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THE EVOLUTION OF SPACE SIMULATION

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ABSTRACT

Thirty years have passed since the first large (more than 15' diameter.) thermal vacuum space simulation chambers were built in this country. Many changes have been made since then, and the industry has learned a great deal as the designs have evolved in that time. I was fortunate to have been part of that beginning, and have participated in many of the changes that have occurred since. While talking with vacuum friends recently, I realized that many of the engineers working in the industry today may not be aware of the evolution of space simulation because they did not experience the changes that brought us to today's technology. With that in mind, It seems to be appropriate to take a moment and review some of the events that were a big part of the past thirty years in the thermal vacuum business. Perhaps this review will help to understand a little of the "why" as well as the "how" of building and operating large thermal vacuum chambers.

INTRODUCTION

This paper will not attempt to present a catalogue of all of the early chambers, nor will it include pictures, sizes, pump down curves, pumping speeds and test specimen characteristics of each. I have neither the time nor the data to provide such a compilation. Rather, I will present a brief overview of the operating characteristics of chambers with which I am familiar, the mistakes that were made along the way and the evolution that brought us to today's technology. Naturally, I was not every where at once during those years, so this paper will not cover all situations or changes that occurred along the way. I can only speak from my own experience and about those with which I am familiar. Also, because of my experiences during those years, I have developed beliefs and expectations about specific vacuum equipment which will be covered here. As this paper frankly deals with these issues, I hope no one will take offense with any thing said or any conclusions reached. We all know that every one was doing his best along the way to provide the industry with the equipment it needed to be successful. The facts are that some equipment succeeded better than others.

In the industry today, we feel confident that chambers will operate effectively to provide the environment required for satellite testing. There were times during the early years however, when reaching high vacuum with a satellite inside the chamber was problematic at best. The confidence we have today was not easily attained, but is the result of years of trial and error, theory that proved to be unworkable, experience slowly acquired and considerable work that went on simultaneously in this country and around the world.

CHARACTERISTICS MATRIX

In an attempt to organize the past thirty years into a logical sequence, I have developed a characteristics matrix that arbitrarily breaks the period into three phases. Included in the matrix is a summary of the dominant technology and some of the problems experienced by the industry during each phase. As in most attempts to condense complex issues, this one results in some over simplifications. Many of the characteristics overlap, and no attempt is made to list the relative importance of each. But perhaps it will provide a reference to consider to as we progress through the years.

PHASE ONE

The first large thermal vacuum chambers were completed in 1962 and included those built at General Electric, Valley Forge, Pa; Lockheed Missiles and Space Co. Sunnyvale, Ca; NASA Goddard, Greenbelt, Md; and Jet Propulsion Labs, Pasadena, Ca. Shortly after, chambers were built at NASA, Houston, Tx; McDonnell Douglas, St. Louis, Mo; TRW, Los Angeles, Ca; RCA, Princeton, NJ; Hughes Aircraft, Los Angeles, Ca; and McDonnell Douglas, Huntington Beach, Ca. The creation of these chambers was the result of industry's need to test full sized satellites in the environment of outer space. Since this was the pioneer group, the technology applied on these new chambers was based on what was being practiced at the time. Vacuum technology in the early 1960's consisted mostly of what had previously been used in the building of small and medium sized chambers. At that time, we all wondered if the technology that had worked for small chamber could be applied to the design of large chambers.

CONTRACTORS

The two prime contractors for the first chambers, excluding the two at NASA, Houston, were F. J. Stokes Corporation in Philadelphia, Pa. and Consolidated Vacuum Corporation in Rochester, N. Y. It is interesting to note that neither of these two companies is in the business of building large space chambers today. Both companies had dropped out of the prime business by the mid 1960's. From those pioneers and their experiences, we all learned valuable lessons and their designs contributed to the industry for some years afterward. I have always had a great respect for those two companies and their subcontractors who were willing to strike out into a new and previously untried technology.

CONFIGURATION

What did those first chambers look like? To begin with, their prime mode of high vacuum pumping consisted of a cluster of large diffusion pumps (in excess of thirty in some cases) coupled in some chambers with 20° K helium cryogenic pumps. The chambers were either vertical cylinders or spheres, and most were either top or bottom loaders. The spheres were generally 39' and the cylinders were over 18 feet in diameter. On one of the chambers, the owner believed it to be necessary to bake the chamber to 400° F before each test. This belief was based on years of testing bell jar systems at high vacuum. That particular chamber is still operating and has never been baked out since its acceptance test in May, 1962. The oil sealed roughing pumps used in those days were similar in design to those used today. Some were quite large however, and looked like something out of a Jules Verne submarine. The intermediate range pumps were either diffusion ejector pumps or roots type mechanical blowers.

