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Mission Research Corporation
P.O. Box 1209
La Jolla, California 92038

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This report discusses technical issues related to the satellite x-ray test facility (SXTF); this work is the first phase of a longer range effort. The primary purpose of this first phase was to identify the significant technical problems involved in design and operation of a vacuum test chamber and its support equipment, and the basic instrumentation requirements for operating the test chamber and the satellite under test, and to outline methods for solving problems. The discussion focuses on important technical issues related to vacuum tank design, instrumentation, and operation. These issues → next page

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20. ABSTRACT (Continued)

are vacuum tank size and wall construction, EM damping grid, electron backscatter control, geomagnetic field suppression, cold wall options, solar illuminator, and site instrumentation. A summary of findings in each of these technical areas is included.

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SECTION 1

INTRODUCTION

This report discusses technical issues resulting from the first phase study of the DNA Satellite X-ray Test Facility (SXTF), performed under contract DNA001-76-C-0318. The work was performed during the period June 1 - November 30, 1976.

The primary purpose of this first phase study was to identify the significant technical problems involved in the design and operation of the vacuum test chamber and its support equipment, and the basic instrumentation requirements for operating the test chamber and the satellite under test, and to outline methods of solving the problems.

The discussion herein focuses on the important (in our opinion) technical issues of the program related to vacuum tank design, instrumentation, and operation. These issues are vacuum tank size and wall construction material, EM damping grid, electron backscatter control, geomagnetic field suppression, cold wall options, solar simulator, and site instrumentation.

Detailed technical work has been published separately in the form of reports and memos. In the present report, these will be referred to and their important conclusions summarized.

During this contract, IRT Corporation was a subcontractor to MRC for investigation of user instrumentation specifications as well as for detailed site instrumentation specifications. Visits by MRC and IRT to the major satellite manufacturers supplied much of the data base for this study and provided additional facts upon which to refine the basic site specifications and technical factors. This information is presented in reference 1.

SECTION 2

PROGRAM REVIEW

The SXTF Site Survey Working Group (SSWG) initially met in June 1976 at which time the preliminary program objectives and facility specifications were defined. MRC was involved in the site visits to NASA Plumbrook Station, Sandusky, Ohio; the Arnold Engineering Development Center, Tullahoma, Tennessee; and Kirtland Air Force Base, Albuquerque, New Mexico. Visits by MRC and IRT were made to the following satellite manufacturers*: Ford Aerospace [DSCS-1 (with TRW); SMS-1, 2; GOES-A, B, C] Palo Alto; Hughes [WESTAR 1, 2; MARISAT; COMSTAR, SATELLITE DATA SYSTEM], Los Angeles; General Electric [LANDSAT 1, 2-C; NIMBUS 5, 6, G; DSCS 3]; King of Prussia; and RCA [NOAA-2, 3, 4; ITOSE-2; TIROS-N; RCA SATCOM; TRANSIT; DMSP], Hightstown. Telephonic information was obtained from TRW [DSCS 1 (with A/F); DSCS 2, FLTSATCOM, DSP], El Segundo, since no visit could be arranged before the conclusion of this first phase.

A number of technical factors were identified during the SSWG program. MRC was tasked by the statement of work to study the following factors:

1. Tank size - Tank size will be determined by satellite size (including solar booms extended or folded), the electromagnetic damper grid,

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*Satellites which have been or will be produced by each manufacturer are in parentheses.

the e^- backscatter control grid, and the cold wall. It is desirable for the satellite-to-wall capacitance to approach, as close as possible, that of the satellite in free space.

2. Tank shape - Several shapes are being considered: spherical, right circular cylinder with a flat floor and a hemispherical top, and a right circular cylinder with hemispherical top and bottom. The shape of the tank is probably not critical from a simulation quality point of view. A flat floor is more convenient for working in; but it must be supported against air pressure, a very costly mechanical approach. The shape of the largest satellites to be tested will be important in determining the tank shape.

3. Electromagnetic damper - A metal[1] SGEMP test chamber will need some type of electromagnetic damping because, without it, it would be difficult to separate the effects of the field reflected from the walls from those of the initial driving field. If the tank were large enough, reflections would not be a problem due to the long time between the driving and reflected fields.

4. e^- backscatter control grid - The purpose of this grid is to keep electrons backscattered from the walls of the vacuum tank from entering the working volume of the simulator and affecting the response of the satellite being tested. The grid itself must be sparse enough so that not many electrons are backscattered from the grid wires, yet the grid must appear electrically continuous so that the working volume is all at the same potential and electromagnetic noise cannot be transmitted to the satellite being tested.

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[1] Non-metal chambers were considered. Outgassing and structural problems eliminate all but fiberglass. That material was rejected because present day construction techniques for such structures are not well developed.

5. Geomagnetic field suppression - The electron Larmor radius in the surface geomagnetic field (0.5 gauss) is about 2 meters for a 1 keV electron. The synchronous orbit field is about 2×10^{-3} gauss, for which 1 keV Larmor radius is some 500 m. In order to simulate correct Larmor radii, i.e., to not disturb the orbits of electrons, some field cancellation may be necessary.

