IN-PLACE ASSEMBLY AND TESTING OF SATELLITES

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ABSTRACT:

This paper describes an innovative approach to testing satellites that reduces test flow time and risk. The approach uses a uniquely designed assembly stand, created by INTRASPACE, that accommodates the satellite assembly process as well as in-place environmental testing. The satellite is assembled, functionally tested and environmentally tested on a single assembly stand platform. The platform rotates in 2-axes to facilitate access to all areas of the spacecraft. For environmental test, a "bell jar" vacuum dome is placed over the spacecraft. Vacuum, Thermal Vacuum and Acoustic Testing are made possible by the modular arrangement of the dome, liquid nitrogen cold walls, quartz heating tubes and high power acoustical transducers. Since the vacuum dome is made of RF transparent material, environmental testing closely simulates the on-orbit operation. For example, this approach permits measurement of the multipacting phenomenon under actual RF link operations.

The in-place test concept reduces test setup time, test breakdown time and spacecraft handling. The flow-through time saved during the test is about 25%. The test parameters were selected using MIL-STD-1540B as a guide. The test stand has been tested to 10^{-6} TORR and provides for a rotisserie mode during thermal environments.

INTRODUCTION:

Spacecraft have historically been assembled and tested in several different locations with each assembly and test performed on its own specialized test stand. Each of the different assembly points and tests requires significant set-up and tear-down time and poses a risk to both schedule and spacecraft. Through an Internal Research and Development (IR&D) effort INTRASPACE has produced an innovative assembly and test concept that minimizes risk to both schedule and spacecraft. This development effort lead to the creation of the In-place Test Stand (IPTS) concept and to the creation of the first IPTS at the INTRASPACE facilities at North Salt Lake City, Utah.

REQUIREMENTS:

The IPTS will be required to support all testing of the partially and fully assembled satellite through the environments specified for small satellites. These, as specified by MIL-STD-1540B[1], MIL-HDBK-340[2], and DOD-HDBK-343[3], are acoustic, pressure, vacuum, thermal vacuum, thermal balance, and thermal cycling. The IPTS is required to have a capability and/or safety factor of nominally three, with a minimum of two, above the requirements of the anticipated worst case testing for applicable satellites. For the Taurus Standard Small Launch Vehicle and a small low earth orbit spacecraft with an anticipated five year on-orbit life these requirements nominally become:

Acoustic:	157 dB overall (the spectrum† is given in Figure 1) with a fully powered up and functioning satellite;
Pressure:	There are no pressure requirements other than that of the IPTS not limiting access to the spacecraft pumps, valves, motors, tubing, etc.;
Vacuum:	Pressures less than 10^{-5} TORR maintainable for greater than eight hours with a fully powered up and functioning satellite including full functional testing of all RF links;
Thermal Vacuum:	Pressures less than 10^{-5} TORR maintainable for greater than eight

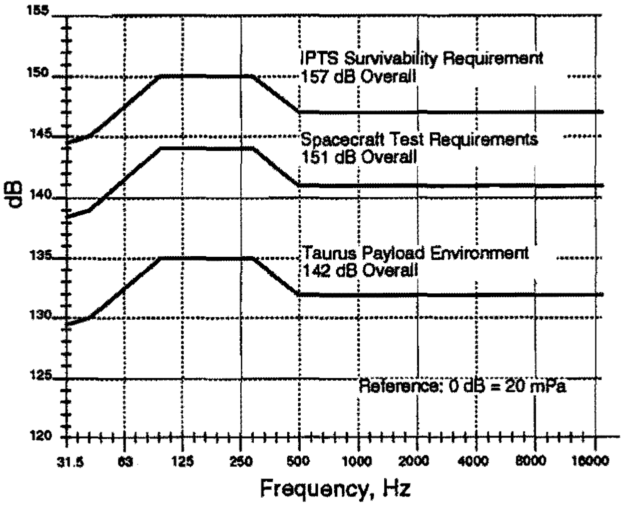

Figure 1 Acoustic spectra for the IPTS

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† The spectrum chosen was the anticipated Taurus acoustic spectrum plus 3 dB since Taurus has not yet flown, plus 6 dB for qualification testing, plus 6 dB for IPTS safety factor.

