# Comparative Analysis of a Silane Cylinder Delivery System and a Bulk Silane Installation (ESH B001)

**SEMATECH**
Technology Transfer 95092976A-ENG

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**Abstract:** This document presents the results of one of the tasks of the Silane Safety Improvement project (ESH B001), which conducted a comparative analysis of a silane cylinder and bulk silane delivery system that addresses cost of ownership, safety, and risk. It is meant to provide a benchmark status of existing bulk silane systems and compare them to information documented in the S71 Silane Safety Improvement survey. It will provide data for planners and management to evaluate the benefits and risks associated with bulk silane installations and make technical data-based decisions to meet current and future needs for the semiconductor industry.

**Keywords:** Silane, Bulk Gases, Gas Distribution Systems, Cost Analysis, Specifications, Equipment Safety

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## 1 EXECUTIVE SUMMARY

This document presents the results of one of the tasks of the Silane Safety Improvement project (ESH B001), which conducted a comparative analysis of a silane cylinder and bulk silane delivery system that addresses cost of ownership, safety, and risk.

The bulk silane information was gathered during visits to facilities with bulk silane installations. The installations included a federal facility, an industrial cylinder packaging and distribution site, and a bulk silane generation facility. Information was also acquired from literature, specialty gas suppliers, and semiconductor company bulk silane proposals and inquiries.

Bulk silane facilities provide some consistent applications with engineering controls as exhibited by an open air facility, controlled access, water deluge systems, dedicated nitrogen purge systems, and security systems. Incidents associated with bulk systems appear to be negligible compared to silane cylinder gas management systems. The main factor associated with the lower number of incidents for the bulk system appears to be the minimal need for human interface with the systems. The major factor related to cost savings is the cost associated with purchasing silane in bulk and the savings associated with labor to support the installation.

Cylinder systems have been widely accepted and applied within the semiconductor industry, whereas bulk silane systems are associated with questionable perceptions. Some community risk and business interruption concerns need to be overcome before bulk silane delivery is accepted. Consistent, reliable information and data will provide a basis to reassess the advantages of bulk silane installations in a dynamic manufacturing environment.

This report is meant to provide a benchmark status of existing bulk silane systems and compare them to information documented in the S71 Silane Safety Improvement survey. It will provide data for planners and management to evaluate the benefits and risks associated with bulk silane installations. The benchmark information in the report will provide information and references to help make technical data-based decisions to meet current and future needs for the semiconductor industry.

## 2 INTRODUCTION AND PROJECT DESCRIPTION

With the increasing demand for semiconductor products, silane usage is expected to increase. One domestic manufacturing facility has an annual capacity of approximately 3000 metric tons of silane. Currently efforts to identify safe silane alternatives suggest that no new technology is expected to provide solutions in the near future. Point-of-use generation technology is an area for further strategic application, but it has not been demonstrated as a viable technology. Therefore, in the short term, bulk silane installations may provide a needed technology to meet volume production, provide consistent high quality products, and minimize the likelihood of incidents.

Silane ($SiH_4$) is a colorless, pyrophoric compressed gas that can ignite spontaneously in contact with air. The SEMATECH S71 Silane Safety Improvement project attempted to assess the risks associated with silane use and document the reported silane incidents and resultant consequences. The results of a SEMATECH survey (Technology Transfer #94062406A-XFR) showed the following:

- The release of silane resulted in fire approximately 59% of the time.
- The gas delivery system was involved in over half of the incidents
- Cylinder change-outs were involved in 23% of the incidents.

These incident data suggest opportunities for improving gas delivery systems and cylinder change-out procedures.

It is argued that bulk silane installations can potentially reduce silane incidents because of design enhancements of the gas delivery system and minimal source container change-outs. Bulk installations also minimize the human interface with the system. The human/equipment interface was reported as a major contributory factor to silane incidents. Proven safety engineering practices incorporated into the silane cylinder delivery systems also can be used in the bulk installations. The main difference between cylinder and bulk systems is the amount of labor needed to support the installation. The improvements with silane cylinder delivery systems are well documented, including the reduction in silane incidents (see Technology Transfer #94062405A-ENG). However, the reported incidents associated with bulk systems appear to be few and not sufficient to calculate for a meaningful comparison with cylinder systems.

# 3 EXISTING USES OF BULK SILANE SYSTEMS

SEMATECH's Silane Safety Improvement project S71 (Technology Transfer #94062405A-ENG) noted six facilities in the U.S. using or designing for bulk silane delivery systems. The major silane users or industries using high volume silane are xerography, glass, and photovoltaic manufacturers. In addition, specialty gas manufacturers and distributors have been using bulk silane delivery systems since early 1980.

One of the authors visited and reviewed three domestic bulk silane facilities to benchmark the status of bulk silane use. The facilities were a bulk silane generation facility, a specialty gas distributor that uses a bulk silane tube trailer to fill silane cylinders, and a National Aeronautics and Space Administration (NASA) installation that uses a bulk silane/hydrogen tube trailer to conduct high temperature tunnel tests. Semiconductor manufacturing facilities were visited to discuss their plans for bulk silane installations; however, they were in the early planning stages and project specifications were still being developed.

The target benchmark facilities were asked to provide the following data:

- A schematic of the bulk tube trailer manifold system
- Written procedures for maintaining the bulk silane systems
- Process Hazards Analysis documentation
- A history of hardware or procedural revisions made to the bulk system
- A description of emergency responses since the initial installation
- Cost of ownership information
- Designs or proposed designs to address community risks with corresponding references
- Quality data to insure system integrity/reliability
- Training programs specific to the bulk silane system

- Preventive maintenance schedules or practices
- A history of unscheduled downtime for inadvertent or unanticipated reasons

Two of the SEMATECH specialty gas suppliers have been involved in bulk silane shipments to international facilities for a total of 11 years.

# 4 REGULATORY REQUIREMENT

The regulatory requirements for the storage, handling, and use of silane and, in particular, bulk silane are addressed in a variety of codes and regulations. The regulatory considerations are addressed in Appendix A.

Additional references that can be used in the design phase of the silane bulk installation are as follows:

- National Fire Protection Association guidelines
  - NFPA 68, Guide for Venting Deflagrations
  - NFPA 69, Standard on Explosion Prevention
  - NFPA 70/Article 500, The National Electric Code
- Insurance company technical and engineering support organizations (e.g., specific system controls and requirements)

## 4.1 Uniform Fire Code (1994)

The 1994 Uniform Fire Code, 80-1 Storage, Dispensing and Use of Silane and Its Mixtures, is a recent modification to the pyrophoric requirements of earlier Uniform Fire Codes (UFCs). Article 80-1 was developed by industry and the fire service. The regulation was intended to develop a material-specific standard for conventional silane storage and use conditions. The 1994 UFC Section 8003.8 has provisions for sprinklers, explosion control, mechanical ventilation, classified electrical service, and emergency power as well as requirements for detached or exterior storage if quantities of pyrophoric gas exceed 2,000 $ft^3$. Silane or mixtures of silane greater than 2% by volume must be stored and used according to UFC Standard No. 80-1.

The UFC Standard 80-1, Storage, Dispensing & Use of $SiH_4$ and Its Mixtures details specific requirements. Standard 80-1 addresses requirements for

- Flow orifice limitations (0.01”)
- Mechanical ventilation velocity of 200 lfpm across unwelded fittings and connections to a piping system
- Dedicated purge gas systems and demonstrated purge gas procedures
- Compressed Gas Association (CGA) authorized fittings
- Buildings that conform with UBC requirements
- Outdoor separation distance based on quantitative research of $SiH_4$ overpressure events.