6. Cold walls - Satellites are designed to radiate the heat they generate into the very cold surroundings of space, without the environment radiating a comparable amount back to the satellite. In a chamber, a means of absorbing the heat radiated by the satellite, typically a cold wall, may be necessary if the operational mode is such that the temperature of the satellite rises above the design limits. Manufacturers (Hughes, TRW, G.E., and Ford Aerospace) specify cold walls at or near liquid nitrogen temperatures to surround most of a satellite working in a room temperature environment during *subsystem and system level tests.*

7. Solar simulator - Satellites in space derive their power from batteries which are charged by solar cells driven by the sun. Satellites on the ground are normally powered by external power supplies during test or checkout. However, hardwiring to the satellite during a SGEMP test is undesirable because of the currents generated in the wire by photons. It may be desirable to utilize a solar simulator, then, in the test chamber. The degrees of solar simulation and the alternatives will be studied.

8. Instrumentation - A significant task for satellite testing involves the diagnostic and controlling electronics. For example, the vacuum chamber pumpdown will be computer controlled and the satellite electrical response to the photon pulse will be acquired, stored, and reduced via sophisticated electronic systems. The total instrumentation system for the facility is a significant (5 to 7% of facility cost) budgetary item.

9. Other factors

9.1 Clean air quality - Maintaining the cleanliness of the spacecraft may necessitate a clean room atmosphere in both the preparation area and the vacuum chamber.

9.2 Satellite handling equipment - Movement of the spacecraft through the facility can be accomplished with available satellite-peculiar equipment. Movement of the spacecraft within the vacuum chamber should receive special attention. It is expected that satellites will be irradiated in different orientations and at different heights from the floor. A crane, or similar handler, will be operating within the constraints of a double grid and possibly a cold wall. The reliability of such a device is a prime consideration in view of the spacecraft value.

9.3 Operations staff - The number of resident personnel needed to operate the facility significantly affects the project operating costs, thus a facility design goal is to minimize that staff.

SECTION 3

INTERACTING PARAMETERS

INTRODUCTION

The significant technical considerations for the SXTF in this effort are shown in Table 1. Their mutual interaction is quantified as strong (S), medium (M) and weak (W). A strong interaction is one which significantly perturbs the interacting parameter and incurs a major cost impact (> 1% of facility cost). For example, in Section 4 of this report it is shown that the cost of a spherical steel tank is very nearly proportional to the cube of the radius. If a 24 meter tank is assumed as a baseline, then the cost for each added meter of radius is about 1 million dollars.

A medium interaction perturbs the interacting parameter, but incurs a medium (< .1% of facility cost) cost impact. For example, a crane or similar satellite handling device will be needed inside the tank for proper positioning, but the additional cost for a larger (or smaller) crane is only a small percent of the initial cost for procurement and installation.

A weak interaction has only a minor effect on the interacting parameter and results in minor cost changes, e.g., the cost of radiation control is dependent on the number of tank penetrations (apertures through the tank wall, e.g. connector feed throughs, viewing ports, personnel access doors), but the cost is not significantly perturbed, if the number of penetrations increases or decreases by some small number.

TABLE 1: Interacting Parameters

	TANK RADIUS	TANK MATERIAL	PUMPDOWN TIME	DUMP TIME	CLEAN AIR QUALITY	EM DAMPER GRID	e^- BACKSCATTER GRID	COLD WALL	GEO. FIELD SUPPRESS.	SOLAR SIMULATOR	POWER REQUIREMENTS	TANK PENETRATIONS	UTILITY CRANE	VACUUM PUMPS	E.W. SOURCE	AD. CONV. SOURCE	RADIATION CONTROL	SIMULATION QUALITY	SOURCE COLLIMATION	SPACECRAFT ORIENTATION	SATELLITE DIMENSIONS	OPERATIONS STAFF	INSTRUMENTATION
TANK RADIUS			M	M		S	M	M										S			S		
TANK MATERIAL									S								M	W					
PUMPDOWN TIME						W	W			W	M		W	S									
DUMP TIME					S																		
CLEAN AIR QUALITY													W	W								W	
EM DAMPER GRID							M	M	W			M	M					S	S	W			S
e^- BACKSCATTER GRID								M			M	M	M					M	S	W		M	S
COLD WALLS									W			M						M	M	S	M	M	M
GEO. FIELD SUPPRESS.											W							M					M
SOLAR SIMULATOR											S									W		M	S
POWER REQUIREMENTS													W	S	W	W							W
TANK PENETRATIONS														M			W			S			
UTILITY CRANE																					M		W
VACUUM PUMPS																						W	W
E.W. SOURCE																		S				W	W
AD. CONV. SOURCE																		S				W	W
RADIATION CONTROL																							
SIMULATION QUALITY																							
SOURCE COLLIMATION																							
SPACECRAFT ORIENTATION																							
SATELLITE DIMENSIONS																							
OPERATIONS STAFF																							S
INSTRUMENTATION																							

Strong Interactions

1. Clean Air Quality vs. Dump Time

Although dump time (time for tank environment to change from vacuum pressure to atmospheric pressure) is not a critical time, it is necessary that it be reasonable, i.e., within 4 to 6 hours. If a clean air environment is required, then suitable filters must be placed in the air intake lines, thereby reducing the volume of air flow per unit time. In order to retain a reasonable dump time, larger intake lines may be needed. The size of these lines will vary, then, with the degree of air quality required.