hours, a minimum ambient internal temperature range of -130°C to 100°C maintainable for greater than eight hours with a thermal gradient less than 3°C per hour, transition from one extreme to the other, and stabilize, in under two hours, all with a fully powered up and functioning satellite including full functional testing of all RF links;

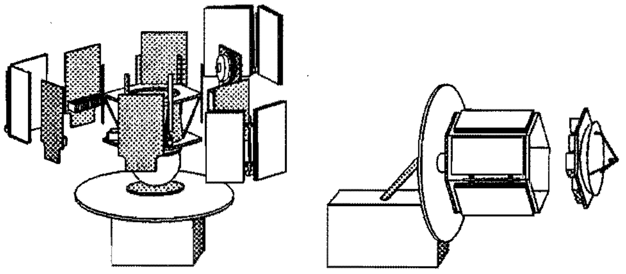
Thermal Balance: Pressures less than 10^{-5} TORR maintainable for greater than eight hours, spatial differential ambient internal temperature ranges of -130°C to 95°C, line heat source greater than 500°C (simulating sun point heat source on-orbit) with opposite walls less than -100°C, capability to rotate the spacecraft with respect to the line heat source at selectable rates and a minimum rate of 0.1 RPM, all with a fully powered up and functioning satellite;

Thermal Cycling: Cycle the ambient temperature within the satellite over a range greater than 70°C in under one hour, avoiding condensation on the cooling half of the cycle, and stabilize at each extreme for a complete functional test of the spacecraft.

Vibration testing is not included as a requirement as most satellites of the class developed by INTRASPACE exceed the 180 kilogram (397 pounds mass). Vibration testing would be performed on the subsystems as required before installation into the entire spacecraft. However, INTRASPACE is currently reconsidering this decision and may decide to include some capability for vibration testing in the final version, if it is feasible and practical. Pyro-shock testing is not included at this time because the requirements for this type of test vary radically between different spacecraft with some having virtually no requirement at all for this type of test.

PREMISES:

The basic premise was to assemble and test the spacecraft on one stand while minimizing the amount of physical movement of the spacecraft and test set-up and tear-down time and while allowing all the necessary tests to be performed. This required that the test stand have enough freedom of movement to allow the assembly and test personnel complete access to all parts of the spacecraft without disassembly of the spacecraft or removal from the test stand. For safety purposes and for minimum risk to the spacecraft, it was decided that this would require a mounting plate that could rotate freely in the vertical axis and be able to rotate $\pi/2$ radians (90°) in a horizontal axis as shown in Figure 2. This would allow staff standing on the floor complete access to all parts of the spacecraft. Whenever possible, subsystems would be pre-assembled on clean benches in the same clean room area before installation into the spacecraft.



Rotates 360° in vertical axis for ease of assembly

Rotated 90° in horizontal axis for ease of assembly

Figure 2 Vertically and horizontally rotating IPTS

The second premise was to allow the spacecraft to remain on the stand while as many tests as possible were performed. The added constraint was that the spacecraft had to be fully functional during most of these tests. This, in effect, required that the tests be brought to the spacecraft; the opposite of what is typically done in the industry today. This required the creation of a "bell jar" type dome and base below the spacecraft mounting fixture. The dome would be used to create the vacuum environments for the vacuum, thermal vacuum, and thermal balance tests. The temperature aspects of these tests would be provided by thermally controlled walls inside the dome. The dome itself would have to be RF permeable.

The third premise was that EMI/EMC testing of the spacecraft would be performed with it still on the IPTS and thus the IPTS would have to be moved into an EMI/EMC chamber.

