NASA TECHNOLOGY FLIGHT EXPERIMENTS PROGRAM

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Abstract

In addition to its scientific and life sciences experimental programs, NASA conducts flight experiments directed at development of space systems technologies. The experiments are conducted to obtain research data, to evaluate the performance or operation of experimental hardware in the space environment, or to validate components, subsystems, or systems prior 10 application in future spacecraft or missions.

The requirements for specific technology experiments, and the priority assigned to them, vary significantly depending on the maturity of tile technology. Some of the flight experiments address technologies still in the early research stage, while others are conducted to validate technology at relatively advanced levels of maturity. This paper discusses the overall technology flight experiments program and reports in some detail (m fear current or recently flown experiments ranging from research to technology validation al the system prototype level.

Introduction

Because of the cost of access to space. and the cost of modern spacecraft and missions, designers and project managers cannel afford the risk of using components or subsystems incorporating untested m unvalidated technologies. Ground testing and simulation capability can often serve adequately in validating a new technology. However, there are still many instances in which the effects of microgravity, radiation, or other space environmental factors simply cannot be tested or modeled on the ground. In-space experimentation may be essential to resolving key questions of understanding, or developing a reliable design data base., or validating the performance of a component or system in the actual operational environment.

In-flight experimentation has been used in aeronautics research and development for many years. Both military and commercial aircraft have been modified for use as research aircraft or technology demonstrators. The Air Force/Calspan T-33 and (:-I31 in-flight simulators in the United States, tile DLR VFW 614 and 110105 aircraft and helicopter in-flight simulators in Germany, and similar vehicles in other countries have proven valuable in evaluating advanced control and other concepts prior to application in new aircraft developments. On several occasions these experimental aircraft have also been used to investigate advanced control systems being designed for space systems such as the Space Shuttle and Hermes.

Over the years, the aeronautical community has refined the process of progressing from conceptual study through computational analysis, ground testing, and simulation -- 10 flight testing when justified as a necessary extension to time earlier steps. Because flight experimentation may be quite costly, the necessity must be clear.

In-space experimentation is a relatively new capability. But experience in operational space. flight and space environment characterization is still limited, and operational space system deployment is very expensive. For time reasons, and with increasing availability of suitable test vehicles, in-space experimentation is already a large and growing activity which is becoming a valuable tool in space systems design and development. However, because it is generally even more expensive than atmospheric flight testing, the process of selecting experiments must be even more rigorous.

Many of NASA's manned space flight, exploration, and scientific missions have themselves been experimental in nature. And considerable technology validation has been accomplished during some of the primary mission programs, either of necessity or because it was deemed more economical than experimentation prior to program initiation. This paper discusses only experimentation on technology -- technology (ice.lnc(i important for future space systems but not yet been specified for incorporation in a particular system development.

Technology Flight Experiments Program

The NASA technology space flight experiments program is conducted to obtain research data, evaluate the performance or operation of experimental hardware in the space environment, or validate concepts, components, subsystems, or systems prior to application in future spacecraft or missions. The information is used to validate models, verify ground prediction, and -- most importantly -- reduce the risk of incorporating new technology in future systems.

In addition to developing technology for its own missions, NASA has responsibility for facilitating the transfer of space technology to the military, to other user agencies, and to industry. The flight experiments provide an effective mechanism for validating maturing

technologies not yet adopted for incorporation in operational systems. The high cost of space access mandates that only those technology experiments which clearly require exposure to the space environment, or which are most cost-effective relative to ground testing, be selected for flight. It also dictates that reduction of experiment cost must be a continuing and vital requirement.

A wide variety of launch vehicles and platforms may be utilized for the in-space experiments, with the choice depending on experiment requirements and cost considerations. Expendable launch vehicles (ELVs) ranging from small sounding rockets to Titans with piggyback upper stages are used when appropriate. The Shuttle Orbiter has been a particularly great asset, with experiments carried in the middeck (Figure 1), in simple "getaway special" ("GAS") cans mounted on the side wall of the cargo bay (Figure 2), or in autonomous payload packages which provide their own power, thermal, data, and telemetry capabilities. Experiments which require larger volume or weight, or may need access to Shuttle avionics, data or other services, may utilize carriers called Hitchhikers located in the Shuttle bay (Figure 3). The Columbia flight early in March 1994 carried the largest number of engineering research and technology experiments -- eleven in all -- ever flown on a single mission.

Figure 1: Middeck 0-Gravity Dynamic Experiment (MODE) performed in the Shuttle Middeck

The SPACEHAB carrier, providing additional middeck facilities in the Shuttle bay (Figure 4), has recently become operational and its two flights have already included several significant technology experiments. Free flyers placed in space by either ELVs or Shuttle (Figure 5) provide another option. And technology experiments are now being planned to utilize the unique capabilities of International Space Station Alpha (Figure 6).