2. EM Damper Grid vs. Tank Radius

It is most reasonable to assume that a damper grid will be needed both to reduce reflection of waves radiated by the satellite itself and also to spoil the cavity Q to damp out the tank's normal modes. To a point, a thicker damper will be a more efficient damper. But the thicker the damper the larger the radius of the tank, thus presenting a significant cost impact.

3. Geomagnetic Field Suppression vs. Tank Material

The tank material affects the design of the magnetic field suppression coils. Steel has a magnetic permeability on the order of 200 and will shield the inside from the earth's field and fields produced by external coils. Aluminum will have no effect on the applied field. Since the fields produced by the photon exposure are fast oscillations of decreasing magnitude, they will not cause any significant permanent magnetization of the steel.

4. Power Requirements vs. Solar Simulator

The type of solar simulation necessary will have a considerable impact on facility power requirements because the mixed gas simulators may require up to 2 MW for operation. Less sophisticated systems require much less power.

A further impact on cost is the magnitude and type of power necessary to operate a spacecraft during testing. The question is whether or not the spacecraft can be operated completely on battery power during the test. This will depend on the battery capacity and craft power consumption. But it must be determined if or to what degree simulation quality is affected by the lack of solar power. A suitable alternative may be a partial solar cell complement with a correspondingly smaller solar simulator operating in concert with battery power.

5. Vacuum Pumps vs. Pump Down Time, and vs. Power Requirements

The quantity and capacity of vacuum pumps will have a direct bearing on the pump-down time. The power requirements will vary with the number and capacity of the pumps, but the expected power consumption is expected to be about two megawatts.

6. Simulation Quality vs. Tank Radius, and vs. EM Damper Grid

The larger the tank radius the more nearly the tank characteristics approach the realistic space environment and the more closely the response of a satellite will resemble that of a satellite in its operational mode. Actually, the presence of the tank will prevent perfect simulation so that an EM damper will be necessary. The better the design of the damper, the better the response of the satellite will approximate its orbital response.

7. Source Collimation vs. EM Damper Grid and vs. e^- Backscatter Control Grid

Without source collimation, the e^- backscatter grid must occupy a large percentage of the inner surface area of the tank. This is not only costly to fabricate and install but it has a cost impact on tank operations by the fact that it is in the way. Its presence must be allowed for and designed around when other tank equipment is to be installed or moved. With source collimation, the grid area conld be localized and thereby occupy a much smaller percent of the surface area.

8. Spacecraft Orientation vs. Cold Walls

If the cold wall question is resolved by their placement around the tank periphery, then there is no interaction here. If, however, the question is resolved by using a movable cold wall close to the satellite, then design and fabrication costs will be dramatically affected by the complex specifications and additional developments needed.

9. Spacecraft Orientation vs. Tank Penetration

This problem is a function of satellite operational characteristics. If a spacecraft can be operated in a non-vertical and non-horizontal position, then a penetration for the source from the side of the vacuum tank is satisfactory. If the spacecrafts expected to be tested must be operated in a horizontal or vertical postion (such as is the case with satellites using heatpipes for temperature stabilization), then in order to be able to irradiate the top (or bottom) of the craft, a different and much more costly penetration is necessary. This penetration will come from below floor level on a diagonal and may affect the cost of the tank.

10. Remaining Strong Interactions

10.1 Satellite Dimensions vs. Tank Radius - The larger the satellite the larger the tank and the higher the tank cost.

10.2 Instrumentation vs. Tank Items - More site instrumentation is necessary if there is an EM damper grid, a e^- backscatter grid and solar simulator. The operations staff will increase in order to maintain and operate the added instrumentation.

Medium and Weak Interactions

Tables 2 and 3 present brief explanations of the medium and weak interactions.

