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PROGRESS REPORT
SNAP 2
NUCLEAR AUXILIARY POWER UNIT DEVELOPMENT
APRIL-JUNE 1961
(Title Unclassified)

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EDITOR
M. SHACKELFORD

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I. SUMMARY

System design effort during the report period was directed toward updating the system configuration and design point analysis based upon the latest experimental component data. The significant changes in design point parameters during the report period are listed indicating improvement in several component efficiencies. The orbital startup analysis has continued on the determination of the exact sequence of events during preheat and injection of the mercury. A choice between dual injection and insulated radiator-condenser technique is to be made on the basis of NaK freezing requirement, power for startup, startup time, and system weight.

Technical data on operation and performance results of the S-2-DS (SNAP 2 Development System) operating at SNAP 10A design conditions, are reported in NAA-SR-6694, "Progress Report, SNAP 2/10A Reactor, April-June 1961."

Two design concepts are being pursued on the SNAP 2 radiator-condenser: (1) copper-clad honeycomb-steel tubes, and (2) aluminum shell-steel tubes. The honeycomb concept is currently in fabrication and the brazing of the first panel is scheduled for July 1961 at Rohr Aircraft Corp. The completed radiator-condenser consists of four panels formed into a conical assembly. The tubes are imbedded into the steel honeycomb and the copper brazed onto the outer surface of the honeycomb. A representative 20-in. by 40-in. panel, including tubing and manifold weld joints, was satisfactorily completed at the North American Aviation, Los Angeles Division, as an aid in determining the manufacturing process. The completion of fabrication of the full-scale radiator-condenser for application in PSM-1 is scheduled for September 1961. Current indications are the unit will be delivered on schedule. A more advanced flight type design of this concept is currently in the design stage and includes tapered copper fins to reduce overall weight.

Individual copper fins have been tapered successfully by the chemical milling process, but standard machining techniques have not produced acceptable results. Typical weldments are being made to solve the problems associated with welding of thin wall tubing and manifolds in constricted areas. This weight-optimized design also includes rectangular tubing which simplifies the assembly and brazing process, and the cross-sectional area is reduced in the subcooler section in

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order to reduce the liquid mercury inventory. A test panel which includes all the typical construction features is being fabricated at the NAA Los Angeles Division.

The final technical proposal for fabrication of an aluminum shell-steel tube radiator-condenser is being prepared by Solar Aircraft Co., the selected supplier. One of the important requirements of the design is the titanium plating of the steel tubes prior to brazing the tubes to the aluminum skin. This diffusion barrier between steel and aluminum prevents the formation of brittle intermetallic compounds, while facilitating a strong brazed joint. A development program was pursued in order to determine the most acceptable fabrication process.

Extensive optimization studies have shown that the minimum weight radiator-condenser will be obtained with the use of a beryllium shell, which can satisfy the heat transfer, structural, and meteoroid protection requirements. A reference design is now being developed, and a brazing program has been initiated to solve typical joining problems. A representative panel which incorporates all significant features of the design will be fabricated before full-scale procurement is considered.

The experimental mercury injection tests on the PCS-I boiler have been completed and the data thus obtained has provided insight into the startup characteristics of that boiler. The primary objectives of the injection tests have been met, namely, the determination of boiler transient characteristics, time constants, stability, and conditioning effects.

The performance test rig was used for the injection tests. A Chem pump, pumping against a closed valve, was used to provide injections. When the valve, which was located at the boiler inlet, was opened, the subcooled liquid mercury was squirted into the hot boiler. Injection flow rate was controlled by the position of the valve. Several injection flow rates were investigated. These flow rates were 10, 13 and 21 lb/min. A choked nozzle was used to simulate the normal boiler exit condition, i. e., CRU turbine nozzle. After passing through the nozzle the vapor was condensed, thus completing the flow loop.

Two CRU-III units were tested during the current reporting period. The first unit, CRU-III-1D, rotated a total of 1 hr and 22 min without achieving design operating conditions. This test was discontinued upon observation of a large

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decrease in turbine bearing lubricant pressure. The second unit tested, CRU-III-3B, operated a total of 235 hr, (the last 140 hr continuous, at 40,000 rpm, 1000°F NaK temperature, 115 psia turbine mercury inlet pressure) at which time an alternator bearing failure occurred.

Developmental two-phase alternators have achieved 87% efficiency in 700°F mercury environment at 40,000 rpm. This exceeds the 84% objective. The alternator stator sealing problem appears to be solved by use of the interlaminar glass coating and the glass-lined bore tube. Several CRU-IV type alternator stators have been hot performance tested and leak tested with acceptable results.

Design and fabrication of the S-2-PSM-1 system test are proceeding on schedule. Building 032 which will contain the system test is scheduled for completion in August 1961. The APU vacuum tank is presently in fabrication and is scheduled for delivery early in July 1961. The fabrication of the honeycomb steel tube radiator-condenser is on schedule and due for delivery September 1961. The NaK system components, which include the electrical heater to simulate the reactor, the ground startup heater, the expansion compensator, and the simulated orbital startup pump, are on schedule. The simulated reactor is in fabrication and will be completed in July 1961. The ground startup heater and the expansion compensator are being tested. Design drawings are being prepared for the simulated orbital startup pump and fabrication will be initiated in July 1961. The NaK system piping materials have been received and fabrication will be initiated in July 1961. The NaK loading system, which includes a vacuum system and NaK cleanup system, is completed and has been tested. The APU load ring and the simulated reactor support structure are being fabricated. Delivery of the load ring is expected in August 1961. Delivery of the support structure will be in the latter part of July 1961.