Although diffusion pumps were the prime mode of high vacuum pumping, a helium cryogenic pump had recently been developed by CVI Incorporated in Columbus, Oh. Unfortunately, the aerospace companies did not generally know in those early days how much pumping speed would be needed to maintain the chamber and specimen at high vacuum (10^{-6} Torr or better). In any case, the number of diffusion pumps could be reduced by adding 20° K cryogenic pumps as a supplement. These pumps had massive speeds (in excess of 1,000,000 liters / Sec) and were intended to provide enough speed to cover the unknown gas loads in satellite testing. A typical 39 ft spherical chamber could attain a vacuum of $2x10^{-10}$ Torr empty with all diffusion pumps and cryogenic pumps operating simultaneously. The pumps were certainly effective and the chambers were definitely vacuum tight.

LESSONS LEARNED

During this first phase , the industry learned several important facts:

1) Gas loads, and consequently, pumping speed requirements, were not as high as had been assumed.
2) Diffusion pumps could, and would at the worst possible times, back stream oil into the chamber and onto the specimen.
3) It was not necessary to bake out a chamber to reach high vacuum.
4) Cryogenic pumps could not, by themselves, attain high vacuum.

Because of item #2, the industry decided that it was time to abandon diffusion pumps and move into the second generation of vacuum chambers. The chambers of phase two were called "selectively pumped" because their high vacuum pumps were each selected to pump certain gases. But before we proceed into the next chamber phase, let's talk for a moment about the characteristics of high vacuum pumps.

HIGH VACUUM PUMPS

As you know, cryopumps that operate at 20° K are able to pump all gases except hydrogen, helium and neon. The vapor pressures of these three gasses are too high at that temperature to allow the chamber to reach high vacuum. Although neon is not usually an issue in vacuum chambers, both hydrogen and helium can be severe problems. Outgassing is the main source of hydrogen and can often be the limiting factor in high vacuum work. Helium levels can also be significant when leak checking has been or is being done in the chamber. Consequently, if the diffusion pumps were to be eliminated in future designs in favor of cryogenic pumps, additional pumps would have to be found to handle these two gases.

PHASE TWO

This now brings us to the second phase in the evolution of large thermal vacuum chambers. This period began around the mid 1960's and was characterized by the elimination of diffusion pumps from large chambers. In the place of diffusion pumps, cryogenic pumps were added and were supplemented with two new pumps. These two were the ion and titanium sublimation pumps and were included to remove helium and hydrogen. Aerospace companies that built chambers during the second phase included Boeing, Seattle, Wa; Ford Aerospace, Palo Alto, Ca; Lockheed, Sunnyvale, Ca; Martin-Marietta, Denver, Co; TRW Los Angeles, Ca; Hughes, Redondo Beach, Ca; and Perkin-Elmer, Danbury, Cn. A new set of prime contractors were now in the business to build chambers; PDM Steel Co in Pittsburgh, Pa, CBI Corp. in Chicago, Il, and CVI Corp. in Columbus Oh.

The industry soon discovered that, although these chambers no longer had diffusion pumps to backstream, they presented a different set of problems that turned out to be characteristic of the new pumping systems. Titanium sublimation pumps had been used previously in smaller chambers in lieu of diffusion pumps. But their purpose in large chambers was to supplement the cryo pumps and handle hydrogen. The purpose of the ion pump was to handle helium and neon. Together the three "selective" pumps would pump all the gases and bring the chamber to high vacuum. Unfortunately, it often did not work that way.

TITANIUM SUBLIMATION PUMPS

Titanium sublimation pumps work on the principle that a layer of deposited titanium captures hydrogen through chemical reaction and thereby "pumps" it from the chamber. Titanium must be evaporated and deposited (sublimated) on the wall of the chamber for the coating to pump successfully. We soon discovered that getting the rod of titanium to reach the correct evaporation temperature could be tiresome, frustrating, and sometimes impossible. I can remember spending hours trying to achieve evaporation temperatures on the rod while the hydrogen partial pressure overwhelmed the chamber. But the worst part of these pumps was their tendency to coat the back end of chambers with a dusty, dirty layer of a titanium compound that defied efforts to remove it. Something needed to be done to successfully pump hydrogen or the industry would be back with diffusion pumps. Titanium sublimation pumps were not the answer.