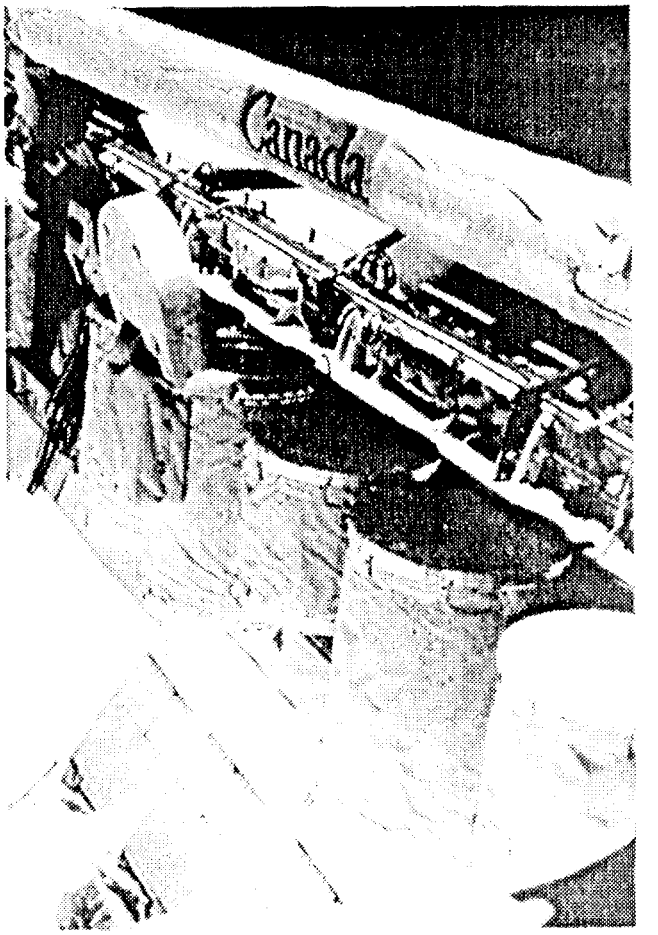

Figure 2: Get Away Special (GAS) cans in shuttle bay

The need for flight experimentation is generally based on requirements for one or more of the following issues:

1) Extended microgravity operation: Drop towers and suborbital rockets can be used for microgravity testing only on the order of seconds to minutes. Many experiments, however, require much more prolonged microgravity conditions -- for example, to achieve steady-state operation in experiments on fluids, to permit sample changes, or to maintain the high-quality microgravity environment necessary for crystal growth experiments.

2) Exposure to space environmental effects: The complex space environment is not sufficiently

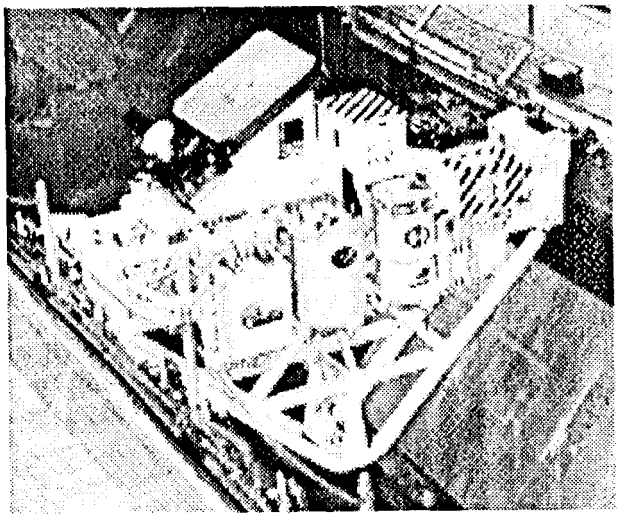

Figure 3: Experiments mounted on Hitchhiker carrier in shuttle bay

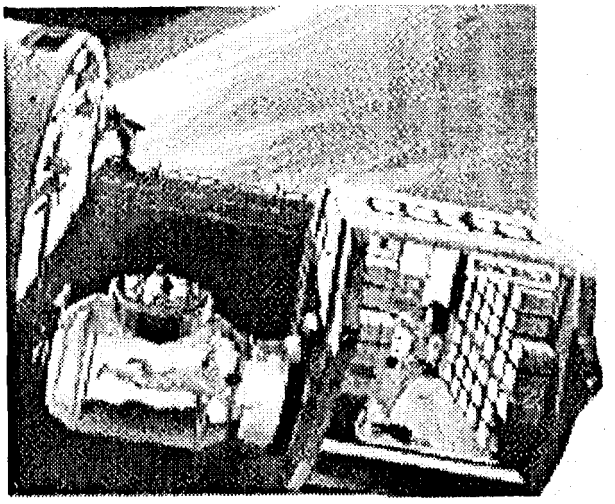

Figure 4: SPACEHAB complements middeck experiments capability

understood and modeled to allow duplication or simulation on the ground. Effects of atomic oxygen and other atmospheric constituents, orbital debris, exhaust plume or other contamination, and radiation on exposed payloads and/or materials are not completely known or understood. The random nature of these effects, particularly the radiation effects, makes ground duplication difficult or impossible.

3) Exposure to the complex operational environment: The nature and complexity of the environment and operations in space necessitates some in-space evaluation of technology. In particular, operations requiring extravehicular activity, teleoperated robotics, or other man-in-the-loop functions are not effectively simulated on the ground.