The fire services are interested in silane controls and have attempted to provide data-based decisions for revisions to the UFC. As silane use and storage are further researched, data-based information may lead to further refinements and enhancements in UFC, Section 80-1.

Besides meeting the requirements for regulations and codes, the semiconductor industry uses a number of industry standards to meet quality and other safety requirements. Industry standards may be based on a number of guidelines listed in Appendix B.

# 5 INDUSTRY PRACTICES

SEMATECH's S71Silane Safety Improvement project noted common engineering practices used in the delivery of silane from cylinders. The project described many common engineering control practices but also noted some engineering inconsistencies; i.e., coaxial versus single line piping systems, gas monitoring versus non-monitoring, the number of purge cycles for evacuating system, etc. The semiconductor industry has dramatically reduced the reported costs of silane incidents with the engineering control improvements as noted in the SEMATECH S71 report.

Because of the nature and quantity of gas used, bulk silane installations were designed incorporating many of the engineering controls used in the cylinder gas systems. The challenges of using bulk installations are generally system reliability, quality, and risk assessment. To elaborate on the basics of the bulk silane installation benchmark design, a NASA silane installation and the design developed by specialty gas manufacturers to support the semiconductor industries will be used as an example.

## 5.1 A Government Facility

A NASA facility was chartered to develop a bulk silane delivery system to support a hypersonic high temperature tunnel model ignition system. The engineers designed the bulk silane system to flow a 20% silane/80% hydrogen mix (by volume) at half pound per second flowrate. Silane is used in the gas mixture as an ignition source for hydrogen fuel. Semiconductor grade gas purity was not a test requirement. The government team surveyed the literature for silane related references. They were also supported by a specialty gas distributor in designing the system. Interestingly, the gas system design is similar to those generally found in the semiconductor industry. A schematic of the installation is in Figure 1.