ION PUMPS

Ion pumps were another source of discontent during the late 1960's and were included in selectively pumped systems to handle helium. This statement may seem to be contradictory since ion pumps are not inherently capable of pumping helium. However, they will pump a small amount of helium if a layer of getter material (titanium I believe) is coated on the inside of the pump. So industry was assured that our helium pumping problems were over; the titanium coated ion pumps would handle it. Again we found a technology that sounded good in theory but did not work in practice.

The problems we faced with ion pumps were first of all based on the fact that most satellites had more helium in them than had been predicted when the chambers were designed. Secondly, although ion pumps could theoretically pump helium, in fact, any significant helium gas load soon saturated the gettering surface and reduced its net speed to zero. Ion pumps could be regenerated when saturated, but only at a high cost and significant loss of time. They were so susceptible to helium contamination that we were removing and regenerating our pumps after only two tests, a situation that was intolerable. I would have been happy to give our ion pumps to anyone who wanted them.

HELIUM GAS LOADS

Of particular interest to those of us in the aerospace industry at that time was the question of the source of the helium gas load. After much searching, I asked one of the satellite engineer to describe every test that the satellite had been through before it was delivered to the thermal vacuum facility. We discovered that just before it arrived, its fuel tanks had been subjected to a helium leak check. But the engineer assured us that all of the helium had been vented after the leak test and should therefore not cause us a problem. What he failed to consider was the fact that when the satellite was placed in a vacuum environment, the fuel tank pressure was then 15 psi greater than that of its surroundings. This pressure difference caused the helium to flow into the chamber at what ever leak rate was characteristic of the tanks. The leak resulted in a higher than expected helium partial pressure and a corresponding need for an effective helium pump. Ion pumps could not handle so much helium on a long term basis.

Let me qualify the previous conclusion by saying that I am sure that both ion and titanium sublimation pumps have their use in vacuum testing and are very effective in some applications. There are industries in which they are used continuously and effectively. We reached the conclusion early in phase two however, that they are not effective for use on large chambers to pump helium and hydrogen. Consequently, in about 1970, we had reached a point of serious concern. Diffusion pumps had been exchanged for selectively pumped systems, and other than the cryo pumps, selective pumping did not work. We could not guarantee that our chambers would pump down to high vacuum under any given set of circumstances. A breakthrough was needed.

TURBOMOLECULAR PUMPS

A break through presented itself around 1971. One day a vacuum equipment salesman came by to show me his line of pumps. I remember being only marginally awake during the interview having just returned from lunch, when he turned the page of his brochure to what he described as his company's new line of turbomolecular pumps. As I scanned the page, I noticed that its pumping speed curve was displayed and showed that it was capable of pumping both helium and hydrogen. This capability was not available on earlier models. I awoke with a start and remember asking him if the graph was accurate, could his T. M. pump actually pump these two illusive gases. He was a bit cautious and replied that he did know for sure, but felt that if his company had said so, it must be true. Not wanting to show too much excitement, I asked him if he would loan me a 6 inch pump that I could install on our chamber for a trial. He brought me one that I installed and tested to exhaustion. Needless to say it worked and the rest is history. Probably no one today would build a large chamber without including a turbo molecular.pump in its vacuum system. The hydrogen-helium pumping problem had been solved.

MID RANGE VACUUM PROBLEMS

The industry experienced other problems during that period. One that gave us particular trouble was the inability to pump through the mid vacuum range in a timely manner. A slow transition through the 10^{-2} , 10^{-3}, 10^{-4} Torr ranges was never a problem with diffusion pumps because it was not necessary to flood the LN_2 shroud to make these pumps operate. Typically, the chamber would be pumped into the 10^{-5} Torr vacuum range, the shroud flooded and the heat flux heaters energized to counteract the cold shroud. With early cryogenic pumping however, the process was not so simple. Cryogenic panels, which typically operate at 20 ° K, were shielded with an LN_2 cooled surface to reduce the panels' radiant heat loss. Consequently, with a selectively pumped system, the pump down sequence typically went as follows: the roughing pumps brought the chamber down to 10^{-2} or 10^{-3} Torr range, the LN_2 shroud was flooded and cooled to 77 ° K, and , as the LN_2 panels reached operating temperature, the cryopanels would be energized and cooled. This worked fine when the chamber was empty, but with a satellite inside, bad things happened. Since it takes several hours for the shroud and cryopanels to reach their operating temperatures, and since the satellite is sitting in a pressure range that permits some convective and conductive as well as radiated heat transfer, the satellite became cold. And the longer it remained in that environment and waited for the panels to become operational, the colder it became. In fact it became so cold that the satellite manager demanded that the heat flux system be energized to prevent the satellite temperature from dropping below its lower damaged-beyond-repair limit. So We did, but only for a split second, only long enough for the heat flux breakers to open or the fuses to blow (if we were lucky) or, worst of all, for the heat flux system to melt into a pile of metal. And so, we were introduced to two previously unknown phenomena, corona discharge and arcing.