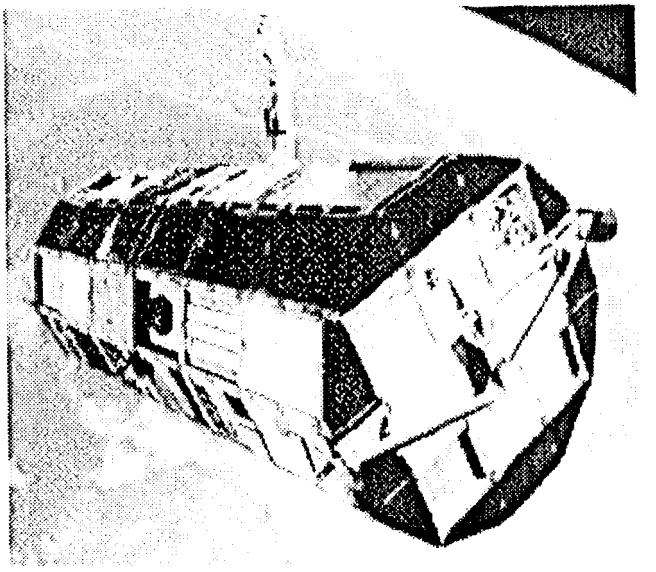

Figure 5: Long Duration Exposure Facility (LDEF)

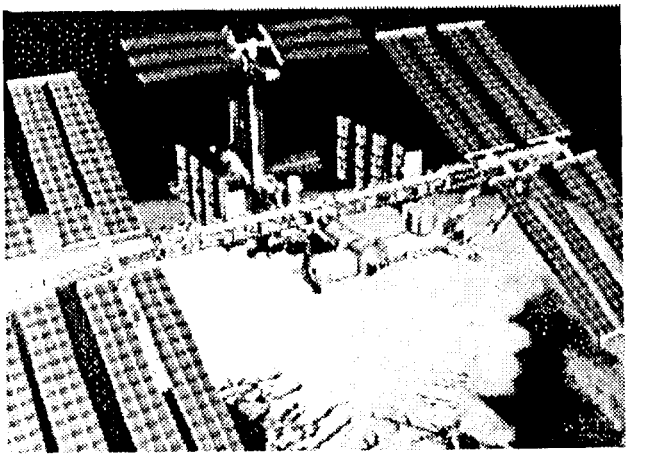

Figure 6: International Space Station Alpha (ISSA)

4) Orbital "viewing" environment: Validation of technologies for optical or other sensing or communication systems depending on earth-viewing orientation may demand space experimentation. In addition, although aircraft or balloons may be adequate for some purposes depending on the spectrum and the need for radiation exposure, reliable testing of some sensing devices or subsystems may be possible only above the atmosphere.

The requirements and priority for different types of technology experiments vary significantly depending on the maturity of the technology in question. In our experiment planning, we have found it helpful to use a Technology Readiness Level ("TRL") -- an incremental scale indicating the maturity of a particular technology or system. The TRL scale (Figure 7) is not meant to be a high-precision instrument or an absolute discriminator.

However, it can illustrate the differences among variions candidate experiments with respect to requirements and the value of anticipated returns. The TRL also serves as a basis for consideration of the evaluation, timing, benefit/cost assessment, and selection of candidate experiments.

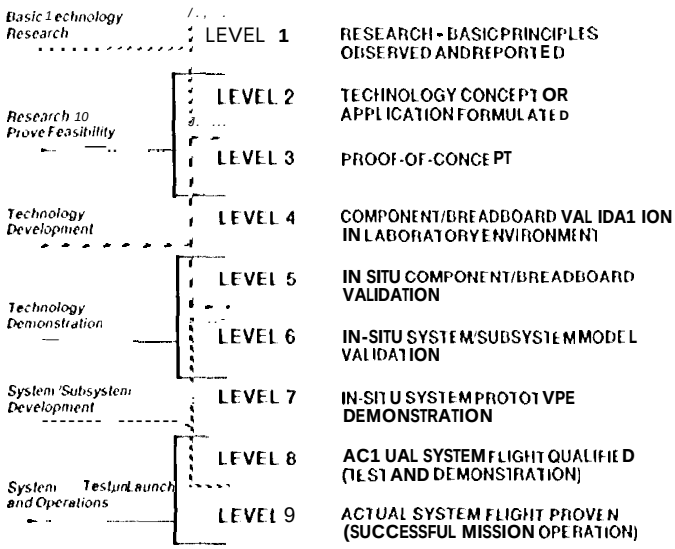

Figure 7: Technology Readiness Levels (TRL)

The nine technology readiness levels shown in the TRL scale range from the understanding of basic physical principles to the deployment of a "flight proven" system. The flight experiments primarily address technology validation at levels 5-7, but may also support research at level 1. Required testing above TRL 7 is generally considered mission- or system-specific and is conducted in development programs rather than as technology experiments. Examples of experiments at TRL 1, 5, 6, and 7 are described later in the paper.

Technology experiment requirements are defined by the "user community" -- the specialists responsible for developing the mission and spacecraft requirements for NASA's manned and unmanned science and exploration programs and for industry space systems. In the In-Space Technology Experiments Program (INSTEP), experiments are proposed in response to a NASA announcement of opportunity, and are evaluated by peer review teams which include the user community and other experts. A rigorous selection process applies strict discipline in feasibility study and cost analysis during the early (low cost) stages. Each selected experiment is subjected to a final intensive "peer review" before entering the flight development phase. Because of the rigorous selection and review discipline, we have been able to maintain an extremely good record of experiment success and cost and schedule performance.