TABLE 2: MEDIUM INTERACTIONS

INTERACTION		EXPLANATION
Cold Walls	Tank Radius	Peripheral cold wall area varies with tank site.
	EM Damper	If cold wall close to satellite, damper can be smaller.
	e^- Backscatter Grid	If cold wall close to satellite, e^- grid can be smaller.
	Tank Penetrations	Tank penetrations reflected as cold wall penetration - most cases.
	Satellite Dimensions	Movable cold wall area varies with satellite size.
	Source Collimation	Movable cold wall advantageous.
Utility Crane	Satellite Dimensions	Heavier (or lighter) satellites need stronger (or weaker) crane.
	EM Damper	Crane placement and movement affected by placement of damper.
	e^- Backscatter Grid	Crane placement and movement affected by placement of e^- grid.
Pumpdown Time	Tank Radius	Longer (or shorter) time needed for smaller (or larger) tank.
		Alt. use different number pumps.
	Power Requirements	Increase (or decrease) in no. of pumps affects power loading.
Tank Radius	Pumptime	Increased (or decreased) tank air capacity means longer (or shorter) pumpdown time.
	e^- Backscatter Grid	Larger (or smaller) tank means larger (or smaller) grid dimensions.
Tank Penetrations	EM Damper	Tank penetrations reflected as damper penetrations - many cases.
	e^- Backscatter Grid	Tank penetrations reflected as e^- grid penetrations - many cases.
e^- Backscatter Grid	Power Requirements	Necessity of grid raises power needed in facility.
	EM Damper	Physical size of e^- grid varies with size of EM damper grid.
Radiation Control	Tank Material	Rough surface characteristics make cleanliness a problem.

TABLE 3: WEAK INTERACTIONS

INTERACTION		EVALUATION
Instrumentation	Power Requirements	More Instrumentation - More Power
	Utility Crane	Remote Control Needed.
	Vacuums Pumps	Computer Controlled Pumps Needed.
	E. W. Source	Control & Diagnostic Inst. Necessary.
	Ad. C. Source	Control & Diagnostic Inst. Necessary.
Operations Staff	Clean Air Quality	Class 100,000 Clean Room Will Necessitate Supervision.
	Vacuum Pumps	Operation and Maintenance Personnel.
	E. W. Source	Complexity Affects Operating Personnel Complement.
	Ad. C. Source	Complexity Affects Operating Personnel Complement.
Pumpdown Time	Solar Simulator	Outgassing Effect (Small).
	e^- Backscatter Grid	Outgassing Effect (Small).
	EM Damper	Outgassing Effect (Small).
	Utility Crane	Outgassing Effect (Small).
Power Requirements	Geo. Field Support	Power Supply Needed.
	Utility Crane	Power Needs.
	E. W. Source	Power Needs.
	Ad. C. Source	Power Needs.
Geomagnetic Field Suppression	EM Damper	Power Supply Needed.
	e^- Backscatter Control	Power Supply Needed.
	Tank Material	Steel shields inside from coil produced fields.

SECTION 4

TECHNICAL ISSUES RELATED TO TANK PHYSICS

In this section we summarize some of our present understanding of technical issues related to the design of the vacuum test chamber. Detailed considerations of these technical issues are documented in the references.

1. Tank Material

The purpose of the SXTF is to simulate the SGEMP response of a satellite in orbit exposed to an X-ray flash. In the course of the satellite's response, electromagnetic energy is radiated away into space, and the energy residing in the electromagnetic oscillations of skin current on the satellite is damped.

In a laboratory simulator, however, the walls of the vacuum tank will cause electromagnetic interference with the satellite response. This EMI can be minimized by using dielectric tank walls, or, if the walls are conducting, by employing an energy absorbing EM damper grid just inside the walls.

The possibility of using a dielectric for the tank was discussed in reference 2. We summarize this discussion here for completeness.

Structurally feasible dielectric materials are building stone, concrete, brick, glass, or fiberglass. To build a vacuum tight tank some 75' in diameter out of any of these materials would be a rather cavalier undertaking, but possible. The first three materials are very porous, and even with an exterior air-tight coating to eliminate air permeating, they would outgas badly from within. Glass is excellent for holding a vacuum, but on-site assembly from prefabricated sections would be very difficult. In addition, one would like to be able to machine and work with the wall materials; this is much easier with metal than glass. Also, the dielectric constant of many glasses is larger than that for fiberglass.

Less objectionable in these respects is fiberglass. It can be quite strong, and indeed large storage and rocket tanks are commonly made from it (although not large vacuum tanks).

We have obtained some relevant fiberglass properties from Owens-Corning.[3] A 75' diameter tank requires fiberglass walls roughly 1 foot thick to prevent buckling under pressure. Figure 1 shows our calculation of the electromagnetic reflectivity as a function of frequency off a 1' thick fiberglass wall, for typical values of the dielectric constant ε (commonly 3.5 to 5.0 at these frequencies).[4] The oscillatory behavior continues regularly at higher frequencies than shown in the plot due to the interference of the signals reflected off the front and rear surfaces.

The figure shows very small reflectivity for all frequencies below 20 or 30 MHz but a relatively high reflectivity near 100 MHz. Since the low-frequency ($\lesssim$ 20 MHz) normal modes of a tank are not well approximated by transverse plane waves incident on the walls, it is not obvious how to translate this small reflectivity into equivalent Q spoiling. Nonetheless the graph would provide a point of comparison with the effectiveness of EM damper grids in a metal tank. In order to seriously consider a fiberglass tank it must be shown that EM damper grids in a metal tank cannot possibly reduce reflections to as small a level as in Figure 1. Equivalent damper grid reflectivities await further calculation, but we suspect they can be designed to an adequate degree.