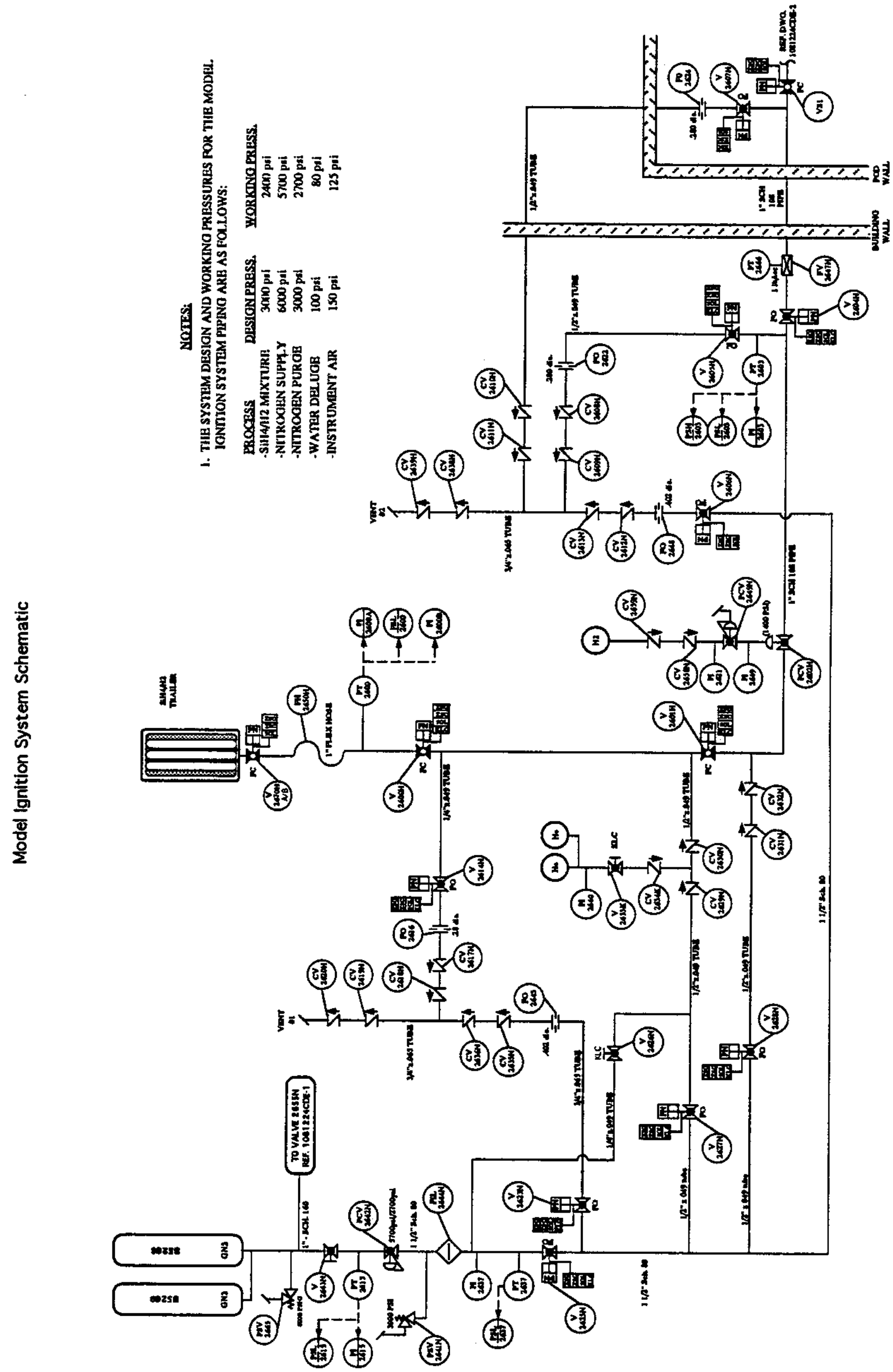


**Figure 1 Government Facility-Model Ignition System Schematic**

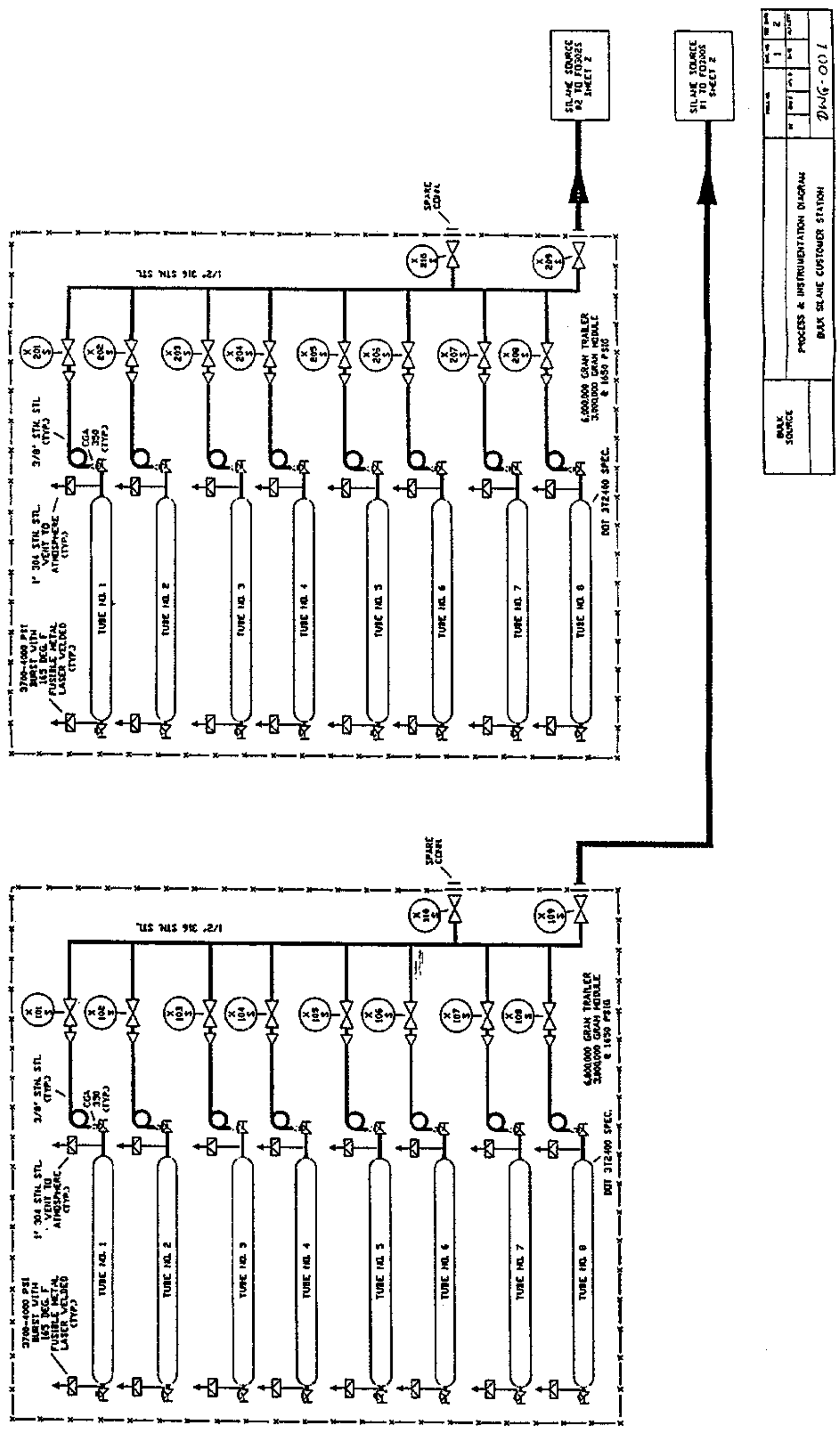


**Figure 2 Compressed Gas Association-Bulk Silane Module Installation Schematic**

The bulk $SiH_4/H_2$ tube trailer has a water volume of 245 $ft^3$. The piping systems are designed according to the requirements of ASME B31.3. The piping systems are single-line stainless steel welded piping with a minimal number of VCR connections. The gas piping was pneumatically tested to 110% of design pressure. No relief valves are designed into the gas mixture system. The $SiH_4/H_2$ purge is equal to 1-1/2 the line volume and the pre- and post-purges are equal to three times the line volume [19].

**Table 1 Government Facility-System Design and Working Pressures [19]**

| Process | Design Pressure | Working Pressure |
|---|---|---|
| | | |
| $SiH_4/H_2$ mixture | 3000 psi | 2400 psi |
| $GN_2$* supply to valve (PCV2642N) | 6000 psi | 5700 psi |
| $GN_2$ purge piping | 3000 psi | 2700 psi |
| Water deluge piping | 100 psi | 80 psi |
| Instrument air piping | 150 psi | 125 psi |
| * $GN_2$ = Gaseous Nitrogen | | |

**Table 2 Government Facility Bulk Silane System/Sub-Systems[19]**

| |
|---|
| $SiH_4/H_2$ supply system |
| $N_2$ supply system |
| $N_2$ purge system |
| Vent system |
| Instrument air system |
| Water deluge system |
| Card key access system |
| Kirk key system |
| Electrical power & grounding systems |
| Sequential control and interlock system |
| Area lighting system |
| Fire alarm system |
| Video monitoring system |

Two silane trailers support the operation. One is hooked up to the gas delivery system, while the other is at the gas specialty supplier's location being filled. Each trailer module contains 30 tubes with a total of 40,000 standard cubic feet of product and approximately 300 lbs. of usable product. Each of the tubes has an individual manual isolation valve; each manifold has valves that can separate the trailer into two halves. The trailer has two discharge valves (2670 H A&B). However, only one is used; the other is a backup. No restricted flow orifices are located within the trailer's manifold.[15]

Another commercially available trailer design incorporates an 8-tube isocontainer that has significantly fewer valves and fittings. This design has a lower probability of a component failure and resulting leak. Each of the tubes can be filled with up to 375 kg of silane or only partially filled.

The bulk silane design incorporates some of the same engineering control practices as cylinder systems. The gas delivery piping system and components are similar except for the purity specifications. The bulk tube trailer is protected with a water deluge system. Three ultraviolet (UV) fire detection sensors monitor the area. Fire-rated walls separate the critical valves and instrumentation from the tube trailer. The tube trailer area is fenced; only qualified personnel are permitted access. The enclosure is monitored by remote video cameras. The nitrogen purge cylinders provide independent support to the facility. Helium cylinders positioned within the facility allow for leak checks of the system. The vent line is purged with nitrogen and discharge is from a vent stack. The facility is in an open-air environment.

The bulk silane facility has a unique safety control system not found at the other surveyed facilities. The design personnel tried to mitigate the likelihood of incidents from procedural errors. The design team installed a Kirk Key system to assure operational procedures are followed in an approved sequential process. The Kirk Key system requires that mechanical keyed locks be activated in a certain sequence; otherwise the valves cannot activate. The keys are controlled as any lockout/tagout program with trained and qualified personnel.

Written procedures are developed and published for all bulk silane operations from the installation of the trailer to hookup, leak checking, system activation, etc. The specialty gas truck driver is specially trained to deliver and hook up the tube trailer with an onsite qualified technician in support. Preventive maintenance schedules have been established for the system.

The government designers used a Hazard Control Analysis to comprehend a critical component failure and high risk events (e.g., fire, deflagration/explosion, and personnel hazards). The Hazard Analysis identified critical risks. The system was designed with safety features and controlled interlocks in place so that no single failure would cause an event. The Hazard Control Analysis included the following:

- Structural failure
  - Overpressurization
  - Valve failure/mispositioning
  - Degradation
  - Deflagration/Explosion
  - Loss of/or inadequate nitrogen purge
  - Improper venting

   - Auto-ignition in the piping
- Personnel burned during pyrophoric gas exposure
- Facility damage resulting from a system fire[19]

The project team believed that the engineering controls would effectively prevent the start of fires. The water deluge, fire detectors, and video systems provide redundancy and mitigation measures for the fire detection and fire extinguishment.

### 5.2 Compressed Gas Association

The Compressed Gas Association (CGA) is interested in bulk silane designs and installations. A task force formed to investigate the subject was able to share safety design information and determine an agreed-upon generic system design. Figure 2 is a schematic of the bulk system installation; Figure 4 illustrates the process and instrumentation schematic.