Representative Experiments

To illustrate the program in this paper we have chosen as examples four current or recently flown experiments. They include one engineering research experiment conducted at a very early point in the technology maturation process and three system validation experiments involving technologies at different levels of maturity. A more complete summary of current and recent experiments is included in the Appendix.

- The Experimental Investigation of Spacecraft Glow (EISG) is a research experiment developed by Lockheed Missiles and Space Company to determine the intensity and causes of spacecraft glow at various attitudes and altitudes. Experiment results will be used to develop coatings and other means to reduce the effect of surface/plasma glows on optical instruments in low earth orbit.

- The Tank Pressure Control Experiment (TPCE) is a Boeing Aerospace Company experiment, first flown in 1991, to test the effect of jet mixing of cryogenic fluids to help control pressure in cryogenic tanks. Results will be used to design lighter-weight cryogenic tanks for future spacecraft.

- The Heat Pipe Performance (HPP) experiment, designed by Hughes Aircraft Company, was flown in 1993 to test the microgravity performance of various types of heat pipes to be used on spinning spacecraft.

- The Cryo System Experiment (CSE), also developed by Hughes Aircraft Company, is a system-level experiment designed to validate the operation and performance of a 65K cryogenic cooler and oxygen heat pipe in the space environment.

These four industry-proposed and fabricated experiments have all flown successfully with the exception of the CSE experiment, which is presently manifested for flight in early 1995. They are discussed with reference to the level of technology maturity and the specific driving requirements for space flight experimentation in each instance. In addition, the nature and benefits of the results are described. Results are discussed in the context of their impact on technology development and subsequent product development. The CSE is detailed as a case study to describe the role of in-flight testing in the development of a technology for an actual product development.

Experimental Investigation of Spacecraft Glow (EISG)[1,2]

The Experimental Investigation of Spacecraft Glow (EISG), a TRL 1 technology research experiment, was flown on STS-62 in March, 1994, to study and characterize spacecraft glow (Figure 8).

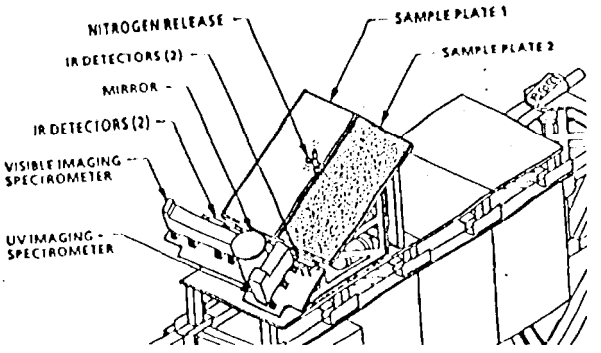

Figure 8: EISG experiment mounted on Hitchhiker (also shown in Figure 3)

Spacecraft glow is a well-known but little understood phenomenon encountered in many spacecraft including, the Space Shuttle (Figure 9) and low-earth-orbit (LEO) imaging free-flyin~, spacecraft. The glow could potentially degrade the performance of optical instruments operating in low earth orbit, especially in the far ultraviolet (FUV) region, by optically contaminating the imagery. It has not been known whether the phenomenon was primarily a surface (i.e. materials) issue or a spacecraft environmental/atmospheric interaction issue. With the fundamental physics not well understood, it was not possible to develop effective countermeasures. Previous flight expel-inlcnts had attempted to achieve glow characterization, but only over a very narrow spectrum and at a fixed altitude. The EISG expel-ilncnt covered a large spectrum, from FUV through 5.6 micron infrared, at orbital altitudes from 105 nmi to 160 nmi, and varying spacecraft attitude.

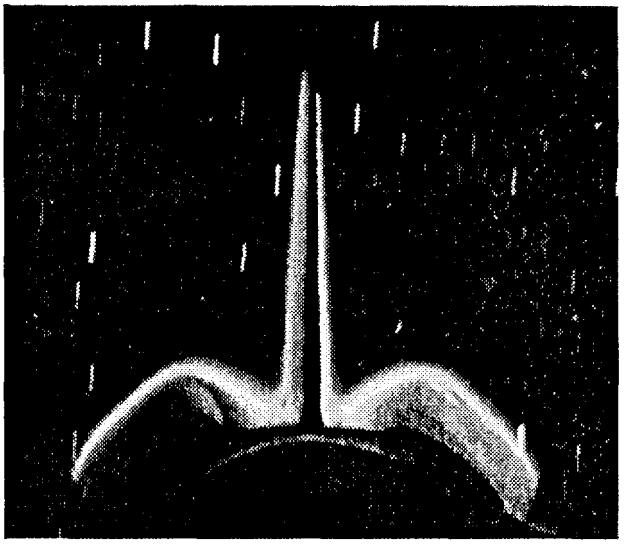

Figure 9: Obiter Glow viewed from aft flight deck

The experiment consisted of a large (1.0 X 1,0 meter) thermally-isolated sample plate, half of which \vas coated with a black paint typically used in instrument baffles (Z306 Chemglaze) and half with a white, insulating paint commonly used in spacecraft applications (A276 Chemglaze). The area above the sample was viewed by visible (VIS) and far ultraviolet (1(1 IV) spectrometers, a FUV photometer and infrared (IR) radiometers to characterize spacecraft glow under a wide variety of conditions. In addition, a US. Air Force payload was used lo augment the experiment and provide simultaneous observations of glow phenomena in the infrared regime. The Spacecraft Kinetic Infrared Test (SKIRT) article consisted of a cryogenically cooled infrared spectrometer dedicated to glow characterization in the 1.0 - 5.0 micron spectral wavelength region. The experiment set out to study surface and gas cloud glows over a wide range of wavelengths; to identify and character-iyc the atoms and molecules responsible for these emissions; and to determine how glow intensities vary as functions of material coatings, surface temperatures, orbital altitudes, and ram attitude angles. The EISG also contained a nitrogen (N_2) gas release system to study basic chemistry with the ram atmosphere which was expected to produce glow producing compounds. Studies also addressed thruster contamination and glows associated with thruster-effluent-doped surfaces.