The delivery of the power conversion system (PCS) from TRW is presently scheduled for September 1961. The boiler has been coiled and fabricated and is currently being leak tested. Assembly of the boiler into the PCS support structure will take place in July. Boiler injection studies will be initiated in July 1961. These tests are scheduled for approximately two weeks duration and upon completion a CRU-III unit will be installed into the PCS. Testing of the PCS will occur at TRW until delivery to AI in September 1961. The breadboard mercury injection components which will accompany the PCS are presently in fabrication

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at TRW. The mercury loading system which will be used at AI is being fabricated. The majority of the NaK and mercury instrumentation has been received. This includes both primary elements and readout equipment. Assembly of the instrument racks will be initiated early in July 1961. The electrical control system to simulate the reactor control for the electrical heater is currently being procured and is scheduled for delivery in August 1961. The analog computer for this control system has been received. The electrical installation drawings for the system test are being prepared.

The use of a thermally insulated low temperature ($< 200^{\circ}\text{F}$) region at the bottom of the APU to house the required control and instrumentation equipment is being investigated and has been found to be feasible. Heat could be dissipated by means of the base ring. This region would house the following equipment; parasitic load controller, APU startup programmer, telemetry signal conditioning equipment, safety circuitry, and reactor temperature control system.

Preliminary discussions with LMSC on telemetry equipment have succeeded in defining the preliminary requirements of a suitable telemetry system for SNAPSHOT.

An investigation of available startup programming equipment has indicated that state-of-the-art equipment is available for flight application. A flexible programmer is being procured and evaluated for PSM-1.

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II. PIPING AND INSTRUMENTATION DIAGRAM (Figure 1)

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III. FLIGHT SYSTEM CONFIGURATION

A system configuration was selected based on system and component weight optimization studies carried out during the report period (see Figure 2). The resulting package parameters are as follows:

180 in. total system length
Current 1509 lb total system weight
135 ft² radiator area

The above items completely define the system envelope allowing the more detailed studies contingent upon their selection to proceed. A preliminary design was completed for the APU in order to assign configuration influence to the individual components or subassemblies. Those items that were large variables in weight or geometry were then optimized individually based on their own intrinsic requirements. Items that proved to be major variables are as follows:

1. Radiator-Condenser (R/C) Area and Configuration. - Weight versus required area was plotted for the design point using the obtainable values for fin effectiveness, emissivities, structure, and manufacturing feasibility. Honeycomb copper fin R/C values were used for the investigation.

The minimum weight on optimum R/C varies from 130 to 140 ft² of radiator and weighs 240 to 250 lb.

2. Shield and Containment Vessel. - Primary shield weight was calculated versus separation distance. Scatter shield weights were plotted in terms of increasing the R/C upper header diameter, this being the major method used to increase R/C area for a given package height.

Weight of the primary shield varied from a minimum of 375 lb to a maximum of 480 lb for the separation distances considered (12 ft to 17 ft-6 in.). The weight penalty of a scatter shield for an increasing R/C header diameter for a fixed length was so severe that this concept was dropped. Increasing total APU length to achieve optimum R/C area proved to be the lightest weight approach.

The shield containment vessel weight was calculated for increasing diameter as above.

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4. SHIELD DIMENSIONS ARE SHIELDING MATERIAL ONLY

Figure 2. Flight System Configuration

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3. Nose Cone. - Though not a weight problem, the nose cone geometry was set by the design of the upper APU. Safety and startup sequences were adopted in order to set component requirements. Destruct charges, piping, ejection mechanisms, etc., were integrated with the reactor-reflector control assembly and a nose cone envelope developed.

All other components proved small enough in weight and/or constant enough in geometry to essentially carry them as constants for the compilation of selection data.

The individual parametric criteria for the large variables plus the constants were then plotted for total system weight versus R/C area for various fixed package heights. Selection of the optimum system was made from this data.

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IV. SYSTEM WEIGHT BREAKDOWN

System weights have been obtained from the studies described in Section III and are shown in Table I. Weights are presented as the current design, SNAPSHOT objectives, and the operational weight objectives that can be achieved after the SNAPSHOT program. An explanation of the current design basis for the weights is included to assign a confidence level to them.

TABLE I
SNAP 2 WEIGHT TABLE

	Current Design Weight (lb)	SNAPSHOT Weight Objectives (lb)	Operational Weight Objectives (lb)	Current Status
Reactor assembly (NaK wet)	156	148	130	Detail design
Reflector-controls assembly	137	110	110	Conceptual design
Piping (NaK wet)	23	20	20	Conceptual design
Startup pump (NaK wet)	26	18	18	Conceptual design
Heater (NaK wet)	10	8	8	Preliminary design
Expansion compensator (NaK wet)	22	14	14	Preliminary design
Boiler (NaK wet, Hg dry)	100	85	70	Preliminary design
CRU and auxiliaries (NaK wet, Hg dry)	52	45	45	Preliminary design
Radiator-condenser (dry)	250	220	190	Preliminary design
Startup system (hardware only, dry)	84	70	62	Conceptual design
Hg inventory	90	75	70	Conceptual design
PCS controls and instrumentation	55	45	40	Estimate
System instrumentation, wiring, insulation	40	37	30	Estimate
Diagnostic instrumentation	50	50	0	Estimate
Structures	66	55	50	Preliminary design
Shield assembly	338	290	200	Preliminary design
Destruct device	10	10	7	Estimate
Contingency	0	50	-	-
TOTALS	1509	1350	1064	

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V. SYSTEM ANALYSIS

A. CURRENT DESIGN POINT

The design point is a listing of system parameters which reflect the best estimates of component performance and which are obtained from weight-reduction analysis. The current design point shall be considered the specifications for future test systems and the flight system, pending later revision.