The specialty gas suppliers, which were surveyed, did not have a Process Hazard Analysis that addressed a fixed facility installation. However, hazard reviews were performed for delivery systems within the gas supplier's manufacturing facility for filling operations. The specialty gas suppliers had conducted a Process Hazard Analysis to evaluate the tube trailer to meet Department of Transportation requirements. The CGA believes it necessary to have a Process Hazard Analysis to evaluate the generic bulk silane installation identified by its task force members; plans are underway to meet this need.

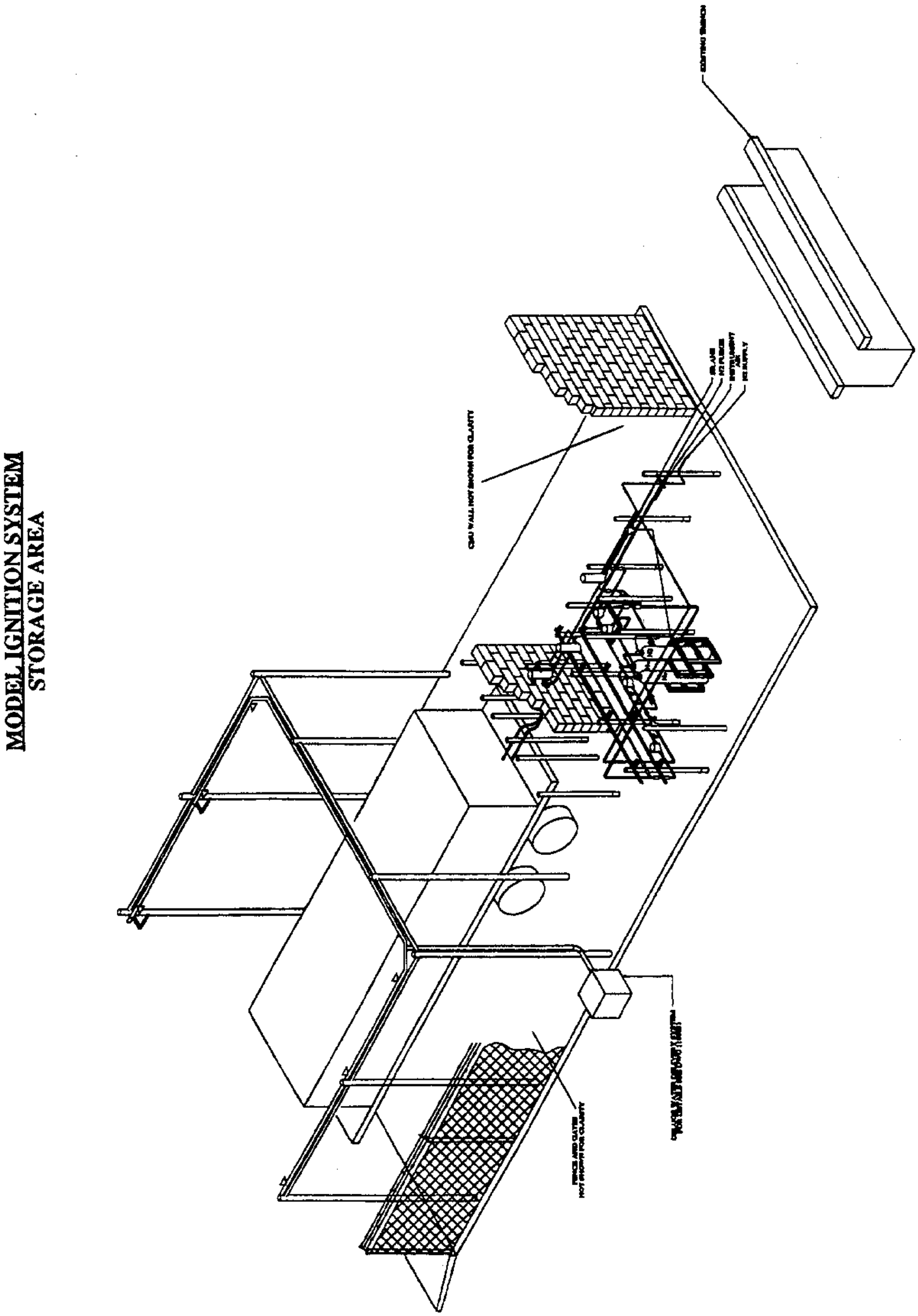


**Figure 3 Government Facility-Model Ignition System Storage Area**

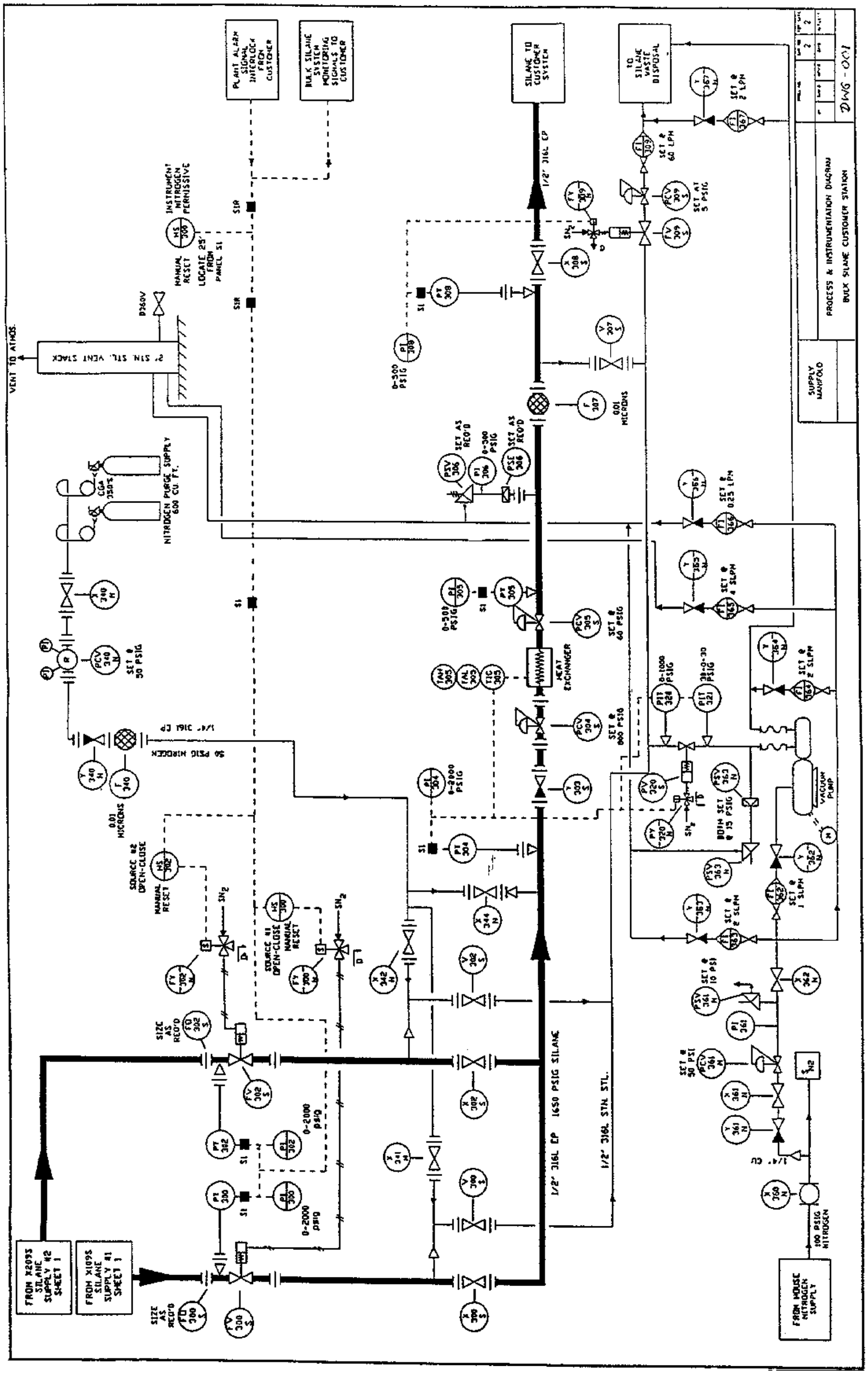

**Figure 4 Compressed Gas Association-Process and Instrumentation Diagram**

**Table 3 Silane Cylinder Versus Bulk System Code/Facility Comparison ( Silane >2% by Volume)**

| *Cylinder* | *Bulk* |
|---|---|
| Capacity - 5,000 grams, 790 psig cylinders | Capacity, 375,000 grams per tube, generally 8 tubes per module |
| Indoor storage must conform to UBC | Outdoor storage, UBC not applicable |
| Indoor storage 50 cu. ft. with 100% increased quantity in approved storage cabinet (Table 8001.13A) UFC | N/A |
| Use-Closed system , 10 cu. ft with 100% increased quantity in approved cabinet. (Table 8001.13A) UFC | N/A |
| Detached storage of silane > 2,000 cu. ft. | N/A |
| Outdoor storage, a maximum volume of 10,000 cu. ft. of gas per nest | Maximum storage volume over 10,000 cu.ft. may require variance |
| Storage distance from property lines, streets, buildings, etc. according to Table 8003.8 UFC. | Storage distance from property lines, streets, buildings, etc. is 25 ft |
| Must meet Class I, Division 2 electrical for indoor storage | Class I, Division 2 electrical |
| If in gas cabinet must have 200 lfpm exhaust across fittings supported by emergency power | Open air, no exhaust |
| Utilize 0.01 inch restricted flow orifice | N/A However, excess flow protection should be considered |
| Use dedicated purge gas system and demonstrated purge gas procedures | Dedicated purge gas system with Kirk Key system to reinforce critical procedures |
| Outdoor storage shall be secured from unauthorized entry | Secured chain link enclosure and facility security system tie-in |
| Video camera | Video camera |
| Must have leaker support cabinet | N/A |
| Welded/VCR connected piping | Welded/VCR connected piping |
| Fire protection sprinkler system | Deluge system with UV sensors and manual fail safe activation. |
| Burnbox , wet scrubber | Flare stack |
| Gas monitors | None |
| Lightning protection not in survey | Via structural frame & grounding |
| Delivery line shielded/coaxial | Shielded as necessary |

In comparing cylinder to bulk system facilities, both use engineering and administrative controls (e.g., security, purge gases, electrical, piping requirements, and fire protection) to help mitigate silane incidents. The main differences are that bulk systems lack forced mechanical ventilation and UBC requirements. Cost of ownership should reflect a savings in operating costs associated with mechanical ventilation systems and electrical support.

## 6 INCIDENTS INVOLVING SILANE

SEMATECH's silane incident survey provided the following information:

| Severity of silane release: | |
|---|---|
| Fire | 59% |
| Explosion | 11% |
| Leak | 11% |
| Pop | 11% |
| Nothing | 9% |

| Operation conducted at time of the silane incident: | |
|---|---|
| Unknown | 36.6% |
| Processing | 24.4% |
| Cylinder Change | 23.2% |
| Maintenance | 12.2% |