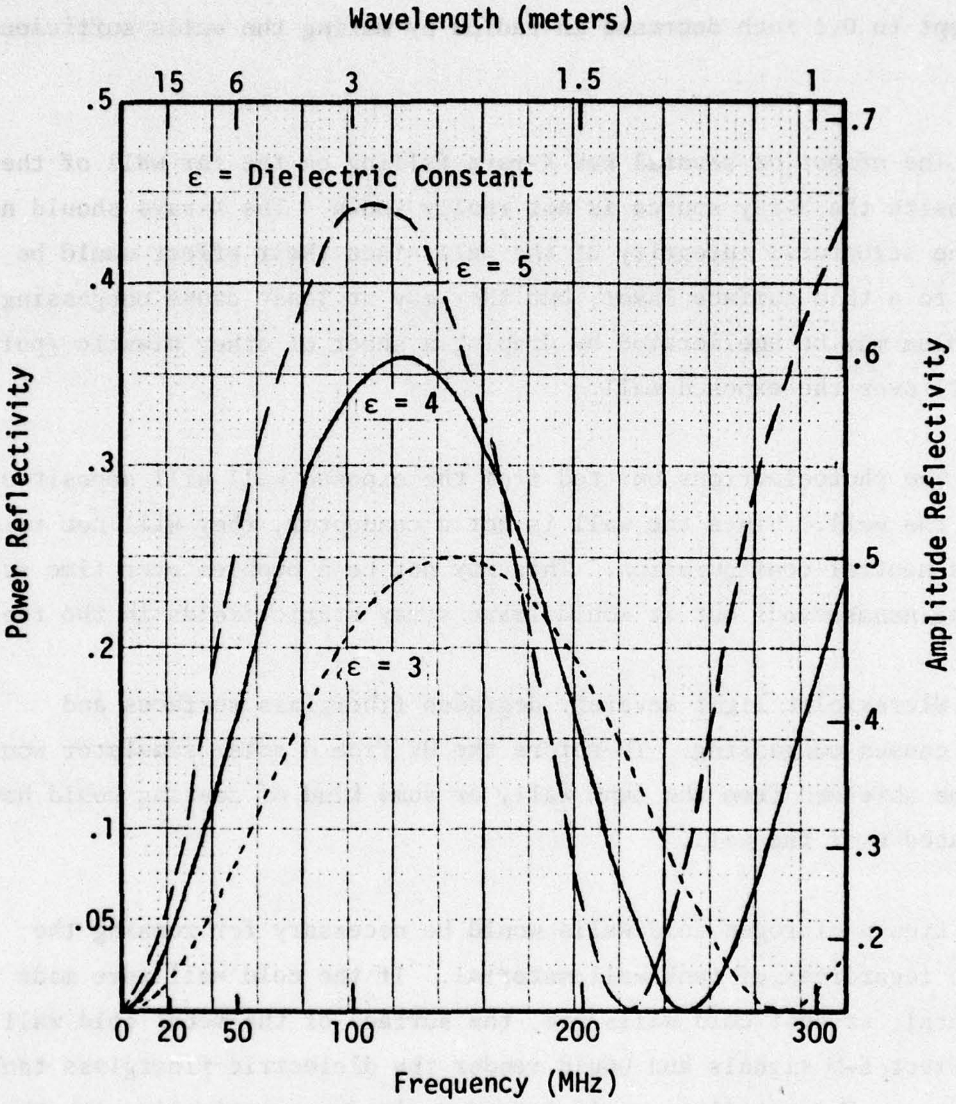

Figure 1. Power and amplitude reflectivities of plane waves off 1 foot thick fiberglass walls.

Fiberglass tanks have certain other disadvantages. Structurally the walls will squeeze in when the tank is evacuated because of the finite modulus of elasticity of fiberglass. But this shrinkage is not large and can be kept to 0.1 inch decrease in radius by making the walls sufficiently thick.

The effect of several keV X-rays falling on the far wall of the tank opposite the X-ray source is not really known. The X-rays should not damage the structural integrity of the wall since their effect would be confined to a thin surface layer, but they may at least cause outgassing. This problem may be ameliorated by draping a sheet of other plastic (polyethylene?) over the exposed wall.

The photoelectrons emitted from the exposed wall will deposit elsewhere on the wall. Since the wall is not a conductor, they will not relax back to a neutral configuration. This may not be a problem over time scales of tens of nanoseconds but it would leave stray static fields in the tank.

Ultraviolet light severely degrades fiberglass surfaces and probably causes outgassing. Therefore the UV from a solar simulator would have to be shielded from the tank wall, or some kind of coating would have to be placed over the wall.