The fourth premise was that acoustic testing would have to be performed in a separate, self contained, specially insulated room. However, for minimization of risk to the spacecraft and to keep the schedule as short as possible the spacecraft would not be allowed to be removed from the assembly test stand. This necessitated the movement of the entire test stand into the acoustic chamber. The combination of all these criteria led to the assembly and test flows shown in Figure 3.

IPTS DESIGN:

The design of the IPTS itself turned out to be relatively simple. The assembly bracket would be the mounting

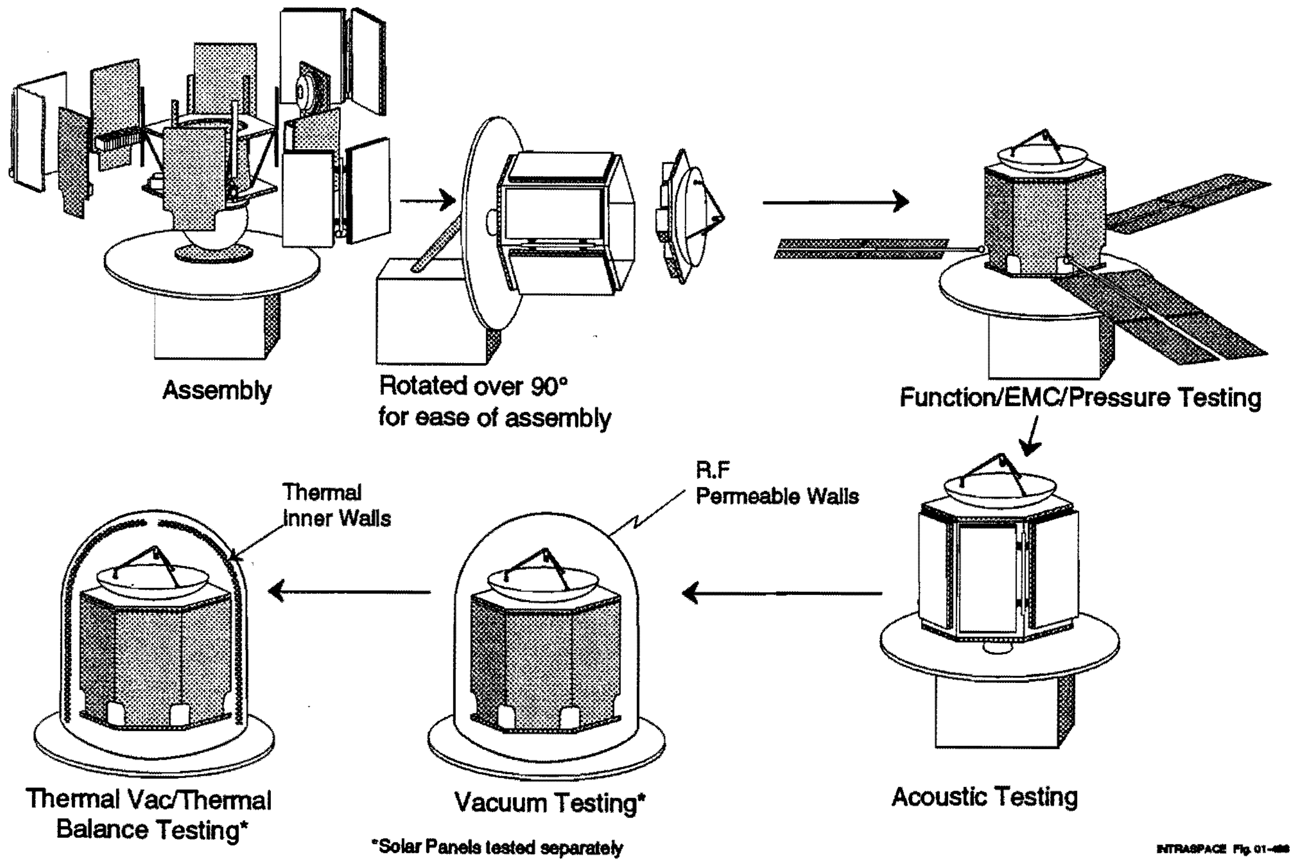


Figure 3 Assembly and test flow utilizing the IPTS

fixture used to mount the spacecraft to the launch vehicle (or, if necessary, a locally manufactured, mechanically similar, duplicate). The assembly bracket would be mounted on top of a rotary fixture. This fixture would be mounted through a wide base plate. It was decided that the base plate would be no larger than was necessary to accommodate the flange area on the bell jar and a very simple locking mechanism for the bell jar itself. Keeping the size of the base plate to a minimum would allow the easiest access to the spacecraft and reduce the use of the base plate as a temporary shelf by test and assembly personnel. This would help limit the amount of surface damage to the base plate during assembly and testing procedures. (Any surface damage in the region where the dome mates to the base plate would have significant effects on the lowest vacuum attainable.) The vacuum equipment would be fitted with the simplest fittings available where ever possible to facilitate removal from the base plate.