The bases for the current design point are the following estimates of CRU component efficiencies and APU power requirements:

Component Efficiencies

Alternator	0.84
Turbine	0.53
NaK pump	0.024
Mercury pump	0.50

Electrical Power Requirements

Payload*	3.0 kwe
CRU speed control	0.1 kwe
Telemetry and reactor control	0.1 kwe
System degradation	<u>0.3 kwe</u>
Total alternator output	3.5 kwe

The major component duty requirements are:

Turbine output*	5.79 kwm
Reactor power*	55.1 kwt
Boiler heat transfer	50.9 kwt
Radiator condenser heat rejection	50.6 kwt

The overall efficiency from core thermal power to payload electrical power is 5.44%.

*Subscripts e, m, and t represent electrical, mechanical, and thermal respectively.

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The design point system operating conditions are:

Reactor

Inlet NaK temperature	1000°F
Outlet NaK temperature	1200°F
Flow	72 lb/min
Pressure in core	30 psia

Turbine

Inlet temperature	1150°F
Inlet pressure (total)	115 psia
Outlet temperature	610 °F
Outlet pressure (total)	7.7 psia
Total turbine flow	20 lb/min
Leaving moisture	3% liquid

Boiler

Mercury inlet temperature	486°F
Mercury outlet temperature	1150°F
Mercury inlet pressure	200 psia
Mercury outlet pressure	115 psia
NaK inlet temperature	1199°F
NaK outlet temperature	998°F

Radiator Condenser

Mercury condensing temperature	600°F
Mercury outlet temperature (mean at pump suction)	375°F
Outlet pressure (pump suction head)	6.5 psia

B. EVALUATION OF PROGRESS

The following is a listing of the more significant changes in design point parameters during the report period.

	<u>Last Design Point</u>	<u>Recent Design Point</u>
NaK pump efficiency	0.020	0.024
NaK pump ΔP (psi)	3.0	3.7
Mercury pump efficiency	0.25	0.50

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	<u>Last Design Point</u>	<u>Recent Design Point</u>
Mercury pump ΔP (psi)	414	364
Turbine seal leakage:		
To bearings (lb/min)	0	0.2
To exhaust scroll (lb/min)	0	0.4
Bearing lubricant flow (lb/min)	15	17
Bearing coolant preheat (kw)	0	0.52
Primary loop heat losses:		
To condenser (kw)	4.0	3.0
Turbine power requirement (kw)	5.94	5.79
Radiator condenser duty (kw)	53.4	50.6

The most probable areas subject to future revision are the following:

1. NaK Pump. - An alternate design will be required if the present pump diaphragm cannot withstand the NaK transients during startup. Changes in pump efficiency and the design point would logically ensue.
2. Reactor Power and Radiator-Condenser Duty. - Either of these quantities may require revision depending upon the disposition of heat from the parasitic load control equipment. The three alternatives are to a) exhaust the heat directly to space, b) exhaust the heat to the radiator-condenser, c) or dissipate the heat in the primary loop. Failure to achieve a 53% turbine efficiency would result in upward revision of each of these quantities.
3. Primary Loop Heat Losses. - These losses are presently based on an assumed piping arrangement and a low-emissivity coating whose emittance has not been tested. More accurate predictions will follow as more information is obtained.

C. ORBITAL STARTUP

Considerable progress has been made during this reporting period on selection and analysis of a SNAP 2 flight startup method. An analog computer simulation of the SNAP 2 primary loop, i. e., reactor, piping, boiler, and pump, was used to study the startup drum rates, required NaK flow rate, reactor

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source requirement, and overall preheating transients. The results of this simulation have been analyzed and have yielded the following ranges for various operating parameters:

Startup drum rate	0.01°/sec
Control drum rate	0.01 to 0.05°/sec
Source power	0 to 10^{-5} watts
Startup flow rate	8 to 15 lb/min

The reason for a range in rates is to cover two possible startup concepts. A choice between dual injection and insulated radiator-condenser technique is to be made on the basis of NaK freezing requirement, power for startup, startup time, and system weight. A major problem area is the temperature transient limitations of the CRU NaK pump diaphragm. The analog simulation showed that a maximum rate of 300°F/hr during primary loop preheating is unacceptable. The pump capability is being re-investigated.

Analysis of the S-2-PSM-1 startup requirements have been completed. Recommendations were made on changes in the piping and valving configuration which would give added flexibility during startup studies. Writing of specific S-2-PSM-1 tests has been initiated. All startup test writing will be completed during the next reporting period.

Initial once-through boiler injection experiments were completed at the Thompson Ramo Wooldridge (TRW) facility. The results have essentially proved the feasibility of mercury injection startups. However, due to length and mass differences between the boiler tested (PCS-I) and the PCS-II flight boiler, additional injections are planned for July 1961 on the PCS-II boiler.

D. CONTROL AND SIMULATION ANALYSIS

Analysis has been completed on analog computer data obtained to determine reactor long-term control requirements. Both unilateral and bilateral control systems were studied. Which of these two types will be employed will depend on whether the parasitic load power is dissipated to space or back into the primary system. Full 3-kw dissipation into this primary loop will cause a 12°F NaK temperature rise. In this case bilateral control will be used. When a control drum with a worth of 4¢/mechanical degree characteristic is considered,

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with bilateral control the step size will be 1° and the resulting reactor temperature will be in the range of $1220 \pm 20^\circ\text{F}$. In the second case where parasitic load power is not dissipated in the primary coolant, unilateral control will be used with temperature control between 1200 and 1220°F . Following are the results of the long-term control study:

	<u>Unilateral</u>	<u>Bilateral</u>
Temperature band	1200 to 1220°F	$1220 \pm 20^\circ\text{F}$
Drum step size ($\$2.50$ drum)	1°	1°
Reactivity step size ($\$2.50$ drum)	4¢ max	4¢ max
Time dead band	20 sec	300 sec

Initial work has been completed on construction of a complete SNAP 2 system mathematical model. This will allow computer startup studies to be made. The latest flight-type components are being simulated.