Liquid nitrogen cold walls would be necessary for running the satellite regardless of tank wall material. If the cold wall were made out of metal, as most cold walls are, the surface of the metal cold wall would reflect E-M signals and would render the dielectric fiberglass tank wall useless. The satellite would interact electromagnetically with the cold wall and the advantage of a dielectric tank would be lost. This could be circumvented by making the cold walls themselves our of fiberglass. Fiberglass actually holds up quite well at cryogenic temperatures. There exist many fiberglass storage tanks for liquid natural gas. Hence it is possible that L-N_2 cold walls could be made out of fiberglass also, but considerable further research would be required. In addition, the thermal expansion coefficient of fiberglass is roughly 10^{-5} cm/cm/°F, indicating that to cool the cold walls from room temperature to L-N_2 temperatures, a drop of 400°F, would shrink the cold walls by about $10^{-5} \times 400 = 4 \times 10^{-3}$ cm/cm. Thus 60' high cold walls would have to be designed to allow them to shrink nearly 3". This would cause considerable stress on those portions of the wall at different temperatures while it is cooling down.

While perhaps none of the above disadvantages is insurmountable, none is very encouraging either. It would require considerable engineering research to safely design a useful fiberglass vacuum tank with confidence. This takes time, costs more, and is fraught with uncertainties. We therefore believe it is smarter to proceed with a metal wall tank where the engineering properties are known and reliable, and design an optimum EM damper grid.

2. EM Dampers

In a metal wall tank some kind of electromagnetic damping will almost certainly be necessary both to reduce reflection of waves radiated by the satellite itself and also to spoil the cavity Q to damp out the tank's normal modes. These modes can be excited by the SGEMP response of the satellite and by the photoelectron burst off the tank wall. Tank Q can be expected to be on the order of 10^3 - 10^4 so tank modes will ring for microseconds if undamped.

The design of an effective EM damper to minimize the wall interference with the satellite SGEMP response is not trivial. Simple analytical calculations can be done only for simple geometries, like plane wave reflections off damper membranes over an infinite reflecting wall, or for mode damping with a single membrane in a spherical cavity. But if the damper effectiveness criterion involves minimizing the disturbance of the satellite skin currents, as it should, then numerical computations are required on a class of satellite shapes for various photon time histories.

In past studies, most of which were made between late 1972 and late 1974, EM field criteria formed the basis of judging damper effectiveness in almost all cases. With the exception of one study (Reference 5) in which a dipole was used to excite the cavity, the studies involved either the damping of a cavity without the presence of a test body or they were studies of the plane wave reflectivity of a damping configuration such as a layer of conducting dielectric or a wire grid (References 6 through 10). The plane wave reflection coefficient can be related to cavity Q under conditions applicable to a realistic test chamber (Reference 6). Since no satellite body model was present in these latter computations, there is no alternative to using a field oriented damping criterion. Field criteria do have the advantage that they are more general than the system oriented variety and, when used intelligently, can be applied to a wide variety of situations.

Field oriented criteria can be given in either the frequency domain or time domain. The most convenient and common frequency domain criteria specify the cavity damping rate at the modal frequencies (Reference 6 and 8). In the time domain, a comparison of the ratio of peak incident and reflected fields, at an interesting location, is the most convenient. The wideband nature of the problem gives these type of criteria a very limited usefulness. The system may not respond to peak fields, for example, but to accumulated energy. Specifying modal damping rates is a problem because conditions that give optimum damping of one mode do not give optimum damping of the others. It is rather clumsy to use such criteria to determine the high frequency (early time) reflected signal in any case.

An example of a more system oriented parameter study is a numerical one performed by Merewether and Foster (Reference 5). In this study, a model of a chamber with a damper system is excited by dipoles of various lengths representing different satellite sizes. The short circuit current running on the dipole was computed in the time domain, with and without the chamber. In addition, the two sets of time waveforms were Fourier transformed and their ratio computed so that a transfer function was determined which showed the deviation of the dipole current in the presence of the chamber and damper. This method of comparison, while not a criterion, at least utilizes a quantity of interest to satellite engineers.

We propose a three phase approach toward the design of a damper membrame that uses as its basic guideline minimizing the disturbance of the satellite's skin current response. The best possible damper is one that absorbs all radiated energy and so duplicates the in-orbit response of the satellite. The worst possible damper is the bare tank wall that reflects all radiated energy. These two cases (free space response, and perfectly reflecting wall response) bound the possibilities. Any real damper will produce a response intermediate (in terms of reflected energy) between these two.

In phase 1 we suggest determining the responses of various satellite shapes to selected photon time histories in free space and in a tank with perfectly reflecting walls to bound the problem. As a worst case, a satellite should be chosen with natural lowest frequency comparable to a normal mode of the tank to provide maximal coupling between satellite and tank. A parallel effort should be carried out to analytically or semi-analytically determine a first choice for a good damper design to be used in phase 2.

Phase 2 determines the responses of the same satellites in a tank with various damper designs and various damper thicknesses. This will show increased quality of SGEMP simulation as damper thickness and tank radius are increased. This will permit a choice of a "best" damper or alternate "best" dampers and a tank radius.

