge.

Within this changing environment where new materials of construction are constantly emerging and once acceptable materials can no longer be used, spacecraft cabin designers must specify and size equipment to actively purify the cabin atmosphere. This requires a well developed design basis. Today, unlike during the early years of crewed space exploration, an accumulated history can provide the information needed for this basis. The following discussion explores the 40-year history behind the design basis and its refinement for use for spacecraft design activities beyond the International Space Station (ISS) program.

EARLY TRACE CONTAMINANT LOAD MODELS

THE SIXTIES – The first documented trace chemical contamination control design basis can be found during the Apollo Program. Eighty-eight chemical compounds were identified as targets for designing a TCC system capable of maintaining each chemical compound's cabin concentration below a specified spacecraft maximum allowable concentration (SMAC). The total contaminant generation rate, excluding methane and hydrogen, was set at 6.5 g/day. Methane (CH_4) and hydrogen (H_2) generation rates were set at 17.6 g/day and 2.2 g/day, respectively. Ammonia (NH_3) had no specific generation rate specified. No documentation supporting these rates

is discussed by the project documentation. A process design based on adsorption and thermal catalytic oxidation, the forerunner to the ISS U.S. On-orbit Segment (USOS) trace contaminant control system (TCCS), was developed under this effort.[1] However, the Apollo spacecraft, like its Mercury and Gemini spacecraft predecessors, used only activated carbon to provide the cabin TCC function.

Developmental activity continued on thermal catalytic oxidation. A developmental effort on a thermal catalytic oxidation system design to accommodate a crew of 9 for 180 days built on the earlier Apollo work. This work identified 150 chemical compounds from several sources including Apollo command module contamination control studies, chemical compounds found in activated carbon samples from Mercury and Gemini spacecraft, an Air Force Biosatellite 30-day test that used a chimpanzee as a test subject, a 30-day crewed experiment, and a 56-day crewed experiment.

The total contamination generation rate was set at 50 g/day based on an extrapolation based on the ratio of the Apollo command module gross weight (4,990 kg) to the gross weight of a space station (99,790 kg) placed in a 125-km orbit.[2] This extrapolation used 2.5 g/day, the total offgassing rate experimentally measured for Apollo as the starting point, and then multiplied by the factor of 20. The underlying assumption is that the mass of internal materials and equipment that contribute to the offgassing load is uniformly proportional to the spacecraft's gross weight regardless of its design or purpose. This, of course, may be difficult to justify because equipment packing density in a small spacecraft may differ significantly from a space station where equipment is mounted in racks.

Generation rates for metabolically-produced CH_4 , H_2 , NH_3 , and carbon monoxide (CO) were specified for this 9-person load as 600 mg/person-day, 50 mg/person-day, 1,000 mg/person-day, and 33.3 mg/person-day, respectively. These rates were derived from data reported by NASA SP-3006 (1964).

THE SEVENTIES – Continued work on a TCC process design for a space station by Lockheed modified the total generation rate for the 150-compound load model. The basis for this modification was that offgassing rate was demonstrated to decay significantly for missions lasting longer than 14 days. Therefore, the generation rates were reduced by a factor of 10 to account for temporal changes in offgassing rate and generation rate differences observed from other studies.[3] The total load decreased to 5 g/day. This same load, adjusted for a crew of 6, was used for further TCC process design and equipment development.[4] The rates for CH_4 , H_2 , and CO did not change. The rate for NH_3 , however, decreased significantly to 250 mg/person-day when using an average sweat rate as a basis.

Development and process modeling of the TCC equipment for Spacelab brought a significant change to the trace chemical contaminant load model development. Sufficient data from Spacelab equipment and payload offgassing tests were available to actually estimate an aggregate generation rate. A total of 196 chemical compounds were identified and rates assigned.[5] The rates for several key metabolically-produced compounds decreased. The CH_4 rate was reduced by 36% to 160 mg/person-day. The rate for H_2 decreased 48% to 26 mg/person-day. The CO rate of 23 mg/person-day represented a 31% decrease. The rate for NH_3 , however, increased to 475 mg/person-day. These changes are attributed to modifications in the basis for their calculation. In all cases, the calculation basis uses average production rates.

THE EIGHTIES – The Spacelab load model was adapted for development of the ISS TCCS equipment. Equipment offgassing data were acquired from Spacelab missions 1 and 3. These data allowed the earlier Spacelab load model to be updated by replacing estimated generation rates with rates derived from flight equipment offgassing data. The highest observed rate for the Spacelab missions to date was used for conservatism. Also, while nearly 20% of the compounds in the load model were not observed in the Spacelab offgassing data sets, all the compounds were retained to maintain conservatism. By retaining all the compounds, the total number of compounds in the load model grew to 214. Because this model was based on Spacelab equipment, it had to be extrapolated to the space station. The spacecraft gross weight ratio technique was used to accomplish the extrapolation. The total generation of non-methane hydrocarbons, not including 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113) was ~60 g/day.[6] Key metabolically-produced compound rates did not change.