| Startup | 3.7% |

| Equipment involved in the incident: | |
|---|---|
| Exhaust | 18.8% |
| Cylinder Valve | 16.3% |
| Cylinder | 13.7% |
| Valve/flange | 13.7% |
| Manifold | 13.7% |
| Line | 7.5% |
| Process | 7.5% |
| Vacuum pump | 5.0% |
| CGA | 2.5% |
| Scrubber | 1.2% |

The survey reported that less than 50% of the equipment involved with the silane incidents was related to the gas delivery systems.

During the site visits and interviews, it was noted that the government facility reported no silane incidents. One specialty gas distributor reported no plant emergencies resulting from the bulk silane trailer since the startup of the system in 1984. The silane manufacturer reported no significant silane incidents with its bulk silane facility other than "typical" pops and minor flare ups with no impact on the quality and purity of the contents of their bulk silane tube trailers.

A specialty gas distributor evaluated a consequence analysis of the tube trailer fleet accident history. They established likely scenarios for accidents involving the silane tube trailers during transportation. The equipment failure frequencies were developed using a fault tree analysis with data gathered over the past 25 years. Only three potential equipment failures were investigated: tube spurious rupture failure, valve failure, and rupture disc assembly failure. Other failure mechanisms were evaluated; however, they anticipated only inconsequential results. The consequence analysis reviewed only a fleet of silane tube trailers equipped with a fused metalbacked rupture disc on each end of the tube. The rear of each tube had a withdrawal valve equipped on it. The calculated equipment failures and their frequencies were as follows:

1. Tube spurious failure, freq: 1.0e-7 events per tube year.
2. Rupture disc failure, freq: 1.39e-7 events / disc year.
3. Tube valve failure, freq: 3.55e-6 events /valve year.[4]

**Table 4 Calculated Accident & Component Failure Release Scenarios and Frequencies [4]**

| RELEASE SCENARIOS: | FREQUENCY: |
|---|---|
| 1-Tube Trailer accident: Rollover fails all valves. | 1.57e-4 events/trlr yr |
| 2-Truck or train hits tube trailer and fails two valves. | 4.72e-4 events/trlr yr |
| 3-Tube spurious failure. Tube ruptures and releases contents. | 1.0e -7 events/trlr yr |
| 4-Safety disc failure releases one tube. | 1.4e -7 events/trlr yr |
| 5-Valve failure release one tube. | 3.5e -6 events/trlr yr |

The survey and interviews noted that users of both silane cylinders and specialty gas bulk silane have experienced some minor incidents. The bulk silane users appear to control and/or manage their installations to avoid high risk types of silane incidents. The cylinder users have minimized their incidents with engineering control practices and administrative controls; however, the interface of human/equipment increases the probability of incidents.

## 7 RISKS

Bulk silane applications pose three major areas of risk: process impacts, business interruption, and safety. The process impacts and business interruption risks are synonymous in many ways. Maintaining consistent purity is one of the most important parameters. Data shows that when silane is produced in a continuous process environment, it has very high purity levels. The contaminants are measured at the sub ppm levels for the identified contaminants. Gas chromotography is used to identify the majority of impurities in silane.

Table 5 shows silane specifications proposed to the SEMI Gas Specification Subcommittee and Analytical Procedures Subcommittee by a bulk silane manufacturer.