Phase 3 is then concerned with the hardware realization of the best damper and its attendant problems, such as thermal control complications, capacitance effects, photo-electron emission, etc. Figure 2 outlines this approach.

Preliminary work along these lines has already been done. A study with linear conductivity profiles has been performed[11] and supports an earlier suspicion that a profile with a local maximum may result in greater damping by using resonance effects to enhance I^2R energy absorption. This study will lead naturally to ones involving other profiles without discontinuities.

A method has been developed to quickly evaluate the effectiveness of damper designs by using an equivalent circuit transmission line to model signal propagation from the satellite to the damper grid on the wall and back.[12] This should make it easier and faster to study the relative merits of various damper grids.

The dampers that have been studied to date all use Joule heating of a conducting medium as the energy absorption mechanism. This is proportional to $\vec{j} \cdot \vec{E} = \sigma E^2$, where $\vec{E}$ is the incident electric field, σ is the conductivity and $\vec{j} = \sigma\vec{E}$ is the Ohmic current density. Thus these grids "operate on" the electric field of the wave rather than the magnetic field.

In addition to this mechanism, it might be possible to absorb energy from the magnetic field as well by taking advantage of energy losses involved in traversing a hysteresis loop. This would presumably involve attributing a magnetic permeability μ to the damper medium, as well as a conductivity σ, such that the constitutive relation $\vec{B} = \mu\vec{H}$ of the medium will result in hysteresis energy loss as the incident wave progresses through the damper. This would absorb energy from the magnetic field as well as the electric field and presumably increase the damping effect. The possibility of doing this is being studied.

PHASE 1

Response of various satellites in a tank with no damping

- *Prescribed photo-emission currents*, or particle pushing codes (2D, 3D)
- Choose satellites with normal modes comparable to tank's
- Compare with response in free space
- Define "Figures of Merit" for simulation quality

Continue 1D parameter study for "best" EM damper configuration.

Look into hysteresis loss damping mechanism.

PHASE 2

Response of various satellites in a tank with damping

- 2D, 3D
- Use "best" EM damper
- Vary tank radius R and damper thickness
- Compare responses with no damper, free space
- Measure "simulation quality" as function of R

Try "reduced coverage" damper.

- covers $< 4\pi$
- 2D, 3D

PHASE 3

Design hardware realization of EM damper grid

Study attendant problems:

- Photo electron emission
- *Capacitance effects*
- Temperature control complications

Figure 2. Outline of EM damping Study.

3. Tank Shape

The shape of the tank is probably not critical from a simulation quality point of view. It must be decided whether the tank should be a sphere or cylinder. If the latter, what is the best ratio of length to diameter, should the ends be flat or spherical segments, should the cylinder stand vertically or lie on its side? The kinds of issues to consider are the sizes and shapes of actual satellites to be tested; whether SGEMP simulation requires the satellite to be exposed from an arbitrary direction thereby requiring the satellite to be suspended in an arbitrary orientation (for a fixed source) and therefore arguing for a spherical tank; uniformity of fluence and time delay considerations for a given extended source configuration; the fact that large flat walls (cylinder ends) would have to be externally supported against air pressure; construction costs of the various designs. These issues will have to be investigated.

4. Observations on Tank Size

It is important to have some grasp of required tank size because of the high cost of increasing the diameter of a new tank. For a new spherical tank of radius R the cost C is very nearly proportional to the radius cubed,

$$C = \beta R^3, \tag{1}$$

where R is in meters and

$$\beta \simeq \$2400./\text{m}^3 \tag{2}$$

judging from the manufacturer's quotes obtained by the Site Survey Working Group. As the radius increases, cost increases at a rate

$$\frac{dC}{dR} = 3\beta R^2 \quad \$/\text{m} . \tag{3}$$

If we work with a radius in the vicinity of $R = 12$ m (diameter = 24 m = 78.7 feet), then $C \approx \$4.15 \times 10^6$ and increasing the radius costs an additional

$$\frac{dC}{dR} \approx \$1.04 \times 10^6/\text{m} , \qquad (4)$$

more than a million dollars per additional meter of radius.

One reason to increase the radius is to increase clear time. If the radius is increased by dR the clear time increases by $dT = 2dR/c$, where c is the speed of light. From Equation 4, increased clear time costs

$$\frac{dC}{dT} = \frac{c}{2}\frac{dC}{dR} \approx \$1.56 \times 10^6/\text{shake} , \qquad (5)$$

about 1.5 million dollars to increase clear time by 10 nanosec.

It is therefore important to learn to live with finite and reasonably small clear times and to design a reasonably good EM damper grid.

Physical Arguments

The technical issues that impact tank size essentially all argue for a larger tank. They are:

1. The larger the tank the greater the clear time, giving undisturbed simulation to a later time.
2. A larger tank allows a thicker and therefore better EM damper grid.
3. The larger the tank the more nearly does the satellite's capacitance to the wall approximate its true capacitance to infinity.
4. The larger the tank the longer do the satellite-produced photoelectrons have uninterrupted flight.