Data from the experiment is no\v providing new insights into the fundamental physics of spacecraft glow anti the atmospheric chemistry which causes it. Incomplete preliminary assessment of the data verified that the glow phenomenon is primarily a surface effect and is therefore likely to be affected by material/coating selection for the optical instruments. It also validated that the black baffle paint is an effective material for FUV imaging devices and that the nitrogen release did not affect glow emissions in this region, meaning that nitrogen can be used as an effective cryogen in these instruments without fear of contamination due to nitrogen venting. Glows in the visible wavelengths were observed to change drastically with altitude, as expected, but were significantly -- and unexpectedly -- reduced during nitrogen releases.

As expected with this and other TRL 1 experiments, tile results bolstered out knowledge of the physics involved and provided some insight into the nature of effective countermeasures, but did not specifically validate a technology for use in future optical systems. Follow-on experiments are being considered that would further the research by adding a mass spectrometer to characterize particular chemical species and, in addition, would validate the glow-reducing properties of selected materials and coatings.

The Tank Pressure Control Experiment (TPCE)[3]

Developed by the Boeing Company, the Tank Pressure Control Experiment (TPCE) (Figure 1 O) is a TRL 5 space experiment developed to meet the need for a critical aspect of cryogenic fluid management technology -- that is,

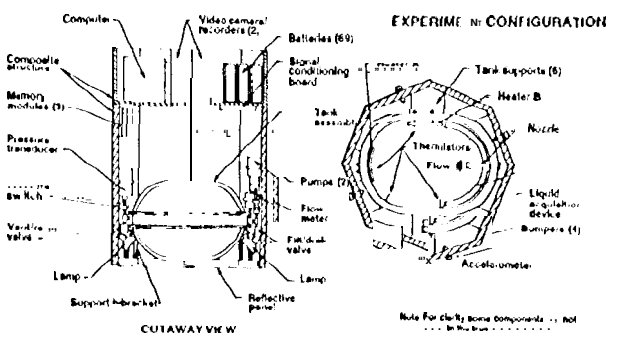

Figure 10: TPCE Experiment

control of storage tank pressures in the absence of gravity by fc)lcccl-coil\'cc[i\'c mixing. The experiment, first launched aboard Shuttle STS-43 in August, 1991 as a GAS payload (Figure 11), used Freon- 113 at near-saturation conditions, at a constant 84% fill level, to simulate the fluid dynamics and thermodynamics of cryogenic fluids in space applications. The objectives of TPCE were to characterize the. fluid dynamics of axial-jet-induced mixing in low gravity, to evaluate the validity of empirical mixing models, and to provide data for use in developing and validating computational fluid dynamic models of mixing processes.

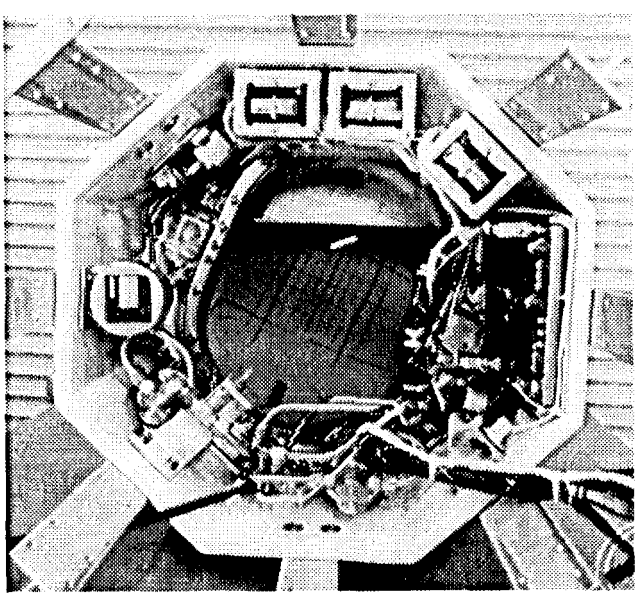

Figure 11: TPCE hardware mounted in GAS can

A reflight of the TPCE experiment was successfully completed on S'1'S-52 in October, 199'2, to examine a potentially-serious pressure spike phenomenon that was observed on the first flight. The observed pressure spikes, which arc the result of sudden nucleation and flash boiling when a fluid is heated over a long period of time, could conceivably result in loss of mission if it were to occur in an operational orbiting cryogenic propellant tank.

Unexpected prior to the initial TPCE flight, the phenomenon is now understood and preventive measures have been developed as a result of the second flight.