The dome design had to be accomplished with either an RF transparent or an RF permeable material that would be rigid enough to withstand many high vacuum cycles over several years. It also had to be of materials that would not outgas volatile substances that would be hazardous to, or plate onto, the spacecraft. An added practical constraint was that the material had to be light enough to facilitate easy placement onto and removal from the base plate. The combination of the requirements eliminated most materials from consideration. INTRASPACE has utilized a proprietary combination of materials that gives a dome that is RF permeable, light enough to be practical, and has a vapor pressure less than 10^{-8} TORR.

To perform the necessary thermal environments, a set of cold/hot walls was devised that will fit interior to the dome and rest on the base plate. This series of walls would shield the spacecraft from the temperature of the dome itself, except directly overhead, and present a uniformly controllable thermal environment to the spacecraft. The wall will be cooled with liquid nitrogen (LN_2) running through cavities in the wall itself and heated with hot nitrogen gas (GN_2) and/or quartz heating rods on the outside of the thermal wall. (The heating method has not been defined as of yet as the question as to whether the thermal walls need to be RF permeable has direct bearing on this.) For the necessary line heat source a series of individually controllable quartz heating rods was selected.

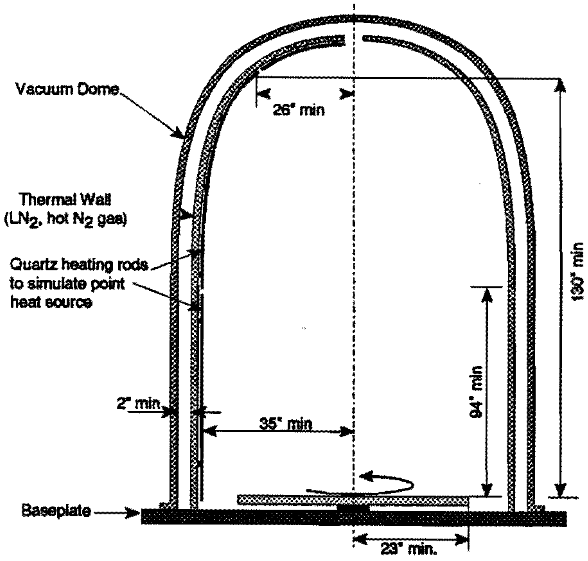


Figure 4 Conceptual design for thermal vacuum chamber

The volume allocated to the spacecraft was to be no larger than the dynamic envelope of the largest launch vehicle nominally considered for launch of a single small spacecraft built by INTRASPACE. The launch vehicles of interest were primarily Scout, Pegasus, and Taurus. The presentation of a relatively uniform thermal aspect to the spacecraft required that there be a minimum of six inches between the interior thermal walls and/or quartz heating rods and the spacecraft. The combination of these factors lead to the conceptual design shown in Figure 4.