**Table 5 Proposed Silane Specification (Drafted 11/14/94) [2]**

| *Impurity* | *Maximum Level* | *Test Method* | *Detection Limit* |
|---|---|---|---|
| Nitrogen | 10 ppmv | GC/DID | 0.1 ppmv |
| Argon | 1 ppmv | GC/DID | 0.1 ppmv |
| Helium | ---- | | |
| Hydrogen | 50 ppmv | GC/TCD | 0.2 ppmv |
| Water | -- | OCD | TBD |
| Siloxane | TBD | TBD | |
| Oxygen | 1 ppmv | Dep. Layer | 0.2 ppmv |
| Methane | 0.1ppmv | GC/FID | 0.02 ppmv |
| Other Hydrocarbons | 0.1 ppmv | GC/FID | 0.02 ppmv |
| Carbon Monoxide | 0.5 ppmv | GC/FID | 0.2 ppmv |
| Carbon Dioxide | 0.5 ppmv | GC/FID | 0.2 ppmv |
| Carbon (alternate) | 0.5 ppma | Dep. Layer | 0.2 ppma |
| Chlorosilanes | 1 ppmv | GC/ELCD | 0.5 ppmv |
| Disilane | -- | | |
| Hydrogen Sulfide | -- | | |
| Acceptor | | | |
| Boron | 0.2 ppba | Dep. Layer | 0.02 ppba |
| Aluminum | 0.2 ppba | Dep. Layer | 0.02 ppba |
| Gallium | 0.3 ppba | Dep. Layer | 0.02 ppba |
| Donor | | | |
| Phosphorus | 0.2 ppba | Dep Layer | 0.02 ppba |
| Arsenic | 0.2 ppba | Dep. Layer | 0.02 ppba |
| Antimony | 0.2 ppba | Dep. Layer | 0.02 ppba |
| Resistivity | *Calculated on net acceptor/donor* | | |
| Metals | | | |
| Iron | TBD | NAA | 0.3 ppba |
| Chromium | TBD | NAA | 0.01 ppba |
| Nickel | TBD | NAA | 0.2 ppba |
| Copper | TBD | NAA | 0.02 ppba |
| Zinc | TBD | NAA | 0.03 ppba |

GC = Gas Chromotography
DID = Discharge Ionization Detector
TCD = Thermal Conductivity Detector
OCD = Oscillating Crystal Detector
FID = Flame Ionization Detector
ELCD = Electrolytic Conductivity
NAA = Neutron Activation Analysis

Particle contamination comes primarily from silicon dioxide, not metals. It has been found that particle counts depend on a number of variables (e.g., individual cylinder cleanliness and passivation, valve integrity, valve type, and the distribution system). Once high purity silane is produced, the main issue becomes the purity of the package vessel.

The use of cylinders increases the risk of introducing impurities to the silane. The cylinder may become contaminated during the loading process or from contamination endemic to the cylinder.

Once the cylinder is filled, a certification process for silane purity becomes expensive and not practical without consuming large quantities of silane during the process.

With bulk systems, the volume to surface area relationship is approximately 5.6 compared to 1.9 for a cylinder. This relationship is a relative measure of reduced probability that silane by-products will be produced when silane comes into contact with the gas vessels walls. Comparing a silane cylinder with a bulk silane vessel, based on equivalent mass, the silane cylinders have over a 3X factor of square foot volume-to-mass relationship. The risk of contamination increases with the larger surface area resulting from the increased number of gas cylinders required to meet the equivalent mass of a bulk system.[3]

A bulk cylinder can have a Certificate of Analysis conducted on the product, and the product could last for an excess of a year. Although there is the same potential for contamination, trace contaminants are reduced by the greater volume of silane within the bulk container. The risk of contamination is also reduced because the number of changeouts is fewer with bulk systems. The large volume-to-surface ratio of the bulk container provides less surface area to generate particles. With a change-out of the bulk system once or twice a year, the risk of line contamination is reduced if the system is leak-tight and procedures are followed. In addition, line filters can be used to effectively reduce particle contamination to the gas line(s). Once the gas lines are initially cleaned, line distance does not become a contamination risk.[3]

Two advantages of bulk silane are the consistency of the product and the volume to surface area relationship. The bulk silane manufacturer evaluated bulk modules that had been used for a year. Upon its return, the silane was analyzed and the results were comparable to the values when the product was initially shipped. Thus, once the bulk trailer units are properly conditioned, there appears to be no effect on silane purity for over a year.[3]

In a business sense, the cost associated with a silane cylinder incident is less than that of a bulk system incident. Silane cylinder gas systems used in the semiconductor industry typically support either a single piece of production equipment or several pieces of equipment, which are supported by an autoswitch-over valve manifold system. If a cylinder-based gas system were to fail because of some equipment malfunction/incident or particle contamination, only a portion of the manufacturing process would be affected not the entire process.

Bulk systems have a greater potential to create a significant business interruption scenario if the main delivery system is contaminated. The proposed bulk system designs for semiconductor manufacturers are sensitive to this. The following practices and design criteria are suggested to help mitigate such an incident:

- Facilitate two separate bulk silane tube trailer installations with Programmable Logic Control (PLC)
- Provide a by-pass with autoswitch-over capability
- Use a redundant main silane supply gas delivery line with autoswitch-over capability
- Install online system particle counters for real-time monitoring of the silane particle contamination
- Hook up an emergency backup silane gas cabinet to a valve manifold box for a short-term fix

- Install alarm systems (e.g., UV fire detection, seismic sensor) designed to be shut down either automatically or manually

The design controls are based on built-in system redundancies. The redundancy tactic is used extensively in semiconductor systems especially in Facility support areas. The drawback is the extra capital cost to facilitate the installation. However, business interruptions are expensive and the cost of redundancy is usually cost-effective. As discussed earlier, the probability of an incident to the silane cylinder delivery system is higher during cylinder change-out and maintenance. The probability of an incident impacting the main delivery system is minimized because once the system is on line, the silane delivery system provides consistent high purity delivery with little need to intrude into the system.

A major perceived risk with a bulk silane system is that of an explosion or detonation. Most semiconductor facilities are supported with a bulk hydrogen system. Past experience suggests that bulk hydrogen systems are not perceived with the same anxiety as silane gas cylinder systems. Pound for pound, the destructive power of silane is less than hydrogen or propane. The TNT equivalency of hydrogen is 30 while silane is 6-9. Some of the models for vapor cloud explosions (VCE) are based on hydrogen release and are extrapolated to silane releases.[7]

The pyrophoricity of silane and the potential for explosions can create a perceived danger in the local community. The Environmental, Safety, and Health, Facility, and Public Relations departments need to formulate plans to address this issue and educate the community. The bulk silane distributors and manufacturer had no specific material or information for this purpose.

Quantifying the explosion potential for the bulk silane installation thus is an important item. A number of VCE models can be used to evaluate the explosion potential for a worst-case scenario. Some VCE models used in industry are as follows:

- The Factory Mutual VCE model using the TNT Equivalency Method
- The Vapor Cloud Detonation (Chapman-Jouget) Model
- The Brookhaven National Laboratory Equation
- Bulk Ignition Model
- Lawrence Livermore’s, Atmospheric Dispersion Model for Denser-Than-Air-Releases
- The Baker-Strehlow Unconfined Vapor Cloud Explosion Model

The models provide some data but are unable to provide reproducible, predictable models for a silane VCE. Research and data are needed to provide a valid and predictable silane VCE model. A silane model needs to take into account the pressure and thermal effects of a silane reaction, ignition, and detonation.