ARCING

The problem with arcing, other than the fact that it can damage whatever is in the chamber, is that it has many causes most of which were mainly unknown to us at that time. As we searched through the literature to learn about the phenomenon, we found that several things influenced the probability of its occurrence. The literature claims that it is caused by just the right combination of circumstances. These circumstances include the voltage difference, the local pressure, the distance between electrodes, the shape of the electrodes and the type of gas around the electrodes. The right combination of these variables would cause first of all, a corona discharge and then a sudden arcing between the two surfaces. The arcing inevitably resulted in a big surge of electrical current and a potential meltdown of either or both electrode surfaces or of the wires and feedthroughs in between. The variable that concerned us most, and over which we had some control was the chamber vacuum. Unfortunately, arcing occurs in the $10^{-1}$to 10^{-3} Torr vacuum ranges, and this is the region in which the vacuum systems were having the most trouble pumping through.

SOLUTIONS

This paper is not long enough to cover all the attempts that were made to successfully and unsuccessfully solve the arcing problem. I will, however, mention the effort that was directed at the design of the cryo pumping system. Changes were made in the cryopumps to allow them to pump the chamber through the mid vacuum range without having to flood the main LN_2 shroud. This meant that it was not necessary to cool the shroud until the vacuum was in the low 10^{-4} Torr range and out of the corona region. The result was that the satellite was not prematurely subjected to a cryogenic environment. Consequently, the heat flux did not have to be energized until the chamber pressure was below the corona region. This was accomplished by building at least part of the cryopanel at the end of the chamber out of sight of the satellite where its LN_2 shield would have no effect on the satellite's temperature. In addition, a pod cryopanel had been recently invented that could be isolated and valved off from the main body of the chamber. Other changes were made in the design of heat flux systems to reduce arcing and I have not heard of any problems experienced recently. It is a problem that should not, however, be ignored or taken lightly. All design efforts that are made to avoid arcing are worth the expense.

LIQUID NITROGEN PUMPS

From the beginning, the industry had problems with LN_2 transfer pumps. A reliable LN_2 pump is essential for successful and continued operation of the vacuum chamber over a typical thirty day test. Centrifugal pumps had been used for many years in other industries. The petroleum industry is a good example of an industry that has had success with centrifugal transfer pumps. Unfortunately, the application of these pumps to LN_2 service was not at first successful. Centrifugal pumps are a natural for providing high flow of liquid over a large pressure range, and pumping water or fuel with them was easy. However, pumping a cryogenic fluid introduces a more serious set of problem.

Liquid nitrogen is typically stored at or near the saturated temperature that corresponds to its storage pressure. As the stored LN_2 flows into the suction side of the pump, the liquid pressure suddenly drops at the "eye" or suction impeller. This sudden pressure drop results in the liquid changing to gas if the LN_2 is not subcooled. This gas or "vapor lock" causes the pump to "cavitate" and prevents the pump from obtaining "prime." Consequently, the impeller spins in the gas pocket and no liquid moves through the system.

All centrifugal pumps require a certain net positive suction head (NPSH) in their liquid supply before they can obtain prime and pump effectively. A typical LN_2 pump requires approximately fifteen feet of head (net) for the pump to operate successfully. The word "net" means that this head (storage tank height) has to be available after all losses and heat gain into the liquid are considered. Early mistakes were made in the design and placement of pumps and of the supply headers between the storage tanks and the pumps. These mistakes often compromised the available NPSH and made it impossible to start the pumps.