To accomplish the third and fourth premises, the IPTS is to be mounted on a rail system to allow movement into a special acoustic chamber with the spacecraft still mounted onto the fixture as shown in Figure 5 for the acoustic environment. A similar arrangement has been designed for the EMI/EMC testing environment chamber. A rail system was chosen for safety and physical stability. Sensitive vacuum equipment would be disconnected from the bottom of the IPTS before movement into the acoustic chamber. The entry into the acoustic chamber would be through multiple "sound dampening" doors to minimize the sound levels in the main clean room area.

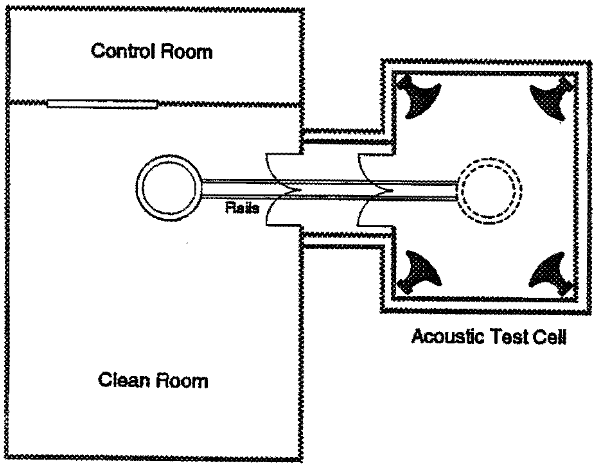


Figure 5 Clean room and acoustic cell showing rail system between them

INITIAL IPTS:

The initial IPTS shown in Figures 6 and 7 included the two degree of freedom assembly stand with feed throughs (through the base plate) for system test and function cabling and the vacuum dome with provisions for investigating the thermal vacuum requirements. The spacecraft is assembled on the stand in the vertical orientation as much as possible with the stand rotated 90° in the horizontal axis when direct access to the top of the spacecraft is necessary. The only other time that the stand is rotated in this axis is when the thermal walls and dome are placed over the spacecraft. Thus the thermal walls and dome are slid horizontally over the spacecraft and fastened directly to the base plate. This eliminates the requirement of ever having any massive object hoisted directly over the spacecraft.

A one inch thick steel plate was used for the base plate of the test stand . Because the forces exerted on the