Research conducted for IBM shows that silane will detonate in a confined area. Lawrence Britton, in a paper on a literature search of silane and some experimental data relating to the effects of a sudden silane release into free air, inlcuded a study that reported that completely unconfined, initially quiescent hydrocarbon fuel gas-in-air cloud releases could not detonate because the flames stopped accelerating once a certain velocity was attained. However, another study using hydrogen in air suggested the existence of a small unconfined vapor cloud that gave significant overpressure effects. A small scale test of a dilute silane mixture did accumulate, causing an explosion. Releases of silane from known flow rates through a vertical vent in air showed the importance of temperature as related to critical ignition velocities. It was noted that “pops” were observed when the silane flow was started or stopped with occasional loud reports after delayed ignition on the one-inch tube.[9]

Britton also conducted a large-scale vent test of silane. He used a silane cylinder with an initial pressure of 1000 psi or higher. The silane was vented from an exit stack with a height of 14 feet. A 0.375 inch square-edged orifice was installed in the test apparatus above the valve to determine flow characteristics. The first series of tests showed the releases gave immediate ignition. One test did not ignite, but he attributed the cause to experimental procedural conditions. A second set of tests was conducted at ambient temperatures of 10°C or less. The vented silane ignited immediately only after the valve was fully shut. Britton theorizes that traces of moisture in the air generally stabilize the silane mixtures and play an important role interacting with the silane jet. There is speculation that interaction with plant equipment or partial confinement could cause a detonation.[9]

The study concludes that silane has some pronounced chemical reducing properties. In confinement, silane can produce a 10.2 pressure ratio. Large quantities of amorphorus silica are released during the combustion process ( 1 kg of silane produces 1.8 kg of silica). Auto-ignition behavior in confined releases is attributed to the radical scavenging of moisture during the reaction. Some mechanisms could cause blast damage in an unconfined gas release without a silane detonation because of hydrogen flame acceleration. Bulk auto ignition can result in local overpressures; however, the models are conservative. Under highly turbulent combustion with confinement or eddy shedding by bluff bodies, detonation might occur. It appears that additional testing and research are needed to understand the results of a silane VCE.[9]

SEMATECH’s S71 project reported that the silane incidents involving gas cylinder systems involved explosions approximately 11% of the time. The bulk silane survey reported no explosions for bulk silane installations. However, Britton cited an explosion in December 1977 involving a 5,000 gram cylinder (initially about 700 psi) that exploded because of a leak. Damage resulting from the explosion indicated a very rapid deflagration. The incident lead to improved inspection procedures for silane cylinders before shipment. After all these years, the procedure appears to be successful.

## 8 COSTS

SEMATECH’s Silane Safety Improvement (S71) report provides some facility cost data as reported by the survey respondents. The silane cylinder facility costs are broken out in the following general ranges.

| *Equipment* | *Cost* | *% of Respondents* |
|---|---|---|
| Gas cabinet & manifold | $20-50k | (51%) |
| Delivery line | $1-10k | (69%) |
| Process manifold | $3-20k | (67%) |
| Exhaust duct | $1-5k | (55%) |
| Scrubber | $1-50k | (58%) |
| Gas monitor | $10-80k | (55%) |

The survey stated that the average reported cost for a silane cylinder installation was $306,000; the median cost for a silane installation was $101,000.

The capital cost of an installation is one portion of the cost of ownership. The cost of training, preventive maintenance, utility costs, consummables, and downtime for cylinder change-out need to be reviewed. The bulk silane cost of trailer or module with a DOT 5-year testing requirement, manifold valve rebuilding, chassis inspection, maintenance, and painting needs to be included in any cost comparison.

One specialty gas distributor provided a hypothetical bulk silane vs. cylinder silane cost comparison.

**Table 6 Cost Comparison (Example #1)[5]**

*ASSUMPTIONS*

Conventional Cylinder Operation

| | | |
|---|---|---|
| Consumption | 1,000,000 Grams/month | Quantity consumed |
| Cylinder Capacity | 12,000 grams | Nominal cylinder size |
| Cylinder Capacity Utilization | 90% | Percent of product removed |
| Average Product Price | $0.40 /gram | Purchase Price |
| Demurrage | $0.00 /day/cylinder | Daily cylinder utilization fee |
| Round trip Freight | $0.00 /cylinder | Cost to ship product to your dock |
| Gas Panels Installed | 10 Panels | Silane panels installed |
| Panel Replacement Cost | $20,000 /panel installed | Cost to replace /commission panel |
| Panel Spare Parts Cost | $1,500 /panel/year | Cost of spare valves, fittings, etc. |
| Average Panel Life | 3 years | Time period before replacement |
| Bottle changes | 2.7 changes/day | Number of changes per day |
| Hours per change, with handling | 3 hours | Time to change & store cyl. |
| Maintenance Hours per Cabinet | 8 hours/yr. | Time required to perform PM |
| Burdened Labor Rate | $25/hr | Personnel cost |
| Labor utilization Factor | 140% | Recognizes that people do one thing at a time. |

Bulk Silane Operation

| | | |
|---|---|---|
| Consumption | 1,000,000 Grams/month | Quantity consumed |
| Tube Trailer Capacity | 6,000,000 grams | Nominal trailer size |
| Tube Trailer Utilization | 95% | Percent of product used |
| Product Price | $0.30/gram | Purchase price |
| Demurrage | $0.00/day/trailer | Daily cylinder utilization fee |
| Freight | $0.00/trailer | Cost to ship product to dock |
| Repeaters installed | 10 Repeaters | Silane Repeaters |
| Repeater Replacement Cost | $30,000/repeater | Cost to replace/commission repeater |
| Repeater Spare Parts Cost. | $1,000/repeater/yr | Cost of spare parts |
| Repeater Expected Life | 7 years | Time before repair/replacement |
| Tube Trailer Changeouts | 0.18 changes/month | Changes per month |
| Hours per changeout | 0 hours | Time to change/warehouse bottles |
| Burdened Labor Rate | $25 $/hr. | Personnel cost |
| Labor Utilization Factor | 140% | People do one thing at a time |
| Monthly Service Charge | $30,000/month | Maintenance/service fee |

*Calculations ($ per Month)*

| Product Costs | Cylinder Supply | Bulk Supply |
|---|---|---|
| Product Purchases | $444,444.00 | $315,789.00 |
| Demurrage | $0.00 | $0.00 |
| Freight | $0.00 | $0.00 |
| | $444,444.00 | $315,789.00 |
| Labor Costs | | |
| Equipment Maintenance | $119.00 | $0.00 |
| Bottle Changes/Warehousing | $4,320.00 | $0.00 |
| | $4,439.00 | $0.00 |
| Equipment Cost | | |
| Monthly Service Charge | $0.00 | $30,000.00 |
| Replacement Parts | $5,556.00 | $3,571.00 |
| Spare Parts | $1,250.00 | $853.00 |
| | $6,806.00 | $34,405.00 |
| Total Cost, ex. Labor | $451,250.00 | $350,194.00 |
| Total Cost, Including Labor | $455,689.00 | $350,194.00 |
| Cost per Year, ex. Labor | $5,415,000.00 | $4,202,331.00 |
| Cost per Year, including Labor | $5,468,272.00 | $4,202,331.00 |
| Net Annual Savings, ex. Labor | | $1,212,669.00 |
| Net Annual Savings, including Labor | | $1,265,941.00 |
| Net Equivalent Employees | 2.0 | 0 |

The savings for bulk silane use can be attributed to buying chemical in bulk quantities, labor burden, and time associated with changing out cylinders. The cost comparison example provides basic parameters that a company considering a bulk system can use to conduct an evaluation. The capital costs of installing a bulk system are not included in the cost comparisons and a return of investment for the capital cost of installation needs to be calculated.