There is a way to artificially subcool the stored LN_2 . To do this, the storage tank's pressure should be vented to atmospheric, and then increased to a value that provides the proper NPSH. Unfortunately, this is a very expensive (in boiled off LN_2) and time consuming process. There have been times, however, when it was necessary to do this to get the test started. It is important to be very careful in the design and placement of LN_2 storage tanks and transfer systems. The main consideration is the storage tank height, the supply line size and pressure drop and supply line insulation. Nothing is more frustrating than a transfer pump that can not be primed.

The industy had other problems with LN_2 pumps, casing temperature, shaft seal alignment and shaft seal leakage to name a few. But the designs changed and we now have reliable pumps that can operate successfully through a long test.

Other lessons were learned, and phase two closed with the space simulation industry emerging on a much sounder technical footing. This point was finally reached because the critical nature of the business demanded that we attain a high level of reliability and effectiveness in the operation of space chambers. Necessity was certainly the mother of invention in this business.

PHASE THREE

Phase three saw several changes in the design of thermal vacuum facilities. First of all, chambers tended to be in the shape of horizontal cylinders or spheres with horizontal doors. Gone for the most part was the building of top and bottom loaders. Top loaders are easy to load but require a building and crane system that are very expensive. Either the chamber must be set down in the ground a considerable distance, or the crane hook and consequently the building must be quite high. Both of these alternatives result in very high facility costs, particularly in California where earthquake loads can be significant. Bottom loaders also tend to be expensive and a bit more difficult to deal with under some conditions. Horizontal cylinders are more economical overall, especially in the larger size chambers.

Chambers built during phase three included those at RCA, Hightstown, NJ; Lockheed Missiles and Space Co, Sunnyvale, Ca; Rockwell, Seal Beach, Ca; Ball Aerospace, Boulder, Co; and CRC, Ottawa, Canada. Also during this period, Process

Systems International of Westborough, Ma. joined the ranks of prime contractors through the purchase of High Vacuum Equipment Corporation.

MECHANICAL PUMPS

Although the design of mechanical pumps has not radically changed in the past thirty years, both oil sealed pumps and roots blowers have been improved. Reduced internal clearances, canned motors and staged intercooled blower systems have resulted in lowered blank-off pressures for mechanical systems and higher pumping speeds in the mid vacuum ranges. These new mechanical systems have helped to reduce the pump down time through the corona region and lower the pressure at which the cryopumps can be brought on line.

APPENDAGE CRYOPUMPS

Another big help in the pumpdown process has been the development of appendage cryopumps. Since these pumps can now be valved off from the chamber, they can be cooled down in advance of need and opened to the chamber without waiting for the shroud and internal cryopanels to cool down. Because of a more accurate understanding of satellite gas loads, several (four to six) appendage 48 inch cryopumps can now do the job of the multi hundred thousand liter per second cryopumps that were once thought to be necessary. In addition, these cryopumps now come equipped with a charcoal gettering material inside the casing that allows them to pump helium, hydrogen and neon. The original compressor/expander systems designed thirty years ago served their purpose, but anyone who has operated one knows the true meaning of the question "will the reciprocating expander and Swiss compressor make it through another test?" Dependability has certainly been improved.

LIQUID NITROGEN SHROUD

The one area that is still of concern in large thermal vacuum chambers is the liquid nitrogen system. In 1984 , I presented a paper at this meeting in Orlando, Florida (ref. 1) on the subject of newly discovered endurance failures of aluminum LN_2 shrouds. At that time, many of the field welded jumper tubes in our chamber at what was then Ford Aerospace had cracked and were preventing the chamber's use for thermal vacuum testing. We did an extensive evaluation of the problem and discovered that the heat affected zones in LN_2 tubing are very susceptible to endurance failures. We concluded among other things that an aluminum shroud probably has a finite life span caused by repeated thermal cycling. Unfortunately, the time to failure is unknown for any given chamber, but is dependent on the shroud's design and the welding techniques used in its construction. Since the second of these two variables is generally unknown for most chambers, it is impossible to predict accurately if and when a given shroud will fail. Other LN_2 shrouds that were designed and built during that period have been replaced or are under consideration for replacement because of cracking tubes. One must remember that shrouds do not fail at ambient, they fail when a satellite is inside the chamber and it is trying to reach high vacuum. Shroud failure has a large potential for causing great financial and schedule related havoc.