Representative results from the original flight are shown in Figures 1 ? and 13 and demonstrate the efficacy of jet mixing for control of pressure and temperature. Data demonstrated that the flow pat terns observed generally agreed with a prior correlation derived from drop tower tests, and several existing mixing correlations were found to provide reasonable performance predictions. Low-energy mixing jets, dissipating on the order of one percent of the kinetic energy of previous mixer designs, were found to be effective and reliable at reducing thermal non-uniformities, promoting heat and mass transfer between the phases, and reducing tank pressure. It was found that active mixing, whether continuous or periodic, offers increased reliability and predictability in space cryogenic systems, and can be accomplished with no significant boiloff penalty caused by kinetic energy dissipation.

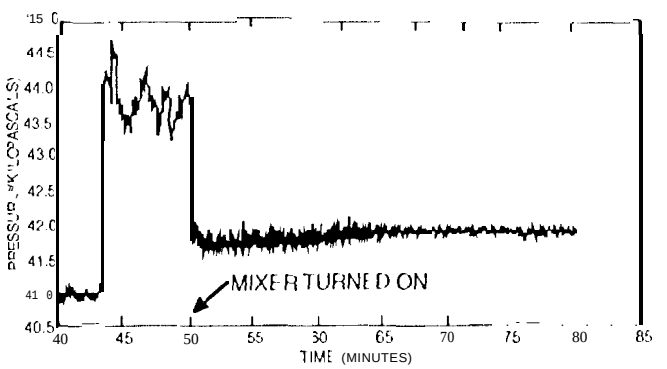

Figure 12: TPCE pressure control

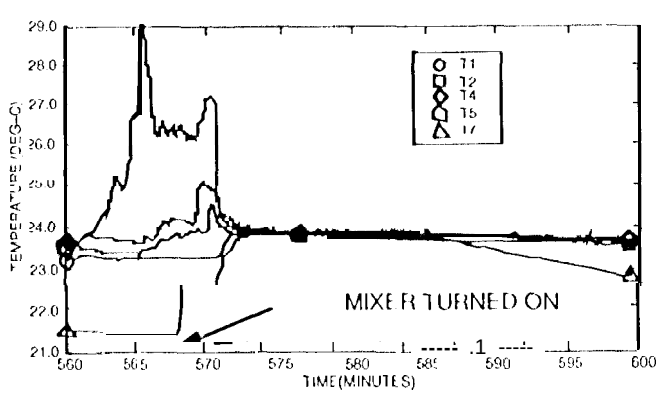

Figure 13: TPCE typical temperature measurements

This experiment demonstrated the validity of an important concept for pressure control of stored cryogens in microgravity. It was typical of TRL 5 experiments in that completion of the experiment did not provide sufficient data for infusion of the technology in operational flight systems, and that the experiment, as designed, was fairly qualitative in the definition of its

hypothesis and, hence, its data requirements (primarily video). It also provided significant insight into the physics of microgravity fluid handling and the thermodynamics of pressure control, information which has been of benefit in understanding problems encountered with liquid-electrolyte batteries used in various space systems. The experiment is presently being prepared by student investigators for a third flight to investigate the effectiveness of jet mixing for pressure control in tanks at 40-50% fill level, a more realistic scenario in operational space systems than the 84% fill level previously flown.

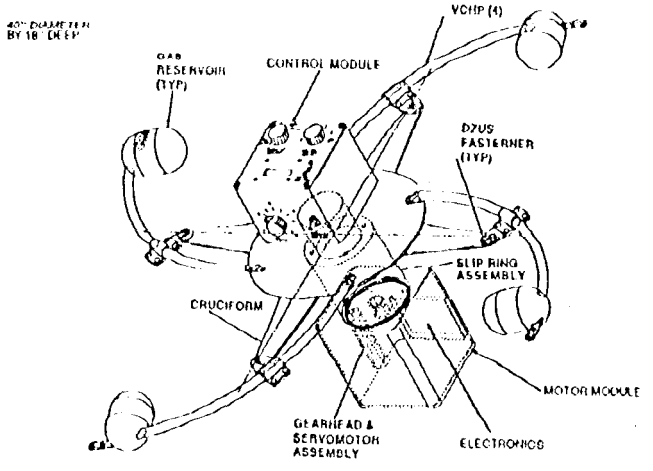

Figure 14: Heat Pipe Performance Experiment Configuration

The Heat Pipe Performance Experiment (HPP)[4,5]

The Heat Pipe Performance Experiment (HPP) is a 'TRL 6 experiment developed by Hughes Aircraft Company (Figures 14 and 15). It is a middeck experiment flown aboard the STS-52 mission in October 1992. HPP tested fixed conductance and variable conductance heat pipes at different rotational speeds to determine their transport capability, rewicking times, and the influence of body forces on the liquid distribution.

The primary mission objectives of the HPP were to obtain quantitative data on the thermal performance of heat pipes in a microgravity environment and to determine the performance of heat pipes as a function of the body force associated with different rotational speeds. The experiment evaluated the sensitivity of 14 state-of-the-art heat pipes to small and large accelerations by obtaining quantitative data showing spatial and temporal profiles under operational and recovery conditions. Flight test results were correlated with 1-g static test results and analytical models for both axially grooved and fibrous wick designs. Rewicking tests were also conducted to determine the time it takes for a heat pipe to reprime and operate isothermally after it has been deprimed due to excessive spin forces.