Another specialty gas distributor developed a cost example comparing cylinder use to a bulk system. The hypothetical example is as follows:

### Table 7 Cost Comparison (Example #2)[21]

| Cylinder supply: | Bulk Supply |
|---|---|
| -1,000,000 grams/yr - Consumption | -1,000,000 grams per module |
| -20 Gas Cabinets | -1 Gas Cabinet (Back-up Supply) |
| -20 Use Points | -5 Valve Manifold Boxes |
| -5,000 grams/cylinder | -$0.20 /gram |
| -200 Cylinders/yr | |
| -0 Valve Manifold Boxes | |
| -$0.40/ gram | |

| | **Cylinder** (Cabinets) | **Bulk** (Modules/Cabinets/Valve Manifold Box) | |
|---|---|---|---|
| *Equipment Layout* | 20-Gas Cab. | 2-Modules/1 G.C./5 VMBs | |
| *Value of Floor Space* | 160 sq. ft.<br>($50/sq. ft) | 900/8/20 sq. ft.<br>$1400 | |
| *Air Handling* | 4,000 CFM<br>$12,000 | 0/200/500 CFM<br>$2,100 | |
| *Toxic Detection* | 20 points<br>$80,000 | 4/1/5 points<br>$36,000 | |
| *Cylinder Inventory* | 60 cyl.<br>$5310 | Module - $36,000<br>4 cyl.- $354 | |
| *Power* | $323/G.C.-$6460 | $2261 | |
| *Container Changes* | 200/yr<br>$75 /each<br>$1,500 | 1/yr<br><br>$200 | |
| *Maintenance (Labor)* | 3 hrs/each<br>$18,000 | 3/3/3 hours<br>$6,300 | |
| *Product Cost* | 1,000,000 grams<br>$0.40 /gram<br>$400,000 | 1,000,000<br>$0.20 /gram<br>$200,000 | |
| **Estimated Total** | | | |
| *Operating Cost/Year* | $531,270 | $284,615 | ***$246,655 (Savings/yr)*** |
| *Capital* | $1,000,000 | $750,000 | ***$250,000*** |

The second case study of the cylinder and bulk system cost comparison shows an operating cost per year savings of approximately a quarter of a million dollars. There appeared to be some reduced facility costs, but the major savings is in labor and product cost. The capital cost will vary depending on the engineering requirements added to the basic design.

The two examples provided by the gas specialty suppliers indicate a cost benefit with a bulk system over a cylinder system. The savings are consistent in both cases depending on utilization.

The labor and product costs are significant. The savings do not take into account any anticipated reduction or elimination of silane incidents because of cylinder change-outs. The capital costs may vary with location and the number of engineering controls and redundancy added to the basic system design. An existing facility may want to conduct a more thorough cost-of-ownership evaluation. A new manufacturing facility should not discount a bulk silane system in their initial planning review because of some recognized operating cost savings.

## 9 SUMMARY

Interest in bulk silane distribution systems continues to grow. The flat panel and solar panel industries are designing and beginning to use bulk silane delivery systems to meet the needs of the industry. The semiconductor industry is interested in the concept; however, no known domestic semiconductor bulk silane installations are in use today. A semiconductor manufacturing facility is planning to install bulk silane systems in the near future.

The current regulatory requirements address silane and pyrophoric systems. The silane bulk system area is in its infancy with regards to regulations. As the systems begin to proliferate, regulatory activity in the area will probably increase, especially if incidents occur. New installations will necessitate close communication with the planners and the local regulatory and permit officials.

The basic designs incorporated with the government installation and the gas specialty distributors are similar in many ways. The engineering controls follow many techniques noted in the S71 report. The likelihood of a major incident is possible but not probable because the human/machine interface with the bulk system up to the valve manifold box distribution system is limited.

The incident experience with the government installation, the gas suppliers, and the domestic silane manufacturer is positive. Literature reports of vapor cloud explosions indicate some conflicting information, depending on the experimental parameters and scenarios. The potential for a process contamination incident is possible, but engineering controls and the minimization of cylinder change-outs and human interface provide positive incentives for a bulk system.

The examples provided by the specialty gas suppliers in the system cost comparisons indicate some positive return on investment with regards to operating costs. The initial capital costs of installation would need to be evaluated depending on the additional engineering controls added to the basic Compressed Gas Association design.

The silane cylinder gas system installations have an historical basis for costs and design improvements. They are proven systems but have been troubled with incidents based on equipment and procedural errors. The semiconductor industry is a dynamic industry and facility planners, Risk Management, and senior management personnel should not discount the bulk silane system as a potentially viable technology for the future.

## 10 RECOMMENDATIONS

The results of the literature review, site visits and interviews with key persons in the specialty gas and semiconductor industry raise several concerns about bulk silane systems. The following issues need to be addressed:

- The literature was inconclusive on the issue of the vapor cloud explosions and the resulting siting locations for the silane modules. Empirical testing needs to be conducted on real silane releases from bulk silane modules. A most probable silane release scenario would provide definitive information on bulk silane releases. The data may be used to define more accurate silane vapor cloud explosion models.
- A Process Hazard Analysis of a manufacturing site installation is being proposed by a committee within the Compressed Gas Association. The results of the analysis may lead to further areas of investigation or research in the area of bulk silane installations.
- There is no reported downstream process contamination experience to rely upon to make the process engineers comfortable with the system. Real-time monitoring and redundant systems are controls available to minimize these issues. Additional systems testing may eliminate the potential rsik of business interruption.

The government facility, the specialty gas distributors, the domestic silane manufacturer, and semiconductor companies provided little information in managing community perceptions. Experience shows that acceptable engineering practices and regulatory approval may not be enough to assuage negative community perceptions. Data and education addressed in the appropriate format and forum may have beneficial results with the community.

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## APPENDIX A
## SILANE-RELATED REGULATORY REQUIREMENTS

***FEDERAL:***

-Department of Transportation (DOT), Regulations for Flammable Materials
-Environmental Protection Agency (EPA), The Clean Air Act of 1990.
-Occupational Safety and Health Act (OSHA), Process Safety Management

***STATE and LOCAL:***

-Uniform Building Code (UBC) 1991, Chapter 9 , Hazardous Production Materials
-Uniform Fire Code (UFC) 1991, Articles 10, 51, 80

## APPENDIX B
## INDUSTRY STANDARDS AND GUIDELINE FOR SILANE

***Compressed Gas Association***

-Standard V-1, Compressed Gas Cylinder Valve Outlet and Inlet

***Semiconductor Equipment and Materials International (SEMI)***

-SEMI F1-90, Specification for Leak Integrity of Toxic Gas Piping
-SEMI F2-94, Specifications for 316L Stainless Steel Tubing for General Purpose
-SEMI F4-90, Guide for Remotely Actuated Cylinder Valves
-SEMI F5-90, Guide for Gaseous Effluent Handling
-SEMI F6-92, Guide for Secondary Containment of Hazardous Gas Piping Systems
-SEMI F13-93, Guide for Gas Source Control Equipment
-SEMI S5-93, Safety Guideline for Flow Limiting Devices
-SEMI S6-93, Safety Guideline for Ventilation

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