A simple but accurate reactor kinetics code has been completed. This code has proved valuable in specific digital computer startup studies. An objective has been set to develop a complete SNAP 2 system digital code. The reactor, boiler, and primary loop models have been completed.

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VI. COMPONENT DEVELOPMENT PROGRESS

A. RADIATOR-CONDENSER

1. Design Status

Two design concepts are being actively pursued for the SNAP 2 radiator-condenser: (1) copper-clad steel honeycomb-steel tubes, and (2) aluminum shell-steel tubes. In the honeycomb concept, four panels are formed into a conical assembly. The tubes are included within the steel sandwich, and the copper is brazed onto the outer surface. Feasibility of this concept was proven by fabricating successfully a representative 20-in. by 40-in. panel, including tubing and manifold weld joints, at the North American Aviation, Inc. Los Angeles Division. The design control drawing for the S-2-PSM-1 radiator-condenser has been released and detail shop drawings have been completed by the fabricator. A reference design for a minimum weight honeycomb unit, including tapered fins and tubing, has also been completed. A drawing has been released for the second concept, which consists of a smooth aluminum skin with tapered steel tubes brazed to the inner surface. An important feature of this design is the incorporation of a diffusion barrier between the steel and aluminum to prevent the formation of a brittle intermetallic compound. A reference design of a beryllium shell-steel tube concept has been initiated as a result of the weight optimization studies.

2. Weight Reduction Program

Weight optimization studies have shown that weight reduction can be achieved in the copper-clad steel honeycomb shell concept by increasing the area over that selected for the first honeycomb design, which decreases the required fin thickness and number of tubes. The use of tapered fins significantly reduces the copper weight, while a reduction of tube cross-sectional area in the subcooler region lowers the required liquid mercury inventory. Individual copper fins have been tapered successfully by the chemical milling process, and preliminary tooling layouts have been completed for the production of shaped tubing. The fabrication feasibility of replacing the copper with aluminum or beryllium fins on the honeycomb is also being investigated. Beryllium brazing experiments have been initiated since extensive optimization studies

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have shown that the minimum weight radiator-condenser will be obtained with the use of a beryllium shell which can satisfy the heat transfer, structural, and meteoroid protection requirements.

3. Overall Thermal and Structural Performance

Calculation of the expected performance of the S-2-PSM-1 radiator-condenser indicates that 106 ft² of radiating area will be required to condense the mercury vapor flow. The remaining 4 ft² of subcooler area will reduce the mercury temperature by 100°F, providing an outlet temperature of 500°F. S-2-PSM-1 employs a CRU-III rather than the flight CRU-IV. Primary loop heat losses are also slightly higher than will occur in the flight system. Structural design loads can be carried by the 1/4-in. cell, 1-mil ribbon, and 5/16-in. thick honeycomb core with 0.005-in. facing sheets. A fin effectiveness of 0.97 was selected for the aluminum shell-steel tubes radiator-condenser, resulting in 0.063-in. aluminum fin thickness and 60 tubes. Boost phase loads are carried mainly by the tapered steel tubes with 0.010-in. wall thickness at the top and 0.025-in. wall thickness at the bottom, supported by the aluminum skin and circumferential frames.

4. Fabrication Status

The fabrication purchase order for the S-2-PSM-1 honeycomb radiator-condenser was awarded to Rohr Aircraft Corporation in April 1961. Brazing experiments and subsequent corrosion tests have been conducted to verify the selection of braze alloys and brazing cycle to be used. Weld specimens have been completed which are typical of the tube-to-vapor manifold and tube-to-liquid manifold joints. All the tooling has been completed, and sufficient detail parts have been fabricated to permit the first quadrant to be prepared for the brazing operation. This fabrication included successful tube bending, explosive-forming and swaging operations on thin wall tubing, welding of tubes and liquid manifold with control of critical dimensions, helium leak test results within specification, honeycomb core machining, and lay-up of the panel assembly. Brazing will be initiated early in July. The final proposal for fabrication of the aluminum shell radiator-condenser has been evaluated, and processing of a purchase order has been started. Brazing experiments which joined aluminum sheet to steel tubes were conducted to verify the proposed manufacturing method.

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5. Test Programs

The copper-clad steel honeycomb radiator-condenser will be assembled directly into the S-2-PSM-1 test in September 1961. Thermal performance and startup characteristics will be evaluated. A radiator-condenser test loop is also being assembled so that the component thermal characteristics may be studied in more detail under varying load conditions. Both tests will be conducted in a vacuum environment. Emittance measurements on various coatings for the radiator surface are being made under vacuum conditions at operating temperature so that accurate values can be independently established. Figure 3 is a plot of the condition for maximum heat rejection versus the solar absorptance with the resulting curves being lines of constant total hemispherical emittance.

In the "tailored" coating formulation and development program, emphasis has been placed on obtaining extremely durable coatings. Coatings such as paints, enamels, and various organics have undergone examination; however, the major portion of the developmental effort is on ceramic-type coatings. Coating development is being directed toward maximum attainable thermal effectiveness.

Point One on Figure 3 depicts the long-term desired "tailored" coating for the SNAP series of radiators. The requirements for this coating are a total hemispherical emittance of 0.90 and a solar absorptance of 0.20. However coatings of equivalent thermal effectiveness would also be acceptable. Point Two depicts the coating developed at the start of the program, while Point Three depicts the best "to date" obtained. This last coating has a total hemispherical emittance of 0.83 and a solar absorptance of 0.20.

In another test program, thermal conductivities of composite radiator shells are being established.

B. FLUID SYSTEM DEVELOPMENT

The objectives of the fluid system testing program are to develop components integral to the liquid metal coolant system and provide general liquid metal coolant technology to the overall SNAP 2 project.