As a result of the flight, a large database on the performance and behavior of heat pipe operation in microgravity was obtained. Application of HPP data will lead to improvements in current heat pipe computer modeling and predictive capabilities. Results of the experiment already confirm that heat pipe design engineers have been too conservative in extrapolating ground performance data to zero-g. In some cases, the orbital performance was 35% to 40% better than ground performance. These results, which substantiated analytical predictions, will allow more confidence in the analytical models, leading to less conservative heat pipe design and ultimately to lighter and more efficient spacecraft. The data also enables less extensive ground testing of production axial groove heat pipes, contributing to directly lowering the cost of these activities.

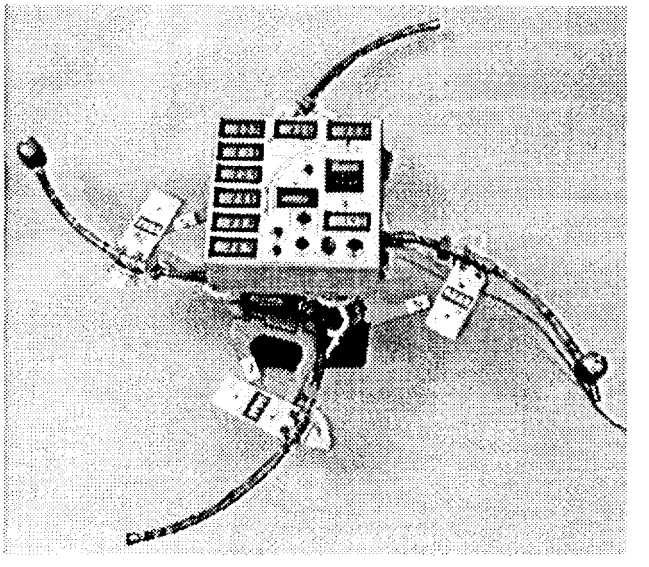

Figure 15: HPP hardware

HPP was designed to accept multiple "competing" heat pipe components or subsystems to trade off performance against other parameters (e.g. cost, manufacturability, flexibility) in an operational scenario. Inasmuch as heat pipe thermal control systems have been qualified and in fact are operational, the validation of new heat pipe configurations, materials, or working fluids at this component/subsystem level requires no system-level validation and offers a cost-effective avenue to thermal control system improvement for future space systems.

The Cryo System Experiment (CSE)

The Cryo System Experiment (Figure 16) is a TRL 7 space-flight experiment conducted by the Hughes Aircraft Company in a cooperative program with NASA. The overall goal of the Cryo System Experiment is to validate and characterize the on-orbit performance of two thermal management technologies that comprise a hybrid cryogenic system. These thermal management

technologies consist of: 1) a new-generation long-life, low-vibration 65 K Stirling-cycle cryocooler, and 2) an oxygen diode heat pipe that thermally couples the cryocooler and an energy storage device while charging. The experiment is necessary to provide a high-confidence zero-g database for the design of future cryogenic systems for NASA and military space flight applications.

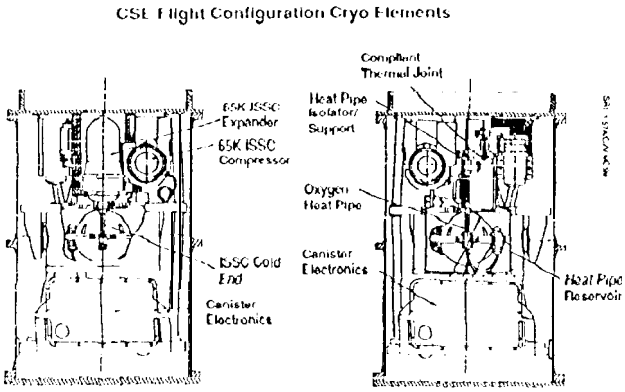

Figure 16: Cryo System Experiment

These technologies promise to satisfy many of the currently defined cryogenic system performance goals for planned NASA and military space programs. The Cryo System Experiment is the next step in the technology development process. Feasibility of each technology has already been demonstrated in Hughes independent R&D ground-based laboratory tests. However, questions raised by the scientific community relative to the performance of these components in a 0-g environment must be answered before these technologies can be optimized for application to flight systems. The flight experiment is configured to: (1) provide data necessary to resolve performance and design issues, (2) validate capability of the hybrid cooling system to meet future mission requirements, and (3) provide for high confidence design optimization of flight system concepts currently being considered.

During on-orbit operation, test data will be recorded to characterize performance of the technology including: (1) oxygen diode heat pipe temperature gradient and transport capacity in steady-state and transient conditions, (2) system vibration levels attributed to the active cryocooler, and (3) integrated, extended operation of the cooling system.

Before proceeding with the design of operational flight systems, an accurate correlation between 1-g and 0-g data is essential to predicting the performance of oxygen heat pipes in 0-g environment. Due to the poor capillary pumping capability of oxygen, there is serious concern in the scientific community that 1-g testing is optimistically influenced by puddle flow and therefore results cannot be extrapolated to 0-g performance. An understanding of the performance of these components in flight is required to develop accurate performance models for designing flight hardware. Key issues to be addressed include unsteady heat transfer capacity and start-up behavior. Extended on-orbit operation is necessary in order to resolve this issue.