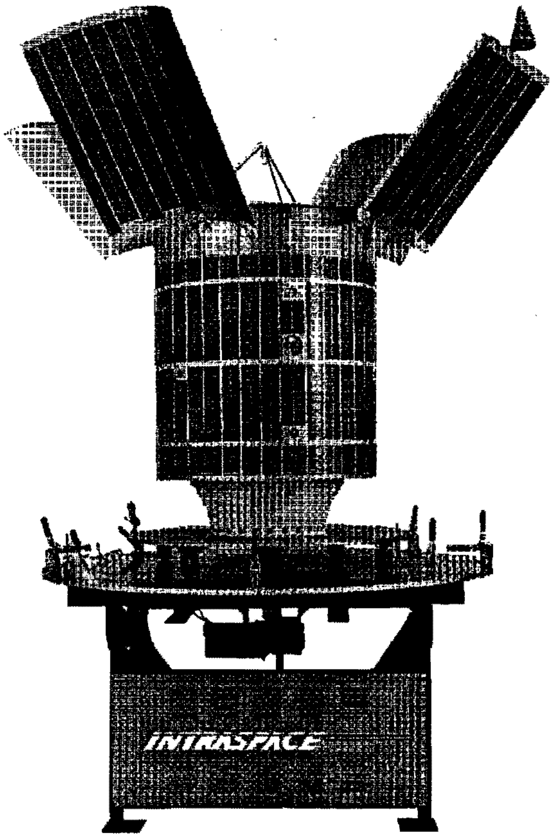


Figure 6 Initial IPTS showing installed spacecraft

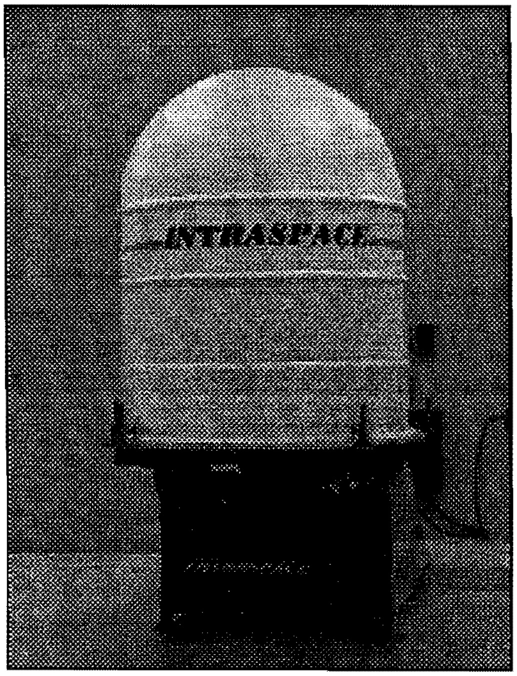


Figure 7 Initial IPTS with vacuum dome

base plate during high vacuum conditions caused significant deflections in the base plate itself, small I-beams were fastened to the bottom of the plate for reinforcement.

The dome was repeatedly tested to a vacuum of less than 10^{-5} TORR and has reached an ultimate vacuum of just under 10^{-6} TORR. The system utilizes a 1400 liter/minute (free air displacement) roughing pump to achieve pressures below 10^{-4} TORR and a 30.5 centimeter (12 inch) cryopump to reach the final pressures. The dome has a slight tendency to absorb gases from its natural environment (atmospheric gases such as N_2, O_2, and H_2O vapor) so that the initial pump down rate after the dome has been at atmospheric pressures for extended periods is noticeably slower than subsequent rates after short exposures. Different pump down rates for empty chambers are shown in Figure 8. With the turntable rotating, the chamber was able to maintain pressures down to $4X10^{-6}$ TORR. During testing with the dome walls at temperatures elevated above 40°C the chamber was still able to maintain pressures below 10^{-5} TORR.

FUTURE PLANS:

The next step in the development of the IPTS is to create the inner thermal walls with the line of heating rods. It is still being considered by the INTRASPACE design staff as to whether the thermal walls are required to be RF permeable as this will have direct bearing on their development time and cost. RF permeable walls will force INTRASPACE into the sue of glasses as a

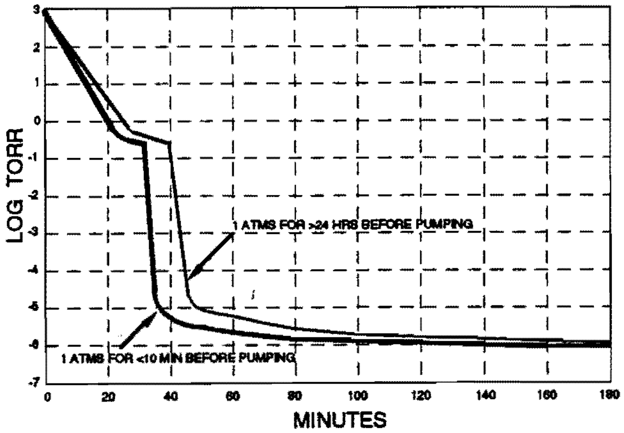


Figure 8 Chamber vacuum pumping

design approach to provide the thermal inner walls. Non-permeable walls will probably be constructed of aluminum or some similar material. Following the development of the walls, they will be installed inside the vacuum dome and thoroughly tested in both thermal and thermal vacuum environments. The original dome's outgassing will also be measured under the elevated temperatures expected. Because of the very low vapor pressure of the dome material, it is anticipated that once the ambient air gases have been removed from the dome, the pressure can still be maintained well below the required 10^{-5} TORR.