To date, a compact lightweight heater has been developed and successfully tested. A void-free expansion compensator has also been designed and tested

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Figure 3. Maximum Heat Rejection vs Solar Absorptance

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which meets all system requirements. A mockup of the primary system (PST) has been fabricated and testing initiated to establish NaK loading and cleanup procedures and generally evaluate the present primary system configuration.

1. Compact Heater Development

The flight-type compact heater has been designed, fabricated, and tested. This unit is to provide simulated reactor heat generation in the primary system (~56 kw) to permit checkout at rated load of the entire power conversion unit. The heater weighs 10 lb fully loaded with NaK and measures 9 in. in length and 4-1/4 in. in diameter. Fourteen cartridge-type resistance element electrical heaters placed in an annulus comprise the heating section. The unit operates at a heat flux of 150,000 Btu/hr-ft² at 56 kw. A continuous power run at 56 kw for 130 hr was achieved. Total life including cyclic time at 56 kw was 165 hr.

2. Expansion Compensator

An expansion compensator designed to absorb 1.5 ft³ of NaK-78 expanding from 0 to 1100°F has been designed and tested. This unit consists of 58 welded bellow discs, 12 in. in diameter. The entire assembly is enclosed in a gas pressurized container which provides the overpressure system control and can adequately serve as meteoroid protection. This unit, with flight-type mountings, will weigh 20 lb loaded with NaK. Successful operation of this unit has been demonstrated in the Primary System Test loop.

3. Primary System Test (PST) Loop

This loop consists of a reactor and boiler mockup (volume and ΔP simulators), compact heater, CRU NaK pump, expansion compensator, and associated piping and instrumentation. Auxiliary equipment consists of a mobile coolant loading and cleanup system, and portable electric seam-welding equipment for system closure.

To date, the following have been successfully tested and evaluated:

- a) NaK coolant loading, cleanup, and handling procedures for flight-type systems.
- b) System closure to eliminate all voids in the coolant.
- c) Operation of the CRU NaK pump in the primary system.
- d) Expansion compensator performance in a system.

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e) System pressure drops.

f) Compact heater performance in the primary system.

C. COMBINED ROTATING UNIT (CRU)

1. Testing of CRU-III's

Two CRU-III units were tested during the reporting period. The first unit, CRU-III-ID, rotated a total of 1 hr and 22 min. Before design operating conditions were reached this test was discontinued upon observation of a large decrease in turbine bearing lubricant pressure. The second unit tested, CRU-III-3B, operated a total of 235 hr, (the last 140 hr continuous at 40,000 rpm, 1000°F NaK temperature, 115 psia turbine mercury inlet pressure), at which time an alternator bearing failure occurred. Detailed discussions of these two tests are given below.

a. CRU-III-ID

This unit was fitted with a "plain" journal bearing on the alternator end and a three-sector journal bearing on the turbine end, each with diametral clearances of 0.002 in. and 0.00195 in. respectively. It was operated on April 25, 1961 in the performance test rig for a total of approximately 1 hr and 22 min. The speed did not increase evenly above 25,000 rpm although a maximum of 35,000 rpm was attained. The lubricant pressure on the turbine bearing registered a drop from 83 psia to 63 psia in 5 min and a further drop to 43 psia in 8 more min. At this time the test was stopped and the CRU removed for inspection of the turbine bearing. There was little evidence on the Sanborn recorder data of an internal rub. Examination of the unit showed 0.0010- to 0.0015-in. deep scoring on the turbine journal, some scoring on the turbine bearing housing, and some uneven pitting on the alternator bearing journal (see Figure 4). Final diagnosis was that the turbine bearing pedestal had distorted creating misalignment of the bearing. This distortion was caused by excessive press fit developed from the high temperature operation of the NaK pump housing.

b. CRU-III-3B-2

The CRU-III-3 unit, after its 2-1/2 sec test in PCS-I-IB-1 during which failure occurred due to foreign particle scoring and locking of the labyrinth

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A. Turbine Journal
Bearing

B. Turbine Bearing
Bushing and
Pedestal

C. Alternator Journal
Bearing

Figure 4. CRU-III-1D Bearing Failure

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seal of the shaft nut, was modified to include changes indicated by the analysis of test CRU-III-ID discussed above. These modifications included:

- 1) The unit was equipped with a new spiral-type thrust bearing and two 3-sector journal bearings.
- 2) The diametral clearance on the turbine bearing was decreased from 0.00195 in. to 0.0016-0.0018 in. to provide increased load-carrying capacity.
- 3) The shrink fit of the turbine bearing into the pedestal was increased by 0.0002 in. to ensure that no mercury lubricant would leak past this point (preventing a reduction in lubricant flow to the bearing).
- 4) The NaK housing fit to the bearing pedestal was changed so that distortion of the bearing pedestal would not take place at operating temperature due to the shrink-fit effects.
- 5) The complete shaft rotating assembly was temperature-soaked at 950°F for 8 hr to ensure dimensional stability.
- 6) A new startup procedure was initiated with the use of cold gas to include complete checkout of the CRU-III configuration and to provide for a comparison of bearing data from the free running rig with CRU data at various speeds. To help accomplish this, cold (400°F) NaK was used to keep the NaK pump diaphragm from overheating.

This unit was assembled in the performance test rig and the cold gas tests conducted May 25, 1961 as test CRU-III-3B-1. The CRU-III-3B-2 hot gas tests in the clamped configuration began May 31, 1961. Between then and 1800 June 17, 1961 a total of 235 hr of operation, including 140 hr continuous, at 40,000 rpm, 1000°F NaK, and 115 psia turbine inlet mercury pressure was obtained. Four test interruptions, chargeable to breakdowns in the performance test rig equipment, occurred during this period. Three were due to the Lapp pumps (see test rig status) and one to burnout of the solenoid in the turbine power mercury supply valve. No evidence of decay in the CRU performance was observed prior to the stoppage. On disassembly, one-half of the bearing

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sleeve, originally in the housing pedestal, was found to be welded to the sleeve on the shaft. Analysis is in process to determine the primary cause of failure.