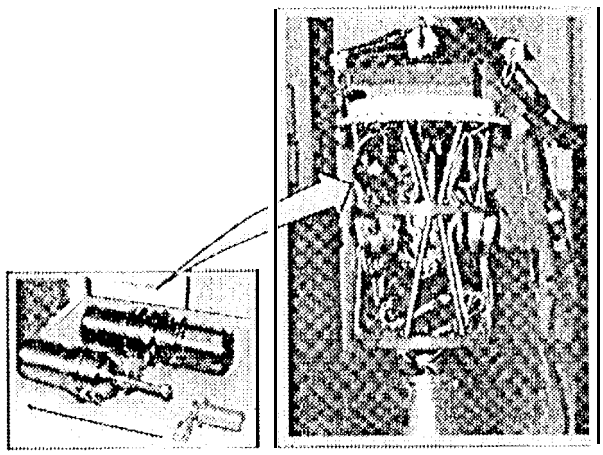

Figure 17: CSE cryocooler and GAS configuration

The cryocooler to be used for the experiment is a third generation, long-life low-vibration Stirling cycle unit (Figure 17). The cooler is a dynamically balanced unit whose expander and compressor assemblies each have an opposing moving mass counter-balance system to minimize the momentum imparted to focal plane optics of space science instruments. This technology is being developed to satisfy anticipated vibration requirements of future space-sensor systems. The cryocooler and its support structure are instrumented to record mechanical vibrations. Laboratory testing will give a good indication of the cryocooler generated disturbance. However, 1-g forces cause piston-displace offset deflections and magnetic field asymmetry that interact to alter the generated vibration. These extremely low-levels disturbances require a 0-g test. The experiment will provide the environment required to accurately perform mechanical disturbance measurements and evaluate cryocooler dynamic balance.

The flight experiment results will be significant to a number of satellites, scheduled for deployment in the late 1990s, for which cryocooler technologies are contemplated, including those in support of NASA's Mission to Planet Earth and Astrophysics Programs.

The CSE is presently undergoing payload integration and test activities at Goddard Space Flight Center in preparation for a launch in early 1995. Ground-based life testing of the cryocooler has been initiated at Hughes in support of the experiment, and will continue into next year for comparison with flight data.

The Cryo System Experiment illustrates an important type of NASA in-space flight experiment in which a relatively mature system technology is validated to

provide the option for subsequent application in a near-future space system development. A successful experiment could be followed by the use of the technology in an operational system.

Concluding Remarks

NASA and in fact the entire space community are well aware of the compelling need to reduce the cost of space systems development and operation. NASA is now aggressively moving toward the direction of smaller, more focused, and cheaper missions. As ao example, NASA has recently announced the Small Space.craf[Technology initiative (SSTI), a new flight program to demonstrate technologies needed to meet that objective. Two "Smallsat" earth observation satellites will demonstrate advanced miniaturization technology for smaller, lighter spacecraft with payload fractions almost double those of today's satellites. Sensors, on-board data processing, data distribution, guidance and control, and power subsystems will also be based on advanced technologies, all directed primarily at cost reduction.

Cost reduction must be a major objective in all future new military as well as civil space systems, and success will depend heavily on the avail ability of new -. but proven -- technologies. The experiments conducted thus far have been very effective in proving new technologies when in-space validation is required. However, the experiments themselves are also expensive, and cost reduction is as important in the experiment programs as it is in the actual development programs. Although wc arc proud of the cost control we have maintained in the experiments 10 date, wc know we must find ways to reduce cost even further.

Wc are Icvicv,'ii)?, a variety of cost-cutting possibilities such as increased osc of common carriers, adapters, test fixtures anti instrumentation, anti simplification of experiment equipment to ensure that only those features necessary to achievement of the primary experiment objectives are included. Furthermore, in addition to the rigorous process of phased program planning, wc are considering a requirement for a critical program review which would automatically be triggered if program cost projections indicate a ten or fifteen percent growth over the agreed-upon cost estimates. Unless the review determines that a significant cost over-wa can be averted, the experiment could be subject to termination.

On the basis of our experience to date, the continuing effort is al further cost reduction may result in some valuable additional fallout. We have had several contractors tell us that oor aggressive cost control measures on the flight experiments has forced them to adopt different approaches in the design and conduct of the experiments -- which io turn have been found applicable to new mainstream development programs as well. If this is true, our technology flight experiments may also be serving as an experiment or) techniques for cost reduction in design and development of major space systems.

But apart from our cost concerns and our cost-reduction focus, we ar c satisfied that in-space technology experimentation has proven itself as a valuable tool in preparing, validating, and reducing the risk of incorporating the technologies essential to design and development of 0111 future space systems. The first round of IN-STEP experiments provided data needed for development and refinement of a wide range of computer models and codes. The validated computational approaches, now being used in space hardware development, reduce or eliminate costly ground testing or overly high design margins previously required for reducing technical risk. The current generation of IN-STEP flight experiments is directed at reducing tile risk in specific technology areas important to development and operation of the International Space Station Alpha -- areas such as vibration isolation, male] ials and environment characterization, and in-space construction and maintenance. And new experiments will shortly be addressing inflatable structures and other innovative technologies that may offer still greater economies in future space systems.

W c think wc have good reason to believe that in-space flight experimentation has taken its place, along with computational analysis, simulation, laboratory and bench testing, and wind-tunnel or atmospheric flight testing, as another weapon in the arsenal of the space systems designer.

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