The final version of the LN_2/GN_2 thermal environment will be a personal computer controlled system that monitors temperatures within the spacecraft and the chamber and controls the LN_2/GN_2 flow through the walls. This system will allow accurate modelling of both test criteria and on-orbit conditions both outside and inside the spacecraft.

After satisfactory incorporation and completion of testing of the thermal aspects of the IPTS, the construction of the acoustic chamber and rail system will be started. The entire IPTS system could be finished by mid calendar year 1992.

When the initial IPTS was designed and manufactured the only launch vehicle of the class of interest to INTRASPACE was the SCOUT. Because of this, the size of the initial IPTS was smaller than that currently considered optimal. Tentative future plans include the upgrading of the base plate to accommodate not only the current dome but the larger dome designed to the sizes given in Figure 4. The larger dome and thermal wall assembly would then be constructed and tested.

The final phase in the design of the IPTS concept will be a set of environmental chambers, all accessible by the IPTS. The concept shown in Figure 9 shows these

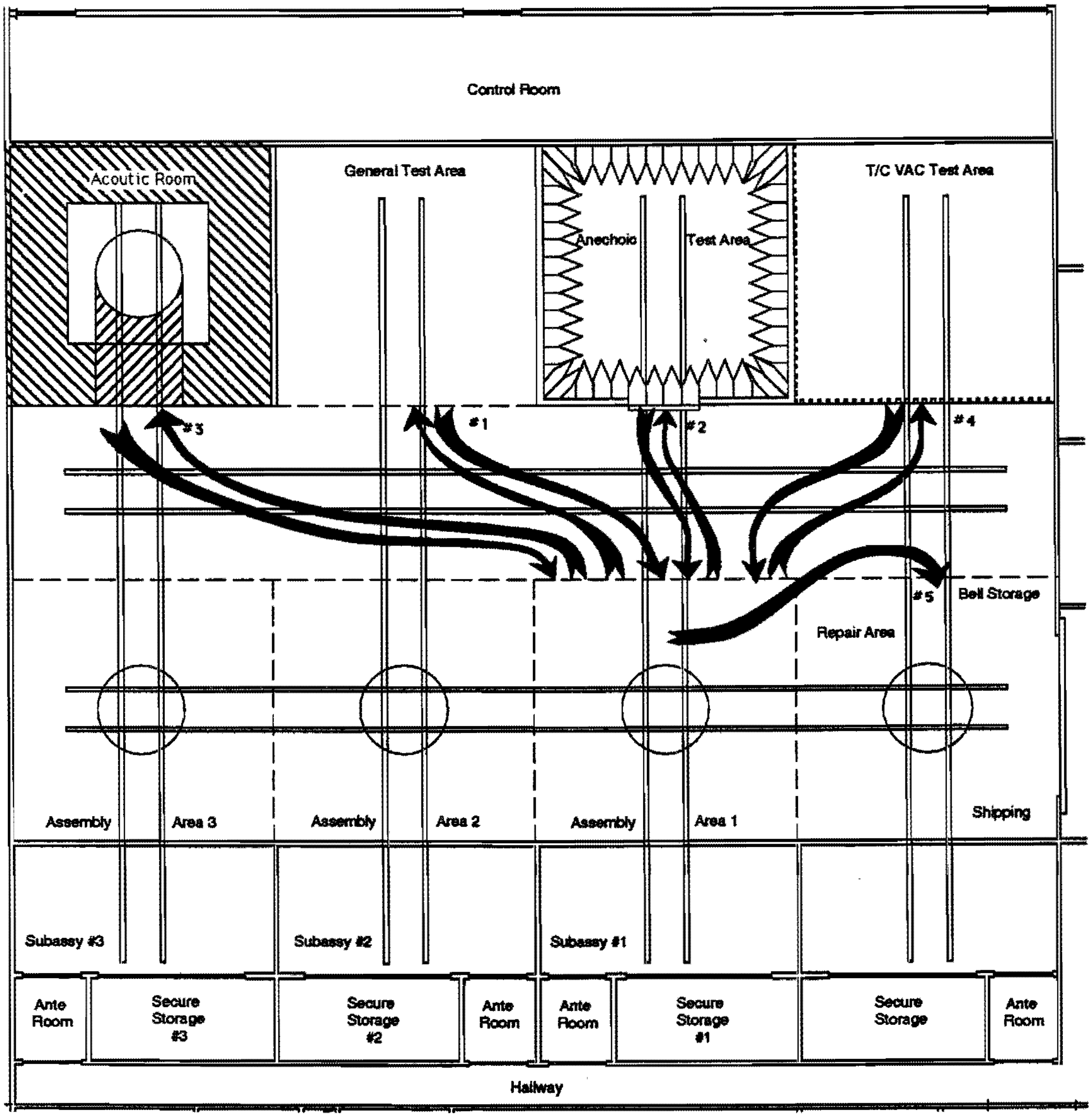


Figure 9 Final IPTS production flow design concept showing up to five concurrent integrations and tests

chambers connected by a rail system supporting the movement of the IPTS from chamber to chamber. This design can conceivably support up through four IPTS/ spacecraft in various phases of integration and test.

TIME AND RISK SAVINGS:
Typically setup and functional testing of the spacecraft within any given test chamber requires as much as 50% of the time to accomplish the test. Post test functional testing and teardown can easily require as much as 50% of the test time again. By leaving the spacecraft on a single test stand, where it had been initially assembled, and bringing the environments to the spacecraft, much of the setup and teardown time can be eliminated. Also, frequently the functional test at the end of one environmental test can be utilized as the functional test before the next environmental test. This has the capability of eliminating several functional tests of the spacecraft.