2. Fabrication Status of CRU's as of June 30, 1961

Five CRU-III units are currently in various stages of rework and re-assembly. All have had some test time and are being reworked to repair test damage and/or to incorporate component changes based on the findings of test analyses. Fabrication of two CRU-IV units has been started. Procurement of long-lead-time elements is proceeding. A detailed summary of the status of each unit follows. (Note that the letter at the end of the number indicates the next test designation for that unit.)

a. Fabrication Status of CRU-III's

CRU-III-1E: Rework is 95% complete. This unit will have two 3-sector journal bearings and a spiral thrust bearing. A No. 7 pump with 0.370-in. diameter impeller and a 0.335-in. diameter spare impeller will be furnished. This unit is scheduled to be used as an S-2-DS spare.

CRU-III-2C: Assembly is 85% complete. Reweld capability is limited due to stock removed from the weld flanges during repeated disassemblies. This unit will have two 3-sector journal bearings and a spiral thrust bearing. A No. 7 pump with 0.335-in. diameter impeller will be used. This unit is scheduled for TRW endurance testing.

CRU-III-3: This unit failed June 17, 1961 in test CRU-III-3B. A detailed analysis of the alternator bearing region is under way to pinpoint cause of failure. The unit had two 3-sector journal bearings and a spiral thrust bearing and No. 7 0.335-in. diameter pump. When reworked it will be used as CRU-III-3C, a TRW endurance test spare.

CRU-III-4B: This unit has two 3-sector journal bearings and a spiral thrust bearing and No. 7 0.335-in. diameter impeller on the Hg pump. It has been cold gas tested and is waiting insertion into PCS-I-1 for acceptance test in the endurance test rig. It will then be sent from TRW to Atomics International for inclusion in PCS-I-2, the power conversion system in S-2-DS (SNAP 2 Development System).

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CRU-III-5B: Rework is 80% complete. This unit is to have the same bearings and Hg pump as CRU-III-1E. It will be integrated into PCS-II-1 for acceptance testing prior to PCS-II-1 delivery to Atomics International for S-2-PSM-1.

b. Fabrication Status of CRU-IV's

Ten sets of castings have been ordered. All the exhaust and inlet scroll castings have been received. Only two alternator housing castings have been found satisfactory. Rolled blading for two units has been received.

CRU-IV-0: These are twin units, fabrication is 45% complete. Two 3-sector
CRU-IV-1: journals, a spiral thrust bearing, and a No. 7 pump with 0.370-in. diameter impeller will be used. These incorporate the special turbine instrumentation and an enlarged turbine interstage collector. One unit will be installed in the performance test rig for evaluation with the second as a spare or backup.

3. Test Rig Status

Two major facilities (the performance and endurance test rigs) have been available for previous CRU testing. A third installation, the acceptance test rig, is currently being completed. The purpose and status of these facilities is as follows:

a. Performance Test Rig

This is the original test rig. It is instrumented to obtain the maximum test data and to provide the greatest flexibility in services. It has been the site of many hours of test operation and has been greatly modified during the past year. Some of its components may be of doubtful reliability over a very long test. It is used to obtain operational characteristics and for development work. The new high-temperature Chem pump is being installed, and work should be completed by August 13, 1961. It is expected that this equipment will avoid the shutdowns caused by the frequent failures of the Lapp mercury pumps.

Flowmeters and pressure gages are being recalibrated. Individual filters are being added in each bearing supply line just upstream of the CRU. Pressure gages are being added to read the pressure downstream of these filters.

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b. Endurance Test Rig

This test rig is equipped to provide the necessary instrumentation and dependable services for long-duration testing. Additional equipment is being added so that it may be used as a secondary performance test rig where the range of parameters desired is not too great. Recent changes include:

- 1) Auxiliary Hg system and liquid level equipment have been installed.
- 2) The Computrans have been removed and Statham differential pressure flowmetering equipment installed.
- 3) A Cox flowmeter has been installed in the bearing lube line.
- 4) Test rig preparation for the next PCS-I-1 test included filling and checking out the NaK loop and calibrating the NaK instrumentation.

The PCS-I-1 boiler tests are now being conducted but continuing difficulties in conditioning this boiler are delaying the installation of CRU-III-4B.

c. Acceptance Test Rig

This test rig is intended to ascertain overall system performance during acceptance testing and thus does not have the capability to provide detailed component performance.

Installation and checkout of instrumentation is continuing on the acceptance test rig. The PCS mockup was used to facilitate the installation of this instrumentation. The NaK- ΔP system has been satisfactorily checked out. Wiring and checkout of the console instrumentation is approximately 90% complete. Auxiliary system heaters and all cooling water plumbing are installed. Mercury plumbing and auxiliary system gage lines have been cleaned. The PCS-II-1 boiler and support structure assembly has recently replaced the PCS mockup. Connection of PCS-II-1 into this test rig is beginning.

Boiler injection tests will be conducted on the PCS-II-1 boiler in this rig, following which the CRU-III-5 will be assembled in this PCS-(II-1) and an acceptance test performed on the complete unit before shipment to Atomics International for PSM-I testing.