THE NINETIES – With the continuation of the Spacelab program, more data on equipment offgassing were collected. The load model developed for ISS was revisited and a more generalized approach developed to allow the model to be more easily applied to new spacecraft development projects. Equipment offgassing data from 6 Spacelab missions and literature on human metabolic generation were evaluated to develop the load model. A statistical mean and standard deviation for the generation rate for each compound referenced to 1 kg of equipment was the result. Typically the mean plus 1 standard deviation is recommended for design purposes. The equipment offgassing rates were also adjusted for temperature effects because most of the equipment does not operate at 50 °C. The temperature adjustment factor of 11.48 was applied to the raw equipment offgassing data. While the resulting load model still contained 214 compounds, the total generation rate decreased to 5.6 g/day based mainly on the temperature adjustment.[7]

Examining in-flight cabin atmospheric quality sample results from the Shuttle and Spacelab programs lead to significant simplification of the new generalized TCC load model. The in-flight cabin atmospheric quality data indicated that only 58 compounds accounted for 97% of the total trace chemical contamination load.[8]

Changes were also made to key metabolically-produced contaminant rates based on a statistical treatment of literature sources that describe the composition and production rates of expired air, flatus, and sweat. New literature sources on endogenous CO production were also considered. The resulting generation rates that represent a 95% confidence interval for the available data set are the following:

1. 329 mg/person-day for CH₄
2. 42 mg/person-day for H₂
3. 351 mg/person-day for NH₃
4. 18 mg/person-day for CO

The 58-compound load model with the most recently-revised metabolic generation rates serves as the starting basis for a new update. This updated load model builds on flight experience acquired during the NASA-Mir and ISS programs as well as incorporates new understanding on metabolically-produced NH₃.

CABIN ATMOSPHERIC QUALITY EXPERIENCE

PASSIVE AND ACTIVE CONTROL – A good quality spacecraft cabin atmosphere begins with good design specifications. The specifications governing the selection of the spacecraft cabin materials of construction and the contaminant generation load model define the passive and active contamination control approaches, respectively. Passive and active contamination control approaches are implemented within the boundary set by the maximum acceptable concentrations of individual contaminants in the cabin atmosphere necessary to preserve human health and safety.

The material selection and control process constitutes the first level of passive contamination control. By specifying materials that possess low offgassing characteristics, the magnitude of the load is controlled. All of the contamination load models that have been developed since the Spacelab model development in the 1970s are based on a common assumption that a rigorous, consistent material selection and control process is in place.

The material selection and control process, when based on a common success criterion that is consistently applied to all spacecraft internal system and payload equipment can be assumed to result in a fairly uniform set of suitable materials of construction possessing common offgassing characteristics. Consistently using well defined laboratory methodologies and analytical

methods provide additional support for this approach that allows for a generalized contaminant load model to be developed that can be used with minimal modification across many crewed spacecraft design concepts. The main point is that at a minimum, a similar or more rigorous material selection and control program must be used for every spacecraft development project. Without such consistency a generalized contaminant load model would not be possible.

The very best material selection and control process can only minimize the overall contamination load. The load cannot be completely eliminated because all materials offgas chemical contaminants to some degree and people always produce a variety of contaminants. An active contamination control system is needed on board the spacecraft to prevent buildup to noxious levels.

When successful, the passive contamination control techniques limit the total chemical contamination load emitted into the cabin to a level below that predicted by the contamination generation load model. By basing the load model development on a statistical treatment of offgassing test data acquired from numerous material screening tests, a well-implemented material selection and control program usually accomplishes this objective. The active contamination control process design is developed on a simple cabin mass balance defined by Equation 1.

$$V \left(\frac{dC}{dt} \right) = g - (\sum \eta v) C \quad (1)$$

Variables in Equation 1 are cabin volume, V; chemical contaminant concentration, C; chemical contaminant generation rate, g; total effective removal, $\sum \eta v$; and time, t.

Design points are derived by solving Equation 1 and simplifying it for steady state conditions. The form of the simplified mass balance equation provided by Equation 2 allows the specifications for process flow rate, v, and single pass efficiency, η , to be defined.

$$\sum \eta v = \frac{g}{C} \quad (2)$$

ISS CABIN ATMOSPHERIC QUALITY – After more than 10 years in operation, the ISS has provided a wealth of archival cabin atmospheric quality data that are useful to refining the contamination control load model for future crewed spacecraft. Examining these data help to define the most prevalent chemical functional classes present, leading to a reduction in the total number of chemical compounds comprising a generalized load model for active TCC system design.

Major Trace Constituent Classes – The primary trace chemical constituents in the ISS cabin atmosphere