Combining these advantages has the capability of shorten overall testing schedules as much as 35 to 40%. With the types of small satellite testing conducted by INTRASPACE, it is anticipated that this test concept could realistically be expected to routinely reduce testing schedules by approximately 25% with its associated labor and cost savings.

A less tangible, but just as important, advantage of this concept is the great reduction in risk to the spacecraft. The spacecraft never leaves the test stand and once fully assembled is never in any danger of being dropped from the test stand or of having any massive objects dropped onto it. These facets of the IPTS could improve safety and possibly reduce liability coverage costs. If full functional testing of the spacecraft is required by the customer both before and after each environmental test, complete back-to-back tests would be accomplished, giving the unusual advantage measurements of repeatability of these functional tests. This could significantly enhance the quality assurance program associated with the spacecraft testing.

CONCLUSIONS:
Tests of the initial In-place Test Stand (IPTS) have demonstrated the feasibility of the RF permeable vacuum testing for small spacecraft. The thermal vacuum and acoustic parts of the IPTS will be demonstrated within the following year. Test schedule savings are anticipated to be approximately 25% for typical small satellites with the associated cost savings. Reduction of risk to the spacecraft would enhance quality assurance and safety programs and possibly reduce liability coverage costs.

REFERENCES:
[1] MIL-STD-1540B (USAF), TEST REQUIREMENTS FOR SPACE VEHICLES, 10 October 1982.

[2] MIL-HDBK-340 (USAF), APPLICATION GUIDELINES FOR MIL-STD-1540B; TEST REQUIREMENTS FOR SPACE VEHICLES, 1 July 1985.

[2] DOD-HDBK-343 (USAF), DESIGN, CONSTRUCTION, AND TESTING REQUIREMENTS FOR ONE OF A KIND SPACE EQUIPMENT, 1 February 1986.