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4. Subcomponent Development

There are five major subcomponent development areas related to the CRU. There are a) alternator, b) bearings, c) mercury pump, d) NaK pump, and e) turbine. Each of these has been the subject of much effort during the current reporting period. The mercury pump and the alternator are in relatively good developmental status. The bearing effort has produced excellent performing units under the cold gas conditions but the designs continue to be susceptible to fouling by "foreign particles" in the CRU under operating conditions. It is extremely difficult to pinpoint the source of these particles to any of the following sources: the test rig; the welding of the assembly; wear of components of the CRU; or "crud" produced by the action of hot mercury upon its contact surfaces possibly augmented by the two regions of rotating magnet flux. This makes it important that the hot bearing test rigs be completed during the next reporting period and tests therein started. The NaK pump while necessarily a low efficiency component is achieving its performance design objectives. However, its requisite configuration results in system startup problems due to the 300°F/hr heating rate limitation on the pump diaphragm. The small clearance between the rotor and the diaphragm limits the amount of thermal dimensional change, and the current maximum heating rate, established to prevent diaphragm distortion, severely restricts the speed of warm-up of the NaK system. This delays the start of rotation, during which time the entire rotating portion of the CRU soaks up heat and expands, further reducing clearances. The CRU-III turbine design has developed 47% at 4700-w output. The CRU-IV turbine design with an improved u/c speed ratio, improved inlet and exhaust scrolls, increased solidity, partial admission, convergent-divergent nozzles, and greater inner-stage dispersion volume is calculated to produce 6000-w output at 53% efficiency. Test data verification will not be available until approximately September 1961 based on current schedules. A separate detailed discussion of each component follows:

a. Alternator Development

Developmental two-phase alternators have achieved 87% efficiency in 700°F mercury environment at 40,000 rpm. This exceeds the 84% objective substantially. The alternator stator sealing problem appears to be solved by use of the interlaminar glass coating and the glass-lined bore tube. Several

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CRU-IV type alternator stators have been hot performance tested and leak tested with acceptable results. Some difficulties are being encountered in the procurement of satisfactory high temperature connectors for the CRU-IV design. Several models from several vendors are being evaluated. Tests to determine the stator thermal shock capability have shown no serious effects. A satisfactory hot spin test of a CRU-IV type alternator rotor has been made. A new test fixture has been built in which rotor pole symmetry studies are being made to attempt to reduce magnetic imbalance.

Various combinations of parasitic load and output power were tested over the full output power range and total harmonic content varied from 3.5 to 6% which is within the 7% objective.

A second dynamometer facility is being constructed.

b. Bearing Development

(1) Problem Areas

A chart is attached showing the "CRU Test Results as Related to Bearings" to date (see Table II). A study of the test results shows five general areas of bearing problems.

- a) A reasonable thermal environment must be provided to the bearings in order to prevent excessive vaporization of the mercury lubricant and avoid large temperature differentials in the bearing area which have adverse effects on bearing running clearances.
- b) Dirt particles from fabrication and rework of the system must be prevented from entering the relatively small clearances of the bearing while operating.
- c) The bearing configuration must be capable of supporting the CRU loads and simultaneously provide maximum resistance to bearing instability or whirl.
- d) The bearing configuration and materials must be designed to eliminate erosion type damage caused principally by vaporization and bubble collapse in the bearing annulus.

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TABLE II
CRU TEST RESULTS RELATED TO BEARINGS

Unit	Test No.	Test Date	Duration	Assembly	Facility	Bearing Type			Bearing Clearance			Results
						Thrust	Alt	Turb	Thrust	Alt	Turb	
CRU-I	7 tests	8/3/59 to 5/30/60	488 hr 29 min	clamped	perf	step	plain	plain		0.002	0.002	Bearing rust caused inability to start on one test -- no other bearing problems
CRU-II-1	6 tests	11/2/59 to 7/9/60	36 hr 39 min	clamped	perf	step	plain	plain		0.002	0.002	No bearing failure
CRU II-2	2 tests	4/26/60 5/4/60	9 hr 5 min	clamped	perf	step	pad	pad		0.001	0.001	No bearing failure
CRU-III-1	CRU-III-1-1	8/16/60	0	clamped	perf	step	pad	pad		0.001	0.001	No test - NaK pump distortion
CRU-III-2	CRU-III-2	9/26/60	5.3 min	welded	PCS-2-1-1	step	pad	pad		0.001	0.001	Loss of bearing clearance thru thermal expansion
CRU-III-1	CRU-III-1A-1	10/18/60	4 hr 31 min	clamped	perf	step	pad	pad		0.001	0.0017	Turbine bearing-failure-high rotating load thermal problem, whirl, distortion
CRU-III-2	CRU-III-2A	10/26/60	10 sec	welded	PCS-I-1A-1	step	pad	pad		0.001	0.0017	Chip in thrust bearing
CRU-III-1	CRU-III-1C-1	11/30/60	1 hr 30 min	clamped	perf	step	pad	plain		0.001	0.0017	Alternator bearing failure after 100 hours
	CRU-III-1C-2	12/1/60	79 hr 25 min									
	CRU-III-1C-3	12/7/60	26 hr 55 min									
CRU-III-3	CRU-III-3A	1/5/61	2.5 sec	welded	PCS-1-1B	step	plain	plain		0.002	0.0017	Chip in high pressure labyrinth
CRU-III-2	CRU-III-2B-1	1/16/61	517 hr	clamped	perf	step	plain	plain		0.002	0.0017	500 hour qualification test plus 60 hrs. at reduced bearing flow - erosion damage
	CRU-III-2B-2	2/9/61	71 hr									
CRU-III-4	CRU-III-4A	3/7/61	2 hr 20 min	clamped	perf	step	plain	plain		0.002	0.0021	Labyrinth seal rub seizure damage all 3 bearings alt brg both shaft and Bushing badly scuffed not welded, turbine brg lightly welded heavy 0.004-0.005 wear ridges. Thrust bearing scored on alt bearing side.
CRU-III-5	CRU-III-5A	3/31/61	2 hr 21 min	welded	PCS-1	step	plain	plain		0.002	0.0024	Bearing wear both journal bearings
CRU-III-1	CRU-III-1D-1	4/25/61	1 hr 22 min	clamped	perf	step	plain	sector		0.002	0.0019	Bearing wear - scoring on turbine brg shaft -21 and bushing and alt brg turbine bearing pedestal distortion probable chief cause
CRU-III-3	CRU-III-3B-1	5/25/61	6.8 hr cold gas test	clamped	perf	spiral	sector	sector		0.0016	0.0016	Cold gas satisfactory alternator
	CRU-III-3B-2	5/31/61 to 6/17/61	235 hr at des cond									
CRU-III-4	CRU-III-4B			clamped	endurance	spiral	sector	sector		0.0016	0.0016	Cold gas tested. Awaiting installation in endurance rig
CRU-III-1	CRU-III-1E					spiral	sector	sector		0.0016	0.0016	Not tested - Being reworked - 95% complete
CRU-III-2	CRU-III-2C					spiral	sector	sector		0.0016	0.0016	Not tested - Assembly is 85% complete
CRU-III-5	CRU-III-5B					spiral	sector	sector		0.0016	0.0016	Not tested - Being reworked 80% complete