5. The larger the tank the smaller effect do the wall-produced photoelectrons have on simulation.
6. Larger satellites can be tested in larger tanks.
7. In a larger tank a given satellite can be moved to different positions allowing different exposure geometries with a fixed source.

Other than shorter pumping times (a minor consideration) and some cost in exposure fluence due to larger source-target distance if the target remains in the center of the tank, we can think of no technical argument favoring a smaller tank.

Hence so far as the tank walls' effect on the satellite response is concerned (simulation quality at a given fluence), technical reasons alone will not specify a best size, as there is no significant technical disadvantage to a larger size. *The larger the tank the better the simulation quality.* The size will have to be determined by a tradeoff of increasing cost with increasing simulation quality. Technical considerations will give a minimum acceptable radius and measures of simulation quality as a function of increased radius, and this will have to be balanced by increased cost with increased radius.

5. Geomagnetic Field Effects

Arguments presented in reference 13 indicate that a surface geomagnetic field of ~0.5 gauss does not disturb the SGEMP response of a satellite very much, and that it may not be necessary to cancel the geomagnetic field.

Briefly, the reason is this. The Larmor radius of an electron of velocity v and energy w in a magnetic field B is

$$R_L = \frac{mc}{eB} v$$

$$\approx \sqrt{2 \quad w(\text{keV})} \quad \text{meters}, \quad (B = 0.5 \text{ gauss})$$

proportional to its velocity. The distance, d, an electron travels in time, Δt, is

$$d = v \, \Delta t$$

also proportional to its velocity. The fraction of a Larmor radius that an electron travels in Δt is

$$\frac{d}{R_L} = \frac{eB}{mc} \Delta t$$

$$= \frac{\Delta t}{114 \text{ ns}} \qquad (B = 0.5 \text{ gauss})$$

independent of the electron's velocity. Consequently in a 0.5 gauss field it takes more than 100 ns for any electron to move a Larmor radius. This does not displace its position very much from what it would have been in the absence of a field, and the resulting small perturbation of the electron's trajectory does not affect the satellite's SGEMP response very much.

More detailed calculations[13] confirm this conclusion. These calculations indicate that

1. The geomagnetic field need not be cancelled to adequately reproduce the first approximately 150 ns ± 50 ns of the satellite's response.

and in particular

2. The main pulse of a satellite's response, which usually occurs before 150 ns, is adequately reproduced even in the presence of a 0.5 gauss field.

Therefore,

3. Whether or not the field need be cancelled at all, and, if so, the degree to which it must be cancelled, is determined by how accurately we wish to simulate the late time (>200 ns) response, and by other limiting factors such as how good the EM damper grid is.

We suspect the true limitation on late time simulation quality will be due to wall reflections after a clear time, and that these effects will be more severe than the geomagnetic field effects.

6. Wall-Produced Backscattered Electrons

X-rays that pass by the satellite target will strike the far wall of the tank ejecting photo electrons. These electrons can enter the working volume of the tank and interfere with the motion of satellite-produced SGEMP electrons. In addition their motions constitutes an electromagnetic current which can excite the normal modes of the tank.

Their numbers can be held down by using a low Z (CH_2?) coating on the tank wall, but some estimates indicate they may still be a problem. The photo electrons can be further controlled by some kind of electron repelling grid to hold them back electrostatically. Early suggestions for this grid[8,14] involved a wire mesh held a foot or so off the tank wall completely surrounding the target space-craft and held at about -60 kV with respect to the tank wall and the outside world.

An alternate design has been suggested[15] that keeps the high potentials localized around the exposed wall area and allows the satellite to remain at the same potential as the outside world. In addition, if an EM damping grid is used, it may well be possible to integrate the electron backscatter control grid with the damper, perhaps by using the outermost membrane of the damper as the high (negative) potential electron grid.

We have also calculated the excitation of the tank's lowest mode by the photo electrons both in the case of iron walls and CH_2 coated walls.[16] The CH_2 coating does not help as much as one might hope for. Iron walls can produce late time electric fields near the center of the tank on the order of 500 V/m, and CH_2 on the order of 200 V/m, with no electron repelling grid. If a grid is used, the excitation can easily be held down to only a few volts per meter.

7. Simulation Quality

We have addressed the general question of simulation quality as it affects the design of an SGEMP test facility.[17] Reference 17 outlines the relevant parameters in a photon exposure environment - those describing the natural environment, the satellite operational configuration, the data links, and the nuclear disturbed environment. It then lists the various assumptions that experimenters must make in order to cary out and learn from a laboratory simulation, and delineates certain practical limitations on the quality of simulations imposed by the photon source, operational state of the satellite, and vacuum tank environment. Two overall approaches are then given, one outlining a high quality simulation, and one of somewhat lower (and less costly) quality. The purpose of reference 17 is to provide a framework in which to view the test procedure and with which to compare opposing factors, investigate required trade offs, and arrive at a suitable test plan.

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