LIQUID NITROGEN SYSTEM

The last subject that I want to address has also to do with liquid nitrogen systems. I firmly believe that when this business started, less was known about LN_2 systems than about any other component of thermal vacuum chambers. In the beginning, we had very little idea of how much heat would be applied to satellites during test. Consequently, as with vacuum pumping speeds, the capacity of LN_2 systems was generally over designed and was sufficient to provide considerable safety factor. The typical system of thirty years ago was capable of handling a 300 KW heat load. In fact, this number has often been used in chambers designed recently. However, over the years most satellite testing has used no more than 50 to 70 KW for normal earth orbit heat flux levels. One's response might be to wonder why this over design would be a problem since it provides plenty of safety factor. The answer and our concern lies in the fact that an over designed LN_2 system can result in a large consumption of liquid nitrogen. This is true even when the system is operating at low heat loads.

LN_2 CONSUMPTION

When discussing LN_2 consumption, we must first consider the thermodynamic cycle by which the LN_2 removes heat from the chamber. Some of the first chambers kept their shrouds cold by using liquid level sensors that operated zone supply valves. When the sensor detected that the liquid had changed to gas in the exhaust header of that zone, it opened the valve and the zone was filled with liquid. In this cycle, the satellite heat load was absorbed as latent heat of vaporization as all the liquid in the shroud eventually changed to gas. This boiling system had worked well on smaller chambers and is probably still in use in some vacuum chambers today. However, it was often found to be inadequate to provide the high flow rates required to meet most chamber heat loads. Its big advantage was that it probably consumed the least amount of LN_2 for any given heat load as long as the flow requirement was not too great. Since the flow of LN_2 was energized by a pressurized storage tank, its main inefficiency was caused by the vaporized LN_2 that was required to maintain the proper tank pressure.

SUBCOOLED LN_2 SYSTEMS

The main alternative to the boiling system is known as the pressurized or subcooled system. It was actually developed in the early 1960's by CVI Corporation and was designed to counter the disadvantage of the boiling system. It has been very successful over the years and is presently in use in most of the chambers around the country today. It works on the principle that as the liquid is pressurized and circulated through the shroud, it picks up thermal energy as sensible heat, but is prevented from boiling by its high pressure. The liquid, after it is discharged from the shroud, is then pumped through a heat exchanger where it gives up its sensible heat to the latent heat of an atmospheric pool of LN_2. The LN_2 that leaves this "subcooler" is now subcooled and returns to the pump where its pressure is increased and it starts its round trip again. This closed loop pressurized system maintains a very stable temperature distribution through a large range of heat loads without vaporizing or vapor locking. This characteristic has significant advantages when high localized heat loads are a problem. However, this system also has one major disadvantage.

The high pressure and flow rates required to keep the subcooled liquid from boiling require large centrifugal pumps with correspondingly high horsepower motors to drive them. In cryogenic systems, all of the horsepower that goes into the pump shows up as boiled or consumed LN_2. In one typical subcooled system of a 39 foot spherical chamber with which I have been recently associated, the LN_2 pumps are 25 Horsepower, and all of this power goes into consumed LN_2. In a typical 30 day thermal vacuum test, the heat flux simulator would radiate approximately 50 KW of thermal energy onto the satellite. This thermal load itself consumes approximately 300 gallons of LN_2 per hour. However, under these conditions, the chamber boils off around 600 gallons per hour. This means that the pump and miscellaneous system heat gains in the chamber run about 300 gallons per hour. At the present cost of LN_2, that company is spending over $2000 per day on wasted LN_2, or almost $65,000 per thirty day test. Since this company is now running about four tests per year, their yearly cost of thermal inefficiency is almost a quarter of a million dollars. Not all of this loss is caused by the pumps, and not all of the pump loss can be eliminated, but there is room for improvement. When space simulation testing started, no one was concerned about the cost of running a thermal vacuum test. Today, the industry has changed. Contracts are awarded on price, and our customers and the taxpayers are rightly concerned about the cost of satellite testing.

Because of these high LN_2 consumption costs, work has been done in the industry to design a better, more efficient thermodynamic cycle to maintain the cold black body temperature of outer space. There are designs for saturated and boiling systems which will remove the sun's heat load at lower LN_2 consumptions. Without going into details, a saturated system could save significantly in operating costs and still provide low enough shroud temperatures. I believe that this is the area in thermal vacuum testing in which the optimum design has not been reached.

GN_2 SYSTEMS

Several companies have developed a new approach to the thermal balance process in lieu of the traditional heat flux/LN_2 shroud technique. Shroud temperatures can be controlled with a gaseous nitrogen system between LN_2 temperature and $+150^0$ F. Heat exchangers establish the pre set temperature and the gas is circulated through the shroud by a blower at the shroud's operating pressure. This technique can provide the required thermal balance on the satellite with a very minimum in LN_2 consumption. This process is not exactly new: the first GN_2 thermal system was designed by High Vacuum Equipment Corporation and installed at the Honeywell facility in St. Petersburg, Forida in 1961.

A NEW CHAMBER

At Space Systems/Loral in Palo Alto, the most recent large space simulation chamber has been designed using the lessons that have been learned over the last thirty years. This chamber will be a horizontal cylinder, 30'x30' and will incorporate the latest in vacuum equipment and system controls that has been discussed in this paper. It will have a flat floor at the same elevation as the building floor to permit access with an air bearing cart. It will have four 48" appendage cryopumps with isolation valves, a turbomolecular pump and the latest data and heat flux control systems. As I considered the technique of system control in its design however, I deliberately avoided the use of computer control of the vacuum process. Some chambers built recently have included in them a vacuum pump down and control system that is computer controlled. Without criticizing what others have done, I believe that manual control and human decision making in the vacuum process is essential to a sound operation of the system. Computers have a important responsibility in providing data in a timely and efficient manner. However, decisions need to be made by people. Well-trained operators learn from making decisions, not from watching a computer.

CONCLUSION

In conclusion, the design of thermal vacuum chambers and the testing done in them have come a long way since their inception only thirty years ago. It seems that everything that was learned, was learned the hard way. As they say in the Navy, safety instructions are written in blood. None of our experiences cost any one any blood, at least as far as I know, but they usually cost us a great deal of sweat and tears, lost time and much frustration. Perhaps this short review of vacuum history will remind the old timers of some of the challenging times we once had and will hopefully prevent the industry from having to relive them again.

THERMAL VACUUM CHAMBER CHARACTERISTICS MATRIX

COMPONENT	PHASE ONE 1960-1965	PHASE TWO 1965-1972	PHASE THREE 1972-
CHAMBER SHAPE	VERTICAL CYLINDER SPHERE	HORIZONTAL CYLINDER SPHERE	HORIZONTAL CYLINDER
CHAMBER LOADING	TOP BOTTOM	TOP SIDE	SIDE
ROUGH PUMPING	BELT DRIVE MECH PUMPS	DIRECT DRIVE M. P.s	DIRECT DRIVE M. P.s
INTERMEDIATE PUMPS	EJECTOR PUMPS ROOTS BLOWERS	ROOTS BLOWERS STAGED ROOTS BLOWERS	STAGED ROOTS BLOWERS CRYO PUMPS
HIGH VACUUM PUMPS	OIL DIFFUSION PUMPS LARGE HE CRYO PUMPS WITH RECIP. EXPANDERS	LARGE HE CRYO PUMPS MODULAR CRYO PUMPS APPENDAGE CRYOPUMPS ION PUMPS TI. SUBLIMATION PUMPS	APPENDAGE CRYOPUMPS TURBOMOLECULAR PUMPS CRYOPUMPS WITH CHARCOAL LARGE HELIUM CRYOPUMPS WITH TURBO EXPANDERS
LIQUID NITROGEN SHROUD	ALUMINUM PIN WHEEL SOLID	ALUMINUM SOLID	ALUMINUM SOLID
LIQUID NITROGEN SYSTEM	BOILING SUBCOOLED SATURATED	SUBCOOLED	SUBCOOLED SATURATED
HEAT FLUX CONTROLS	POWERED VARIACS PROPORTIONAL CONTROL	ZERO CROSS OVER POWERED VARIACS PROPORTIONAL CONTROLS	DIRECT CURRENT POWERED VARIACS
POWER PENETRATIONS	MULTI PIN	INDIVIDUAL CONNECTOR	INDIVIDUAL POTTED
PROBLEMS	D. P. BACK STREAMING LN2 PUMP RELIABILITY SHROUD WARM SPOTS	PUMPING HELIUM PUMPING HYDROGEN PUMP THROUGH MIDDLE VACUUM RANGE ARCING/CORONA ELETRICAL NOISE HELIUM COMPRESSORS RECIPROCATING EXPANDERS PLASTIC CONTAMINATION	SHROUDS BEGINNING TO FAIL HIGH LN2 CONSUMPTION

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