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- e) Bearing alignment must be maintained and thermal distortion reduced in order to insure the required operating bearing clearances.

(2) Modifications

All bearing problems encountered to date have occurred as result of one or a combination of the above factors. Initial CRU-III-1 and -III-2 tests were unsuccessful because of excessive heat in the turbine bearing area. The excessive heat input was decreased by several modifications to the CRU which have been successfully accomplished. These modifications include the following:

- a) A decrease in the heat loss of the NaK pump by increasing the clearance around the NaK pump rotor.
- b) An increase in the thermal resistance between NaK pump housing and the bearing by decreasing housing wall thicknesses.
- c) A decrease in turbine heat input by an improved labyrinth seal design.
- d) Modification of the turbine labyrinth seal configuration to prevent hot vapor from impinging in the bearing area.
- e) A decrease in the heat transfer to the shaft from the NaK rotor by incorporation of a hollow shaft in the bearing area.
- f) Modification of the NaK pump rotor to reduce heat input from the rotor to the bearing.

These improvements were accomplished in steps because of fabrication lead times. They did, however, lead to the successful operation of CRU-III-1 for 100 hr (December 1960) and CRU-III-2 for 560 hr (January 1961).

Installation and removal of CRU's from the PCS using Haynes tubing has resulted in the need for appreciable grinding on the tubing of the system in order to remove the CRU. As a result of this grinding operation, particles the size of cigarette ash have been introduced into the system and caused bearing failures in tests of the CRU-III-2 unit in the PCS-I. A similar problem was evidenced in the test of CRU-III-3 where a chip in the high pressure

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labyrinth seal caused a rub. This problem was alleviated by extensive modifications of the PCS which incorporated disconnect flanges to prevent chips from entering the system. These specially designed flanges are bolted together and seal welds are placed external to the bolt rings. Recent tests in the PCS would indicate that this problem has been alleviated by the modification steps taken. The last two tests of CRU-III-4 and CRU-III-5 have indicated a bearing rub and wear problem. This bearing shortcoming has resulted from large bearing clearances required to reduce bearing supply pressure so that it will be compatible with pump discharge pressures that are available. Increased bearing clearances result in a decreased load-carrying ability and an increased tendency for the bearing to become unstable or to whirl. An improved bearing configuration is desired to simultaneously avoid the whirl problem while allowing high radial load capacity and large clearances in the bearing annulus. Large clearances are particularly desirable in order to allow the bearing to operate with modest quantities of thermal distortion and reasonable particle tolerances in the mercury system.

Erosion damage in bearings has been observed in tests of the CRU-III-1, 100-hr test, and CRU-III-2, 560-hr test. This damage is caused by the formation of vapor on the low pressure unloaded portion of the bearing. The vapor upon entering a high pressure area in the bearing collapses and provides a liquid mercury impact to the bearing surfaces, resulting in damage to these surfaces. The damage can be avoided by preventing the formation of vapor on the unloaded sections of the bearing. A bearing configuration which introduces liquid mercury lubricant to several points in the circumference of the bearing has demonstrated, by limited component test, elimination of this problem. Two of the bearing problems require improved configuration. Promising configurations currently planned for test are described as follows: The 3-sector journal bearing (Figure 5) has exhibited good flow characteristics, low startup torques, excellent load-carrying capacity, and currently no observable tendency to cavitate. This bearing has presently completed 75 hr on endurance at 40,000 rpm in the FRR, (Free Running Rig), with cold Hg to obtain a preliminary evaluation of life and cavitation characteristics in a 100-hr endurance test. In its current state of development, the 3-sector journal bearing has improved stability characteristics relative to the axial groove or plain

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Figure 5. Bearing Types

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bearings which have been used in CRU tests. Present effort is directed towards increasing the stability at extremely low unidirectional and rotating radial loads.

The effect of the following parameters on the stability (anti-whirl) of the 3-sector journal bearing will be evaluated analytically and/or experimentally to obtain the most stable bearing:

Effect of diametral clearance (hydrodynamic).

Effect of inlet hole size.

Effect of hydrostatic axial inlet pad size.

Effect of axial drain groove size.

Effect of increasing or decreasing length.

A 6-sector bearing will also be tested to determine the effect of increasing the number of sectors on bearing stability.

To provide additional assurance of a successful bearing development, an evaluation of bearing configurations having good stability and cavitation-erosion characteristics will be conducted including the following types:

Annular groove journal bearing having anti-whirl provisions (Figure 5-B).

Herringbone type journal bearings designed for maximum stability