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SNAP-19/NIMBUS B INTEGRATION EXPERIENCE

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SNAP-19/NIMBUS B INTEGRATION EXPERIENCE

Arthur W. Fihelly, Herbert N. Berkow and Charles F. Baxter

ABSTRACT

This paper describes the SNAP-19/Nimbus B integration efforts and major interface problems from the user's point of view. Because SNAP-19 was not the primary power supply and the Nimbus B experiments were relatively insensitive to its presence, several potential interface problems of future applications were not encountered. Nevertheless, the experience should aid future endeavors of this type.

The NASA specification requirements are reviewed and the problems attendant to their implementation are explored. In this program, aerospace nuclear safety considerations were found to impose the greatest restrictions both on design and integration. The importance of complete user specifications and nuclear safety evaluations early in the program is emphasized.

SNAP-19/NIMBUS B INTEGRATION EXPERIENCE

INTRODUCTION

On May 18, 1968 the SNAP-19 Radioisotope Thermoelectric Generator (RTG) system was launched aboard NASA's Nimbus B spacecraft. This event marked the culmination of almost five years of intensive effort by NASA, AEC, and their respective contractors. Unfortunately, a malfunction of the launch vehicle's Thorad stage resulted in its destruction by the Range Safety Officer approximately two minutes after liftoff. The system impacted in the coastal waters off Vandenberg Air Force Base and thus the ultimate mission goals were not immediately realized. Nevertheless, the SNAP-19/Nimbus B Program represented a series of very significant first-time events, including the following:

- (1) SNAP-19 was to be the first isotope power system to be flown on a NASA spacecraft.
- (2) The SNAP-19/Nimbus B Program represented the first real attempt to develop an integrated isotope space power system with compatibility of all interfaces.
- (3) This was the first RTG application where the user specified a complete set of requirements and had an opportunity to play an active role which influenced the system development and program conduct.
- (4) SNAP-19 was to be the first operational RTG system to implement an intact reentry philosophy. It also had the largest isotope inventory of any system flown to date.

The integration of an RTG with an unmanned spacecraft presents unique, and often difficult design situations. These are compounded, to some extent, by a lack of experience and a retrofit approach. All RTG applications to date have been as substitutes, or auxiliary power supplies, for existing systems. The present application is no exception. Although integration efforts had a significant effect on the final product, the fact is that neither SNAP-19 nor Nimbus B were originally designed to be used together. Thus, some performance penalties were unavoidable in the retrofit process. On the other hand, the integration problems encountered under this program were not as difficult as those which can be expected on potential NASA missions, particularly deep space probes. There, the RTG will be the sole power source, the mission duration is considerably longer, and the spacecraft will contain scientific instrumentation which is far more sensitive to the presence of the RTGs than was the case with Nimbus B.

Notwithstanding the aborted launch and the fact that problems were encountered on the SNAP-19/Nimbus B Program, a good deal of valuable experience was gained on how to prevent and/or solve such problems on future applications. This paper examines some of the more significant user requirements and integration problems in light of their effects on the program. It will be seen that an RTG power system cannot be treated in the same manner as other spacecraft systems, that nuclear safety requirements have an over-riding influence on both system design and integration, and that the numerous RTG-spacecraft interface constraints must be considered in the earliest phases of mission planning.

SNAP-19 OBJECTIVES

Figure 1 shows the SNAP-19/Nimbus B system. SNAP-19 served the dual role of experiment and auxiliary power supply. The mission objectives, with respect to SNAP-19 use, were as follows:

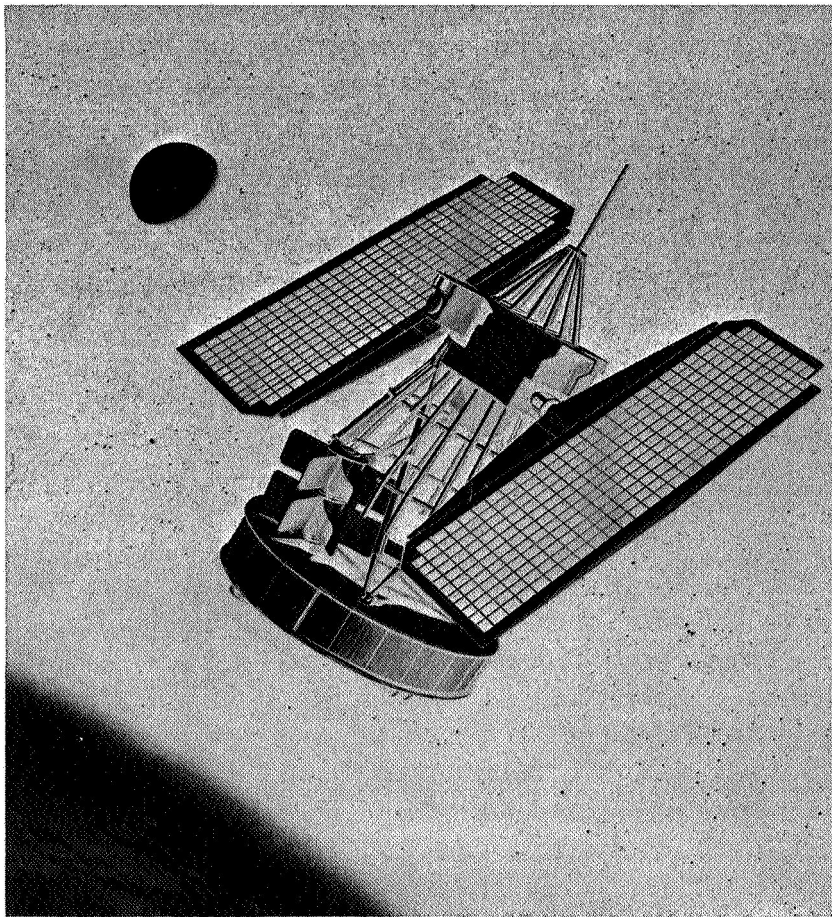


Figure 1-SNAP-19/Nimbus B Arrangement

- (1) To demonstrate experimentally the feasibility of integrating an RTG system with a complex NASA unmanned observatory type spacecraft.
- (2) To assess the performance and operational compatibility of RTG power supplies in long-life operational environments.
- (3) To obtain maximum power availability from SNAP-19 and utilize this power to supplement the prime solar power system.

The feasibility of generating power from RTGs had been demonstrated previously but the complex interfaces had not been encountered prior to this application. From a power requirement viewpoint, the basic Nimbus B objectives were attainable without SNAP-19. The major advantage of the auxiliary power supply was that it could provide an additional margin for success by permitting the storage batteries to operate at a lower depth of discharge during satellite night, allowing more experiments to operate simultaneously for longer periods, and helping to provide in excess of minimum spacecraft power in the event of a partial solar power system failure such as occurred in the first Nimbus mission.

Figure 2 shows the estimated Nimbus B regulated bus power versus time in orbit. The solar power degradation is based upon the actual experience of Nimbus 2. The RTG contribution is assumed to be about 52 watts at launch and 40 watts at the end of one year. The significant point illustrated by this figure is that with solar power alone, some programming of experiments would be necessary beyond three months. If the RTG performed as anticipated, it would negate this requirement, provide significant experiment programming flexibility, and perhaps even prolong the mission lifetime.

NIMBUS B SYSTEM AND MISSION¹

The Nimbus Program is oriented toward the development of long range numerical weather prediction and earth resources studies. The program is also providing advanced sensor development capability of a unique kind for the ultimate use of meteorologists, atmospheric physicists, the operational meteorological satellites, and for the discovery, development, and conservation of world resources. Nimbus B was the third in the series of spacecraft under this program. Its specific objective was to apply satellite techniques to derive quantitative measurements of atmospheric structure relevant to numerical forecasting techniques. This was to be achieved by:

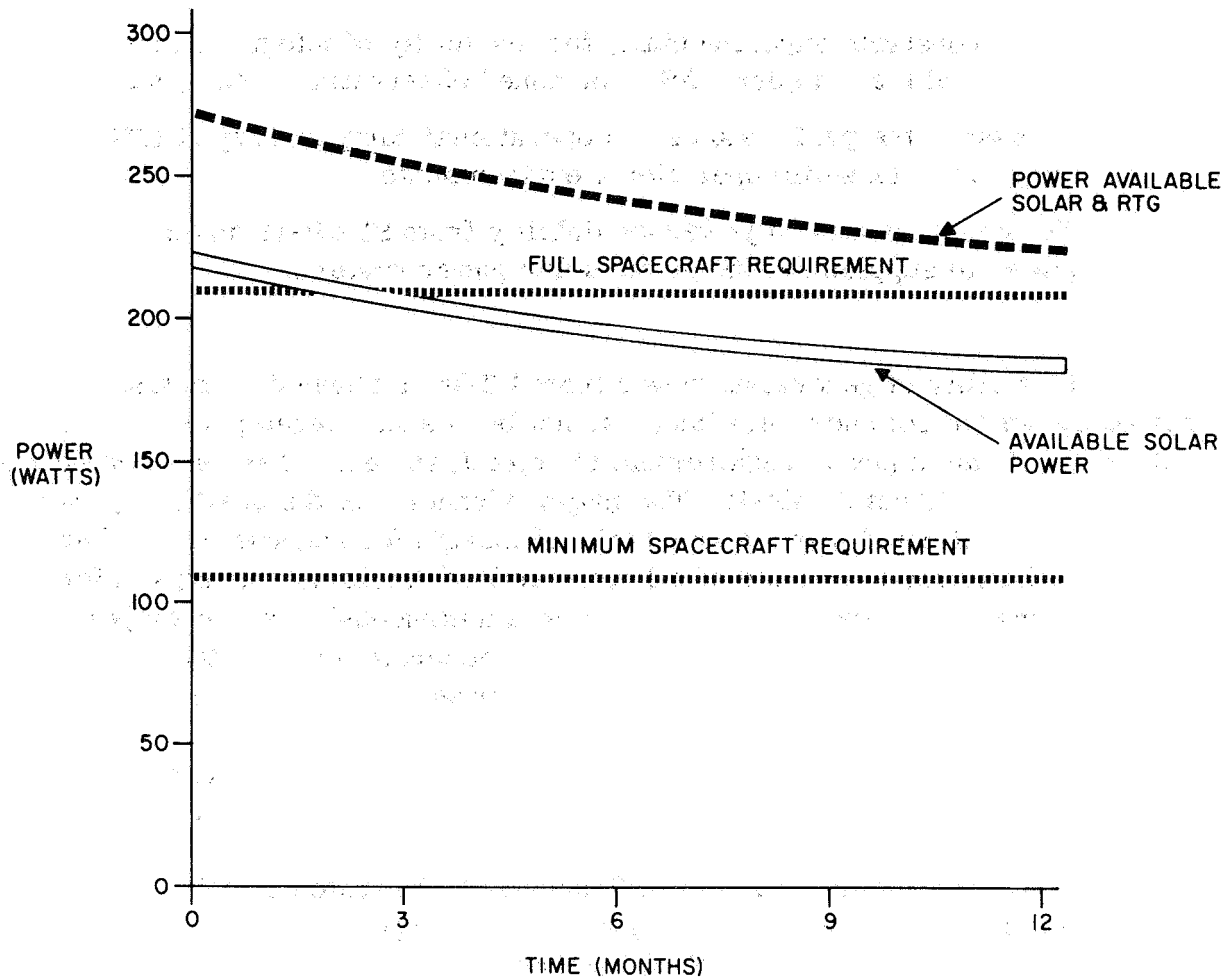


Figure 2-Nimbus B Power Vs. Time

- (1) Temperature soundings and other measurements relating to atmospheric structure.
- (2) Collection of meteorological data by satellite from a network of earth-based fixed and free floating platforms.
- (3) Determination of the earth's heat budget.
- (4) Measurement of direct and reflected ultraviolet radiation.

The Nimbus B spacecraft and its subsystems are shown in Figure 3. The basic structure consists of three major elements: a hexagon-shaped attitude control housing, a toroidal sensory ring, and the solar paddle subsystem. Each element is mechanically and thermally independent, with the exception of structural interfaces. Magnesium is the primary structural material and the entire system weighs about 1250 pounds.

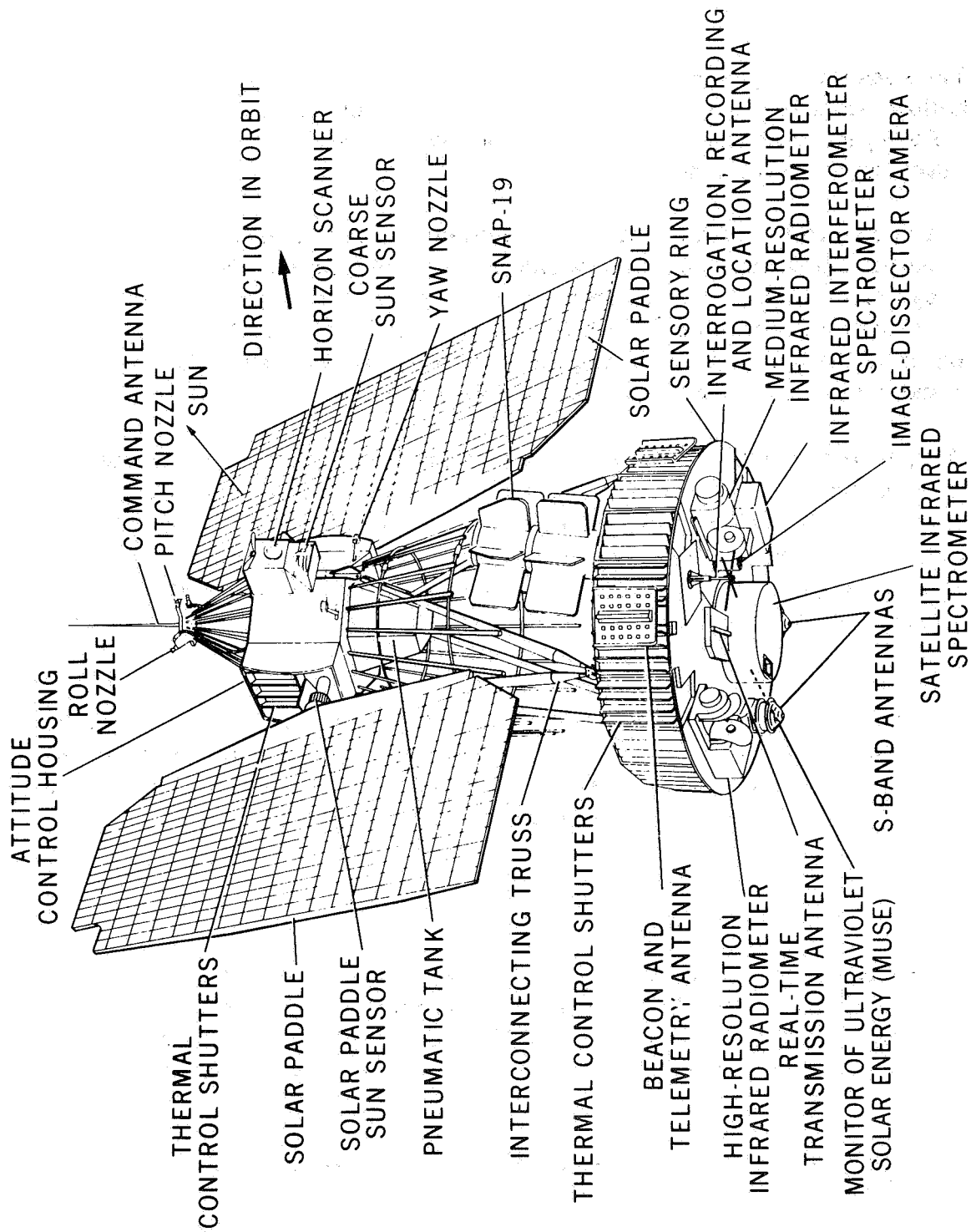


Figure 3—Nimbus B Subsystems

The attitude control housing contains the hardware required for spacecraft 3-axis earth orientation and provides a mounting platform for the sun sensors, horizon scanners, command antenna, and solar paddle driveshaft.

The sensory ring is attached to the control housing by a truss structure. It is a hollow circular torus section composed of 18 rectangular compartments or bays. The spacecraft experiments are mounted in these bays, or from cross-beam structures on the ring.

The spacecraft derives continuous regulated power at -24.5 volts dc from a solar conversion power supply connected in parallel with the SNAP-19 power supply system. The two rectangular solar-oriented paddles provide solar-to-electrical power conversion. In addition, eight nickel-cadmium storage batteries, recharged by the solar array during satellite day, provide power for the experiments and spacecraft subsystems during satellite night.

Temperature control of the sensory ring and control housing is achieved by a passive/active combination of insulation and mechanical techniques. A thermostated active system of controlled louvers, plus multiple layers of aluminized mylar insulation, provide control to the individual bays to maintain a mean subsystem ring temperature of $77 \pm 10^\circ\text{F}$. Proper solar paddle temperatures are maintained through a passive arrangement of reflection filters and high emittance surfaces.

Nimbus B was to be launched from the Western Test Range (WTR) into a circular near-polar orbit of 600 nautical mile altitude. The launch vehicle was a Thorad-Agena D. The spacecraft was to orbit the earth about 13 times each day and its design lifetime was one year.

SNAP-19 SYSTEM²

The SNAP-19 power supply system was developed by the AEC. Figure 4 shows its configuration for the Nimbus B application. The flight design evolved through several iterations, most of which involved the heat source and generator internals. Externally, the generators themselves bear a strong resemblance to their predecessor, SNAP-9A.

Basically, the system consists of two generators mounted in tandem at an angle of 16° outboard from the vertical, a power conditioning unit (PCU) and a telemetry signal conditioning unit (TSCU). Each generator was fueled with about 570 thermal watts of plutonium-238 dioxide microspheres contained in a single fuel capsule and delivered about 28 electrical watts at 2.6 volts dc to the PCU

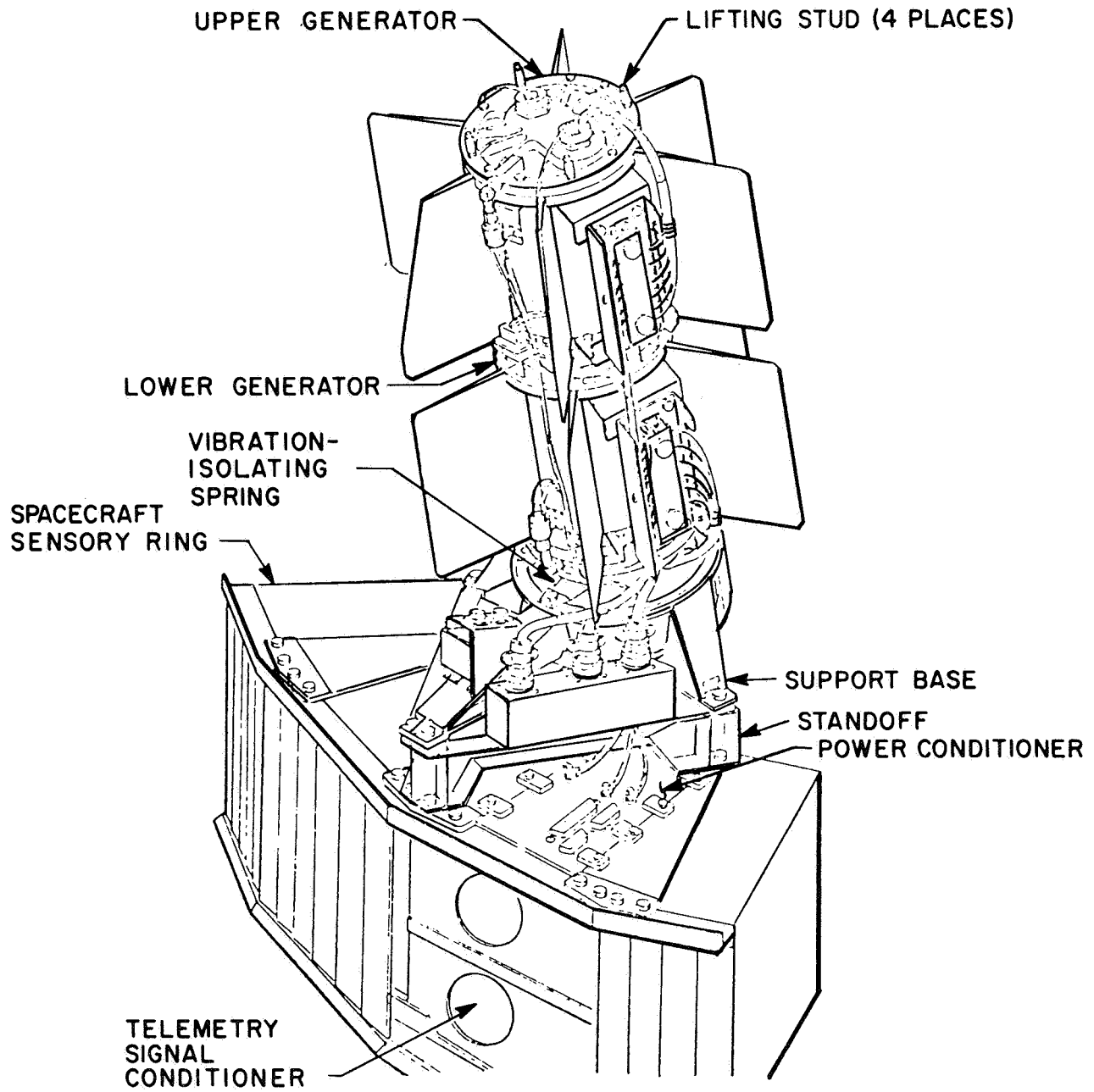


Figure 4--SNAP-19 Arrangement

at the time of launch. The power conditioner correspondingly supplied about 50 watts (e) at -24.5 volts dc to the spacecraft regulated bus. The TSCU receives analog signals from diagnostic sensors in the generators and PCU's, conditions these signals, and supplies them to the spacecraft analog-to-digital converter. The TSCU also furnishes digital signals that indicate whether the system is on or off the regulated bus. Both the PCU and TSCU are housed in standard Nimbus modules and located in the sensory ring bay immediately below the generators.

The generators are mounted on a support structure which consists of a support base and a standoff. The standoff is a triangular aluminum alloy structural adapter that attaches the generator subsystem to the sensory ring. Bolted atop the standoff is the stainless steel support base to which a stainless steel, spoked, vibration-isolating spring assembly is bolted. The generator subsystem is bolted to this spring assembly.

The bracket containing the two electrical receptacles is used to connect the generators to a dummy load or to place them on short circuit. It was removed prior to flight. The three permanent electrical connectors on the standoff connect all wiring between the generators and the spacecraft. This wiring includes generator power leads as well as leads to the TSCU.

The pertinent characteristics of the SNAP-19 system are summarized in Table 1.

The electrical arrangement of the system is shown in Figure 5. Each of the generators is in series with a corresponding dc-to-dc converter in the PCU while the generator-converter combinations are electrically in parallel with each other. Thus, a gross failure of either generator or converter would still permit the system to operate at half power. The TSCU provides 28 signals to the spacecraft telemetry system. Twenty-six of these are analog signals related to system performance while two are digital and indicate whether the converters are on or off the spacecraft regulated bus. The latter condition is effected by relays, in series with the PCU outputs, which are controlled by ground commands through the spacecraft. A total of four commands is available to place either, or both, of the converters on the regulated bus or on a fixed auxiliary load.

USER REQUIREMENTS

As soon as the planned use of SNAP-19 on Nimbus B became official, NASA recognized the immediate need for a detailed set of user requirements. These took the form of a technical interface specification,³ a program specification,⁴ and a program schedule, and represented the first time that an RTG user had presented such requirements to the supplier.

Table 1
SNAP-19 System Characteristics

Component	Material	Size (in.)	Weight (lb)	Normal Operating Parameters	Comments
● Heat Source	PuO ₂ fuel single encapsulation surrounded by reentry heat shield	Cylinder L/D = 2	5.75	Outer surface = 1000° F	570 thermal watts per RTG; helium vented; intact reentry
● Generator			28		2 per system
Thermopile	PbTe 2n-2p	90 couples/RTG	---	T _{hot junction} = 920° F T _{cold junction} = 400° F P = 28 watts at launch (at 2.6 volts dc)	Series-parallel arrangement; argon filled
Insulation	Min-K 1301	Periphery and ends	---		
Housing	Mg-Th Alloy HM31A-T5	10-1/3 in. high; 22 in. fin tip to tip		T _{fin root} = 337° F	Burns up on reentry; sodium silicate-zirconia emissive coating
● Support Structure	Al/SS	---	30		
● PCU	---	Nimbus module 6 × 6.5 × 8 in.	13	P = 26 watts at launch V = - 24.5 volts dc	2 converters in single package
● TSCU	---	Nimbus module 6 × 6.5 × 4 in.	3.5	Consumes < 2 watts 0 to -6.4 volt signal range	power supplied by spacecraft

Total System:
Weight ≈ 105 lb., net electrical power ≈ 50 watts at launch

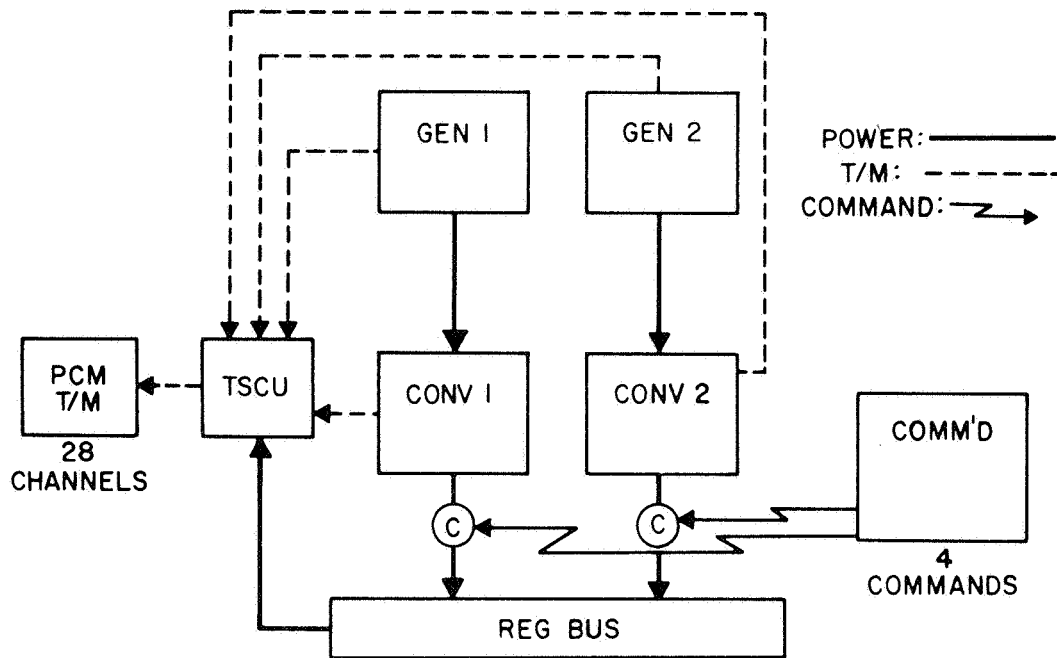


Figure 5-SNAP-19 System Electrical Schematic

The technical interface document was effectively a product or functional type of specification which spelled out interface and performance requirements and provided a basis for system acceptance. The program specification covered items to be delivered, services to be provided, and studies and tests to be performed by the supplier in order to satisfy the Nimbus B program requirements. Finally, the schedule established delivery dates which would assure compatibility with the Nimbus B milestones.

Realistically, NASA could not overlook the fact that detailed designs, and even some hardware, were already in existence both for SNAP-19 and Nimbus B. Thus, some degree of retrofit was inevitable. With the underlying flexibility of being able to remove SNAP-19 from the program at any reasonable time prior to launch with only a small effect on mission success, the NASA requirements had the following objectives:

- (1) SNAP-19 was to be completely compatible with the Nimbus B spacecraft and mission goals.
- (2) SNAP-19 was to be suitably isolated from other spacecraft systems such that any credible failure mode would not endanger mission success.
- (3) Modifications to existing hardware designs would be minimized.
- (4) Fully qualified SNAP-19 hardware would be available in a timely manner to support the spacecraft development and test program.

A lack of prior experience in such endeavors, together with interagency negotiations, prompted several modifications to the specifications before final agreement was reached by all cognizant parties. The approved requirements provided a uniform set of ground rules to which everyone could work.

The major areas of specification requirements and their ramifications are given in Table 2. It must be emphasized that the effects of each interface area are, in some cases, peculiar to SNAP-19, Nimbus B, and the philosophy of this application. Interface requirements which posed little problem to this mission could well be over-riding on subsequent missions. The converse is also true.

Table 3 lists the major hardware items which were required to support this program. It is probably typical of the requirements for similar applications.

Table 2
SNAP-19/Nimbus B Interface Considerations

Interface Area	Consideration	Effect On Hardware and Program
Nuclear Safety	Launch approval; safety is user responsibility	Major
Physical/Mechanical	Satisfy established envelopes; survive launch environment	Significant
Thermal	Maintain spacecraft thermal balance	Minor
Electrical	Spacecraft power system compatibility	Minor
Nuclear Radiation	Personnel access; degradation of spacecraft components	Minor
Magnetic Field	Affects attitude control system	Significant
Diagnostic Instrumentation	Support SNAP-19 experiment	Significant
Development and Verification Testing	Verify performance and compatibility	Major

SPECIFIC INTEGRATION PROBLEMS

In retrospect, it appears that some of the interface problems might have been avoided had they been more thoroughly investigated before the designs were fixed. However, one of the anticipated benefits of this program was to gain experience in integrating RTGs with a NASA spacecraft. Nimbus B, being relatively insensitive to the presence of the RTGs and not being totally dependent on their power, provided an excellent test bed. It is of interest to examine some specific problems encountered in the various interface areas and review the approaches to their solution.

Table 3
SNAP-19 Hardware for Support of Nimbus B Program

SNAP-19 Systems	
No. 1	Mechanical Model
No. 2	Engineering Model
No. 3	Endurance Test
No. 4	Fueled Prototype
No. 5	Electrical Prototype
No. 6	Fueled Flight Backup (Dispersal Mode)
No. 7	Fueled Flight Prime (Dispersal Mode)
No. 6A	Fueled Prototype (Intact Mode)
No. 8	Fueled Flight (Intact Mode)- actual flight hardware
Major Ground Support Equipment	
Ground Support Test Console (GSTC)	
Heat Source Shipping Container	
Generator Subsystem Shipping Container	
Mobile Carriage with Power Supply	
Portable Monitor Package	

Nuclear Safety

It is shortsighted to consider nuclear safety merely as an interface. Rather, it forms the basic criteria for the system design and mission and, indeed, controls many of the other interfaces. More costs, program delays, and performance penalties can be attributed to nuclear safety than to any other single factor. The significance of this can be seen with respect to several major SNAP-19 heat source design changes, all of which can be attributed to nuclear safety.

The original SNAP-19 heat source consisted of multiple capsules of a relatively low melting point plutonium fuel in a segmented heat accumulator block.

Both the capsules and the fuel were designed for high altitude burnup to a fine particulate form with world-wide dispersion prior to fallout. This was the same philosophy which had been applied to SNAP-9A. Because containment of molten plutonium fuel is uncertain, the specifications required demonstration that the fuel not melt at any time prior to reentry. Studies showed that this requirement could not be satisfied under anticipated SNAP-19 operating conditions. The result was a complete redesign of the heat source and a major reorientation of the program. The new heat source consisted of a single PuO_2 microsphere fueled capsule in a modified segmented heat accumulator block. The microspheres were believed to be inert to all credible environments and were sized to be nonrespirable and not an appreciable external radiation source, individually. Accordingly, the reentry philosophy was changed to capsule burnup with high altitude release of the discrete microspheres which would then reenter intact. Further tests and studies revealed uncertainties with respect to microsphere stability during the reentry environment. This led to associated hazard unknowns. While these stability uncertainties were neither proven nor disproven, the fact that the hazard was considered indeterminate prompted another heat source redesign and reentry philosophy change rather late in the program. This final concept evolved into the actual flight hardware during 1967 and consisted of a helium vented heat source encased within a permanent reentry heat shield. It is known as the SNAP-19 Intact Reentry Heat Source (IRHS) and is differentiated from earlier SNAP-19 heat sources in that it prevents fuel release prior to post-reentry impact.

Nuclear safety considerations also necessitated provision for the potential inclusion of an RTG ejection mechanism early in the program while high altitude heat source and fuel burnup were required. It was felt that ejecting the system by command in the event of an ascent abort or prior to orbital reentry would preclude the undesirable thermal shielding effects of the spacecraft and assure the required burnup. While the need for the eject mechanism disappeared in 1966, its effects on integration and performance were permanent. The complex and weighty support base was needed to mount the system cantilevered at a 16° angle from the vertical as is seen in Figure 4. This, in turn, caused mechanical interference between the generator fins, the shroud, and the spacecraft control housing. The interference was eliminated by removing portions of the fins. This was accompanied by a reduction in the generator's thermal inventory in order to maintain design temperatures. The ultimate consequence was a reduction in power output.

Launch vehicle destruct criteria were carefully evaluated, with the aim of precluding conditions which led to the abort of a SNAP-9A launched aboard a Thor Ablestar from the WTR in 1964. Although a non-nominal Thor trajectory was evident during that launch, there were no applicable criteria for mission termination. The second stage was allowed to burn to propellant depletion,

which resulted in a ballistic reentry. In order to provide an answer to questions which arose because of this anomalous flight, NASA performed a study to determine the feasibility of defining an envelope of Thorad performance parameters, using standard range data displays, outside of which a nominal Agena could not achieve an orbit with perigee greater than 90 nautical miles. This would hopefully provide a set of "no orbit" conditions which would constitute a potential criterion for the WTR Range Safety Officer to terminate the mission prior to Thorad separation and loss of all vehicle destruct capability. Impact would be in deep ocean, thus precluding any hazard. The study concluded that the approach was not feasible. During the flight period in which destruct capability exists, there is no way of uniquely establishing with certainty whether the payload will achieve orbit. Further, this approach would lessen the probability of Nimbus B mission success, while still not attaining the original goal.

Termination of the Nimbus B flight had no direct connection with the "no orbit" criterion investigation. The trajectory exceeded the previously defined range safety impact limit line within the first two minutes of flight and the course of action was virtually automatic. The mission would have been terminated in exactly the same time and manner even if SNAP-19 had not been aboard.

The series of interagency procedures known as "launch approval" forms the motivation for all nuclear safety efforts and interfaces. Thus, every safety related study and test performed under the development and integration program had as its objective the demonstration of mission safety to an extent sufficient to obtain launch approval. The Nimbus B/SNAP-19 safety program was more extensive than those of earlier SNAP programs. This was, in large part, due to potential interactions between the spacecraft and RTG systems. However, because the safety investigation was so thorough, it was possible to predict confidently that no hazard existed as a result of the abort.

Table 4 summarizes the major safety test areas under the SNAP-19/Nimbus B Program.

Physical/Mechanical

Several interface problems of a physical/mechanical type arose and most can be attributed, directly or indirectly, to the ejection requirement. Several possible SNAP-19 mounting locations were investigated including atop and below the control housing and sensory ring periphery. Considerations of experiment interference, reliability, physical envelope maintenance, minimum spacecraft structural perturbations, and the potential ejection requirement led to the selected mounting configuration. This called for the RTGs to be mounted in tandem above

Table 4
Summary of SNAP-19/Nimbus B Safety Test Program

Test	Purpose
<p>A. Fuel Form</p> <p>Basic properties</p> <p>Aerothermodynamic</p> <p>Biological</p> <p>Vibration, shock, impact</p>	<p>Safety analyses</p> <p>Microsphere reentry behavior</p> <p>Effects of ingestion and inhalation</p> <p>Effects on particle size</p>
<p>B. Fuel Capsule</p> <p>Impact</p> <p>Launch fire</p> <p>Seawater burial</p> <p>Internal pressurization</p> <p>Aerodynamics</p> <p>Reentry thermal (plasma arc)</p>	<p>Abort survival</p> <p>Abort survival</p> <p>Corrosion and pressure resistance</p> <p>Failure mode and time</p> <p>Obtain aerodynamic coefficients, heat and pressure distribution data for reentry analyses</p> <p>Failure mode and altitude</p>
<p>C. Generator</p> <p>Launch fire and overpressure</p> <p>Aerodynamics (wind tunnel)</p>	<p>Abort survival</p> <p>Aerodynamic coefficients, heat distribution data</p>
<p>D. Spacecraft</p> <p>Aerodynamics (wind tunnel)</p> <p>Reentry thermal (plasma arc)</p> <p>Spacecraft materials combustion</p>	<p>Aerodynamic coefficients, heat distribution data, effects of solar paddles</p> <p>Sensory ring failure mode</p> <p>Investigate reentry combustion of spacecraft</p>

bays 1 and 18 of the sensory ring and canted outboard at an angle of 16° from the vertical. The immediate effects on the spacecraft required a rearrangement of experiment modules to achieve a mass balance in the sensory ring. Increased loads on the sensory ring structure were accommodated by strengthening the outboard and radial shear webs, installing inboard shear webs, and strengthening the upper and lower inboard rings. It was also necessary to provide bolt holes for the SNAP-19 standoff structure.

Two cases of serious physical interference between the RTG fins and spacecraft or launch vehicle were discovered during the integration program. The first of these involved the two outboard fins on the upper generator which were found to extend beyond the shroud exclusion envelope defined by the specification, under both static and dynamic conditions. This problem was noted analytically and verified when one of the early SNAP-19 systems was mounted on a spacecraft model. It was remedied by shaving the corners of these two fins to remove the interference.

The second case of fin interference involved the two inboard fins on each generator. Since the reentry attitude of Nimbus B is arbitrary, a large number of reentry orientations is possible. Analysis revealed that these fins would impact the control housing, or its supporting struts, as a consequence of ejection in nearly every credible reentry mode. Removal of two inches from the length of each of the four inboard fins was necessary to solve the problem, at least in those instances wherein the spacecraft was not tumbling at the time of ejection.

The final fin configuration is shown in Figure 6. The combined radiator area removed from the inboard and outboard fins caused increased internal temperatures which were undesirable. It was necessary to reduce the input power per RTG from 625 watts to 570 watts to restore the design temperature conditions. This reduced the system's electrical power output by about three watts. Although the potential ejection requirement later disappeared, its effects on the SNAP-19 system were permanent.

A significant mechanical type problem was noted in connection with vibration testing of the fueled prototype SNAP-19 when the heat accumulator block and thermal insulation were damaged. Post-test examination revealed that the damage was caused by movement of the fuel capsule in the upper generator during vibration. Although this effect had not been seen in flight acceptance level testing (prototype levels are more severe than flight acceptance levels), the fuel capsule load plate was redesigned and the insulation preload increased to preclude future problems of this nature.

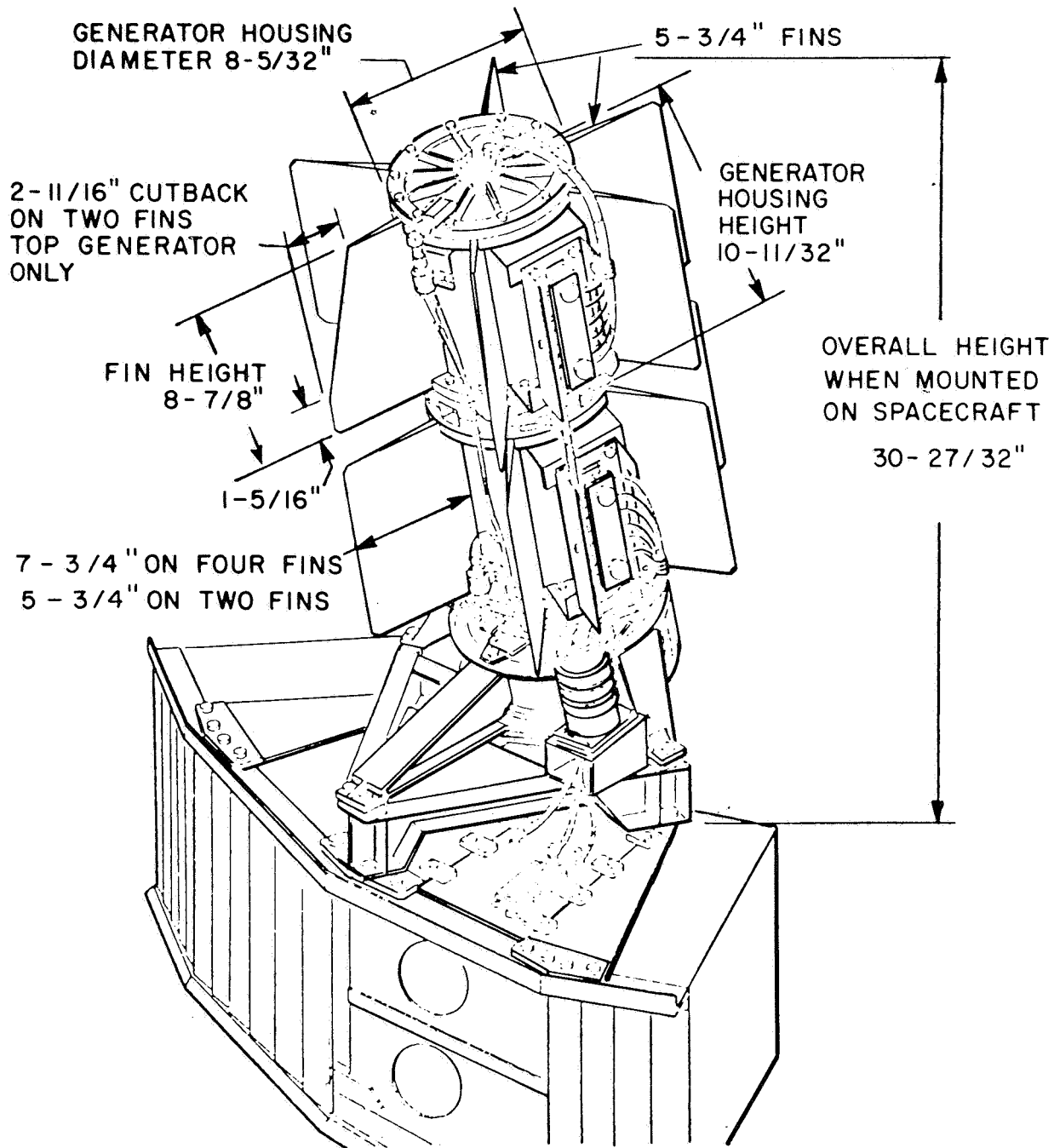


Figure 6-SNAP-19 Final Fin Configuration

Thermal

Thermal interface problems required investigation because of the imposition of a fairly large thermal source (about 1100 watts) into a system which had been designed previously for a high degree of thermal control. The NASA specification was concerned with conduction from the RTGs to the sensory ring through the support structure, from the PCU and TSCU modules to the sensory ring, radiation from the RTGs to spacecraft subsystems, and transportation and launch pad cooling requirements.

The specification permitted a maximum flow of 12 watts from the RTGs to the sensory ring. This required careful design of the support structure to minimize thermal paths. Measurements showed the actual value to be about 13 watts, which was greater than specified but still acceptable. The allowable total conduction from the PCU and TSCU modules into the sensory ring was 14 watts. Once again, tests showed that this requirement was satisfied. However, in order to accommodate even these allowable thermal loads, it was necessary to remove the thermal insulation from beneath bays 1 and 18. Thermal radiation levels from the RTGs to sensitive spacecraft subsystems were found to present no undue perturbations to their performance.

Nimbus philosophy normally requires complete assembly and test of the flight spacecraft and adapter, transport to WTR, mating to the launch vehicle, and launch without altering the spacecraft configuration. An exception was necessary in the case of SNAP-19, as analysis indicated the possibility of seriously damaging the solar paddles if the transport aircraft air conditioning system failed on route to WTR. It was not possible to provide redundant air conditioning. Primarily for this reason, it was decided to transport the SNAP-19 separately from Nimbus B.

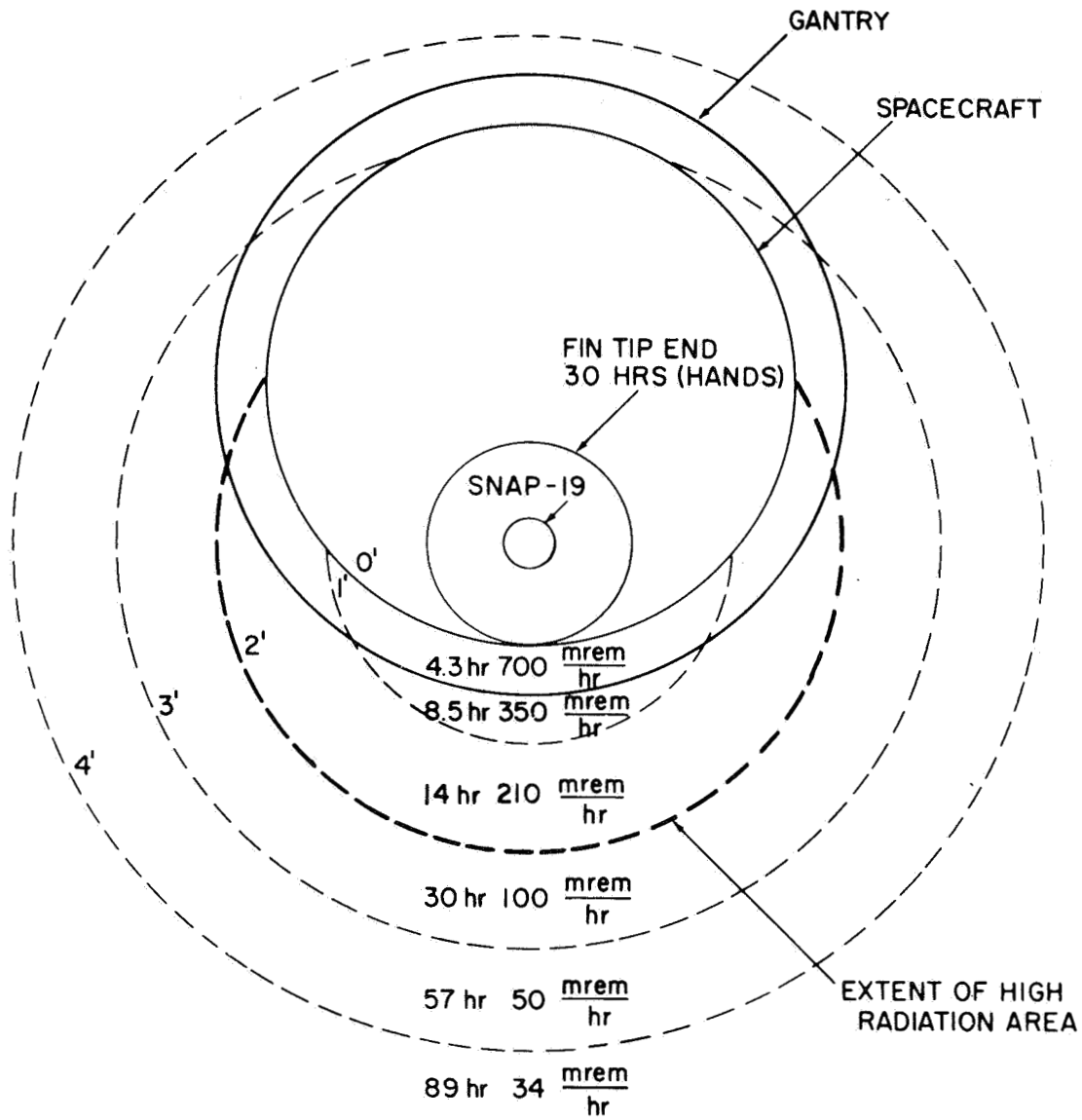
Tests were necessary to determine whether additional launch pad air conditioning capability would be required to accommodate the SNAP-19 thermal source during prelaunch enshrouded conditions. The standard pad equipment was capable of providing about 45 lb/min of 60°F air to the launch vehicle shroud. The tests were parametric in air flow rate and temperature and utilized an electrically heated SNAP-19 system, an electrical systems model spacecraft, and an actual shroud. The existing cooling capabilities were found to be adequate. Additionally, in the event of an air conditioning failure, both Nimbus B and SNAP-19 heatup rates are sufficiently slow to permit the activation of backup equipment.

Nuclear Radiation

Because of the relatively low radiation dose rates associated with the original fuel form, little consideration was given to the nuclear radiation interface during the early program phases. However, the change to the oxide form with its multi-fold increase in neutron emission rate caused this interface to take on added significance. There are two discrete aspects of this problem; biological hazards associated with personnel exposure and radiation effects on sensitive spacecraft components which could affect mission goals. The biological hazard aspect was solved by providing a shielded shipping container for the RTG subsystem which satisfied all AEC and Department of Transportation (DOT) shipping regulations. This large, heavy cask complicated handling to some extent but posed no insurmountable problems. SNAP-19 launch site handling and installation had to be very carefully planned to minimize personnel exposures but all operations were carried out with exceeding the allowable 3 rem/calendar quarter dose for radiation workers. Figure 7⁵ shows the actual radiation isodose curves surrounding the spacecraft mounted SNAP-19 and the corresponding permissible whole body exposure times.

Potential radiation effects on spacecraft components were of a more serious nature since it is unlikely that any shielding weight or volume could have been tolerated at that point in the program when the fuel form was changed. A study was performed⁶ to assess the effects of the combined space and RTG radiation on sensitive spacecraft components. These included diodes, transistors, resistors, capacitors, and solar cells as well as certain spacecraft grease and seal materials. Special emphasis was given to metal oxide semiconductor field effect transistor (MOSFET) devices. The natural and artificial radiation belts existing in the planned Nimbus B orbit consist of protons and electrons with energies of up to 30 and 6 Mev, respectively. It was found, on a radiation damage basis, that the contribution of SNAP-19 was quite small compared to that of the orbital environment. Furthermore, the results indicated that no significant degradation of any component or interference with any experiment would occur during the one year mission plus six months of prelaunch exposure. This conclusion has been verified by Nimbus 2, which has far exceeded its design life in a similar orbital environment.

Although nuclear radiation interfaces presented no severe integration problems on this program, it is worth noting that this is likely to be one of the most restrictive interfaces in future NASA applications, particularly long duration deep space probes. RTG powered spacecraft containing sensitive radiation detectors are being considered for deep space missions of 5 to 10 years duration. Aside from the obvious long term degradation effects on electronics, the allowable total incident RTG particle flux at the detectors is likely to be limited to a maximum



NOTE: EXCEPT WHERE NOTED, EXPOSURE TIMES ARE FOR WHOLE BODY EXPOSURES

Figure 7-SNAP-19 Nuclear Radiation Fields

of 10 particles/cm² -sec to preclude masking of some of the intended measurements. This is several orders of magnitude less than unshielded RTG background. Thus, very sophisticated tradeoff studies between distance and shield weight will be required.

Diagnostic Instrumentation

The original SNAP-19 system contained minimal diagnostic sensors. Since one of the major functions of SNAP-19 on Nimbus B was as an experiment, the NASA specification required additional instrumentation for purposes of assessing orbital performance as well as development and qualification ground test performance. The type and number of sensors were effectively similar in both the ground test and flight units and are shown in Table 5.

Table 5
SNAP-19 Telemetry

Measurement	Number
RTG hot junction temperature	3 per RTG
RTG fin root temperature	3 per RTG
RTG internal gas pressure	1 per RTG
RTG output voltage	1 per RTG
PCU input voltage	1 per PCU
PCU input current	1 per PCU
PCU output voltage	1 per PCU
PCU output current	1 per PCU
PCU temperature	1 per PCU
PCU on or off regulated bus	1 per PCU

The immediate effect of the instrumentation requirement was the addition of two major hardware components to the SNAP-19 program; the TSCU and the GSTC. The TSCU has been discussed previously. It is a flight hardware component whose primary purpose is to condition the signals from the various sensors in the RTGs and PCUs to a range of 0 to -6.4 volts, which is the range compatible with the spacecraft analog-to-digital converter in the PCM telemetry system. The TSCU power requirement, which is slightly under two watts, is furnished by the spacecraft regulated bus.

The GSTC, shown in Figure 8, was used for ground testing only and thus did not present any integration problems, as such. It is important to note, however, that it represents a complex and costly piece of equipment which was required by NASA to support the integration program. Its basic functions were:

- (1) To provide a common set of equipment for complete functional testing of all SNAP-19 hardware, individually or as a system.
- (2) To simulate the RTGs, TSCU, or PCU for system checkout.
- (3) To calibrate the TSCU.
- (4) To supply power for electrically heated RTGs.

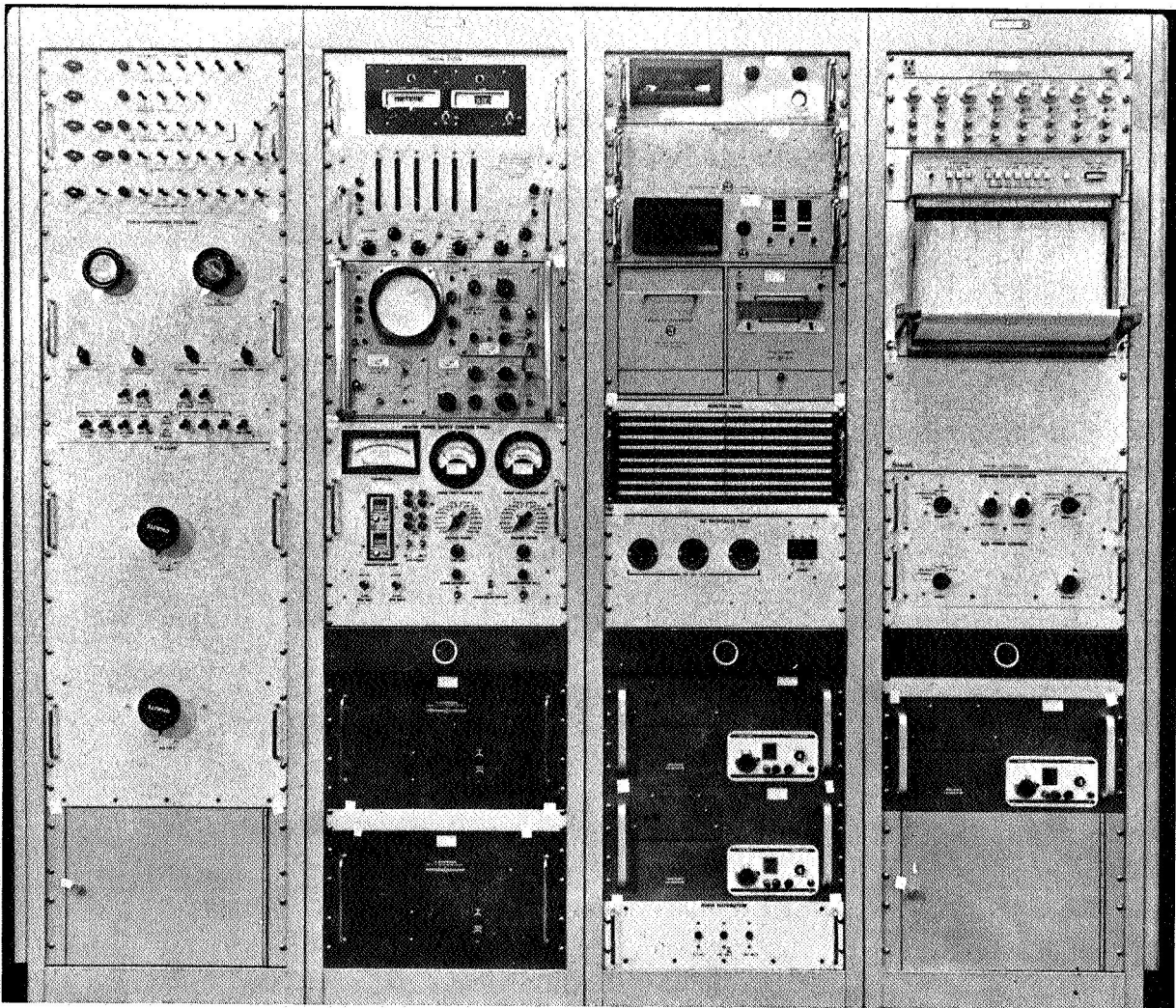


Figure 8—SNAP-19 Ground Support Test Control

- (5) To continuously monitor and print 40 channels of test data and visually display any 8 of these on Brush charts.

Electrical

This was one of the most important functional interfaces inasmuch as SNAP-19 is an electrical power supply and full compatibility with the spacecraft electrical systems was mandatory. Additionally, because of the philosophy of SNAP-19 use on Nimbus B, the electrical interface had to be such that any failure or non-nominal performance of SNAP-19 would have no adverse effect on the spacecraft systems.

The NASA specification required that the SNAP-19 be isolated from the bus by means of diodes and fuses. Isolation diodes were furnished in the PCU while fuses were provided by the spacecraft. It was also found necessary to provide a protective circuit in the PCU which insured against a PCU open circuit condition. The resulting high voltages, above 30 volts dc, could damage the PCU and possibly the spacecraft. The protective circuit detects a converter open circuit condition and automatically places a simulated short circuit on the RTG output. When the converter load returns, the protective circuit becomes inoperative and normal system operation is resumed.

During the course of the program, an electrical incompatibility problem involving excessive RFI noise from the TSCU arose. The NASA specification allowance for RFI noise from the total SNAP-19 system, reflected as noise on the spacecraft regulated bus, was 50 millivolts peak-to-peak with no specific frequency restriction. During spacecraft integration testing, the integration contractor detected a 400 cycle, 1 volt peak-to-peak ripple spike from the TSCU. This condition was intolerable because it exceeded the threshold for destruction of PCM telemetry gates on the same lines as the TSCU and interfered with SNAP-19 telemetry data. The problem was not easily solved. Several modifications involving additional filters, component replacement, and rewiring of boards were necessary before the noise was reduced to an acceptable level.

Magnetic

Magnetic measurements on a fueled SNAP-19 dispersal design system were made at GSFC in November 1967. The initial perm was 2725 dyne-cm/oersted, at 12 feet. After exposure to a 15 gauss on-off dc pulse, it rose to 3131 dyne-cm/oersted, which corresponds to a torque of about 600 dyne-cm in a 600 nautical mile orbit. An early version of the NASA specification limited this torque to 50 dyne-cm because of spacecraft control gas usage but this limitation was later

removed. It was found that this system could be depermed to 415 dyne-cm/oersted by a 50 gauss ac hysteresis field for several minutes.

In April 1968, the SNAP-19 flight model was magnetically measured at GSFC. This as-received moments were 4600 and 3890 dyne-cm/oersted with the RTGs shorted and on dummy load, respectively. Again, deperming was possible, this time to 870 dyne-cm/oersted.

The postulated reason for the unexpectedly high as-received magnetization is the high fields associated with the vibration facility used to qualify the hardware. This postulation is borne out by measurements made at the General Electric Company after the return trip from GSFC using portable magnetometer apparatus and deperm coils. The perm state had not change measurably. A magnetic survey was performed again at the launch site and although provisions were available to deperm the system, this was not necessary since no change had occurred during transport and handling.

No problem was anticipated assuming that the system would not be significantly remagnetized as a result of actual launch vibrations. Calculations showed that even under worst case conditions, the control gas would be adequate for a two year mission.

This experience confirmed that RTGs can be highly magnetic devices but that steps can be taken to lessen the problem.

While the magnetic interface problem on Nimbus B affected only control gas usage, there are planned missions where the effects of magnetic field on experiment feasibility will be far more critical. Future space probes, for which RTGs are likely to represent the only practical power source, will attempt to measure planetary and interstellar magnetic fields. Such probes cannot tolerate magnetic fields in excess of 10^{-6} gauss emanating from the spacecraft due to residual magnetism or circulating currents. This can be compared with the measured 10^{-4} gauss at 12 feet from the SNAP-19 system. It is apparent then that magnetic characteristics will be an important consideration in both the design and integration of future spacecraft.

System Verification Testing

The NASA specification required extensive performance and environmental testing to verify that the SNAP-19 system would function as desired under the anticipated mission environments and that the interface compatibility requirements were satisfied. The basic test sequence is illustrated in Figure 9, which

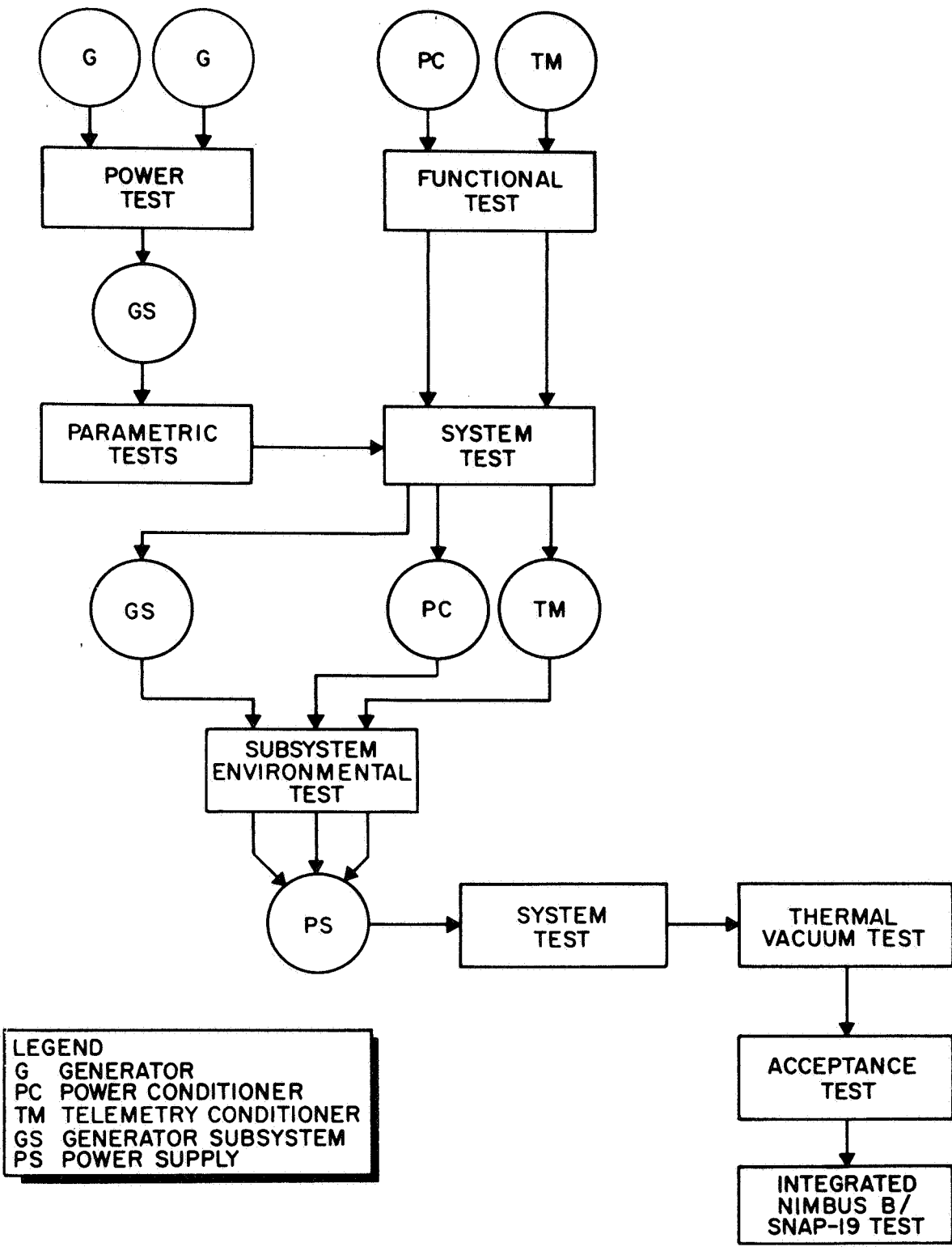


Figure 9-SNAP-19 Testing Program Sequence

does not include any of the component development or safety testing. The environmental tests consisted of humidity, vibration, acceleration, and thermal/vacuum for prototype systems with only vibration and thermal/vacuum tests required for the flight system. In conformance with NASA philosophy, the prototype vibration levels were about 50 percent more severe than flight levels.

Such testing is time consuming and must be carefully planned to avoid schedule delays. Under the Nimbus B/SNAP-19 Program, schedule delays precluded complete testing of some of the early models prior to delivery. Thus the discovery of several problems, which these tests were designed to detect, was delayed until later in the program when the consequences were more costly. A significant amount of re-testing was also necessitated by the several design changes which occurred during the development program.

The use of SNAP-19 on Nimbus B necessitated a deviation from standard NASA testing philosophy. Normally, final acceptance testing of the flight spacecraft is performed with all the flight subsystems. Once testing is complete the configuration is not disturbed. Because of the handling difficulties with fueled generators and the potential hazards associated with environmental testing, however small, a decision was made to use the electrically heated SNAP-19 prototype for final flight spacecraft acceptance testing. In addition, it was found more expedient to transport the fueled SNAP-19 separately from the spacecraft and mate the two at the launch site on R-2 day, just prior to shroud installation.

Neither of these operations caused any real problems but they do emphasize the fact that RTGs cannot always be treated the same as other spacecraft subsystems and that the user might have to deviate occasionally from standard procedures to accommodate the unique characteristics of nuclear power supplies.

CONCLUSIONS

The Nimbus B/SNAP-19 integration experience was, in many ways, unique to this mission and to the philosophy of the SNAP-19 application. All of the problems which arose were resolved satisfactorily within the program constraints, although perhaps not always in an optimum manner. Nevertheless, one of the program objectives was to gain integration experience. This experience will provide guidance for future program planning and implementation with respect to those considerations which are significant in minimizing and resolving problems.

The goals of the Nimbus B mission were deemed sufficiently important to warrant a second Nimbus B program which is presently underway. Launch of

this spacecraft, designated Nimbus B2, is scheduled for the spring of 1969. The degree of success of the SNAP-19/Nimbus B integration program is reflected in the fact that Nimbus B2 will incorporate a SNAP-19 power supply in the same capacity as did the prior program.

Several conclusions can be drawn from this review of SNAP-19 integration experience.

- (1) Radioisotope power systems can be physically and functionally integrated with complex spacecraft although some performance tradeoffs might be unavoidable.
- (2) With respect to SNAP-19 on Nimbus B, most of the significant integration problems were nuclear safety and mechanically oriented. On future NASA missions, nuclear radiation, magnetics, and weight minimization are likely to be major considerations. Assuming that future RTG systems are designed for intact reentry, nuclear safety is likely to have a significantly smaller influence on integration.
- (3) The user must specify interface and functional requirements at the earliest possible point in the program. To minimize retrofit problems, both the RTG and spacecraft must be designed as an integral system based on these requirements.
- (4) The nuclear safety interface should be thoroughly defined and safety design criteria specified firmly during the preliminary design phases as opposed to late in the program.
- (5) Design defects and interface incompatibilities should be detected by testing as soon as hardware is available. Delays in testing can be costly.
- (6) Isotope space power system users will require a thorough knowledge and understanding of the technology and unique characteristics of RTGs in order to assure a successful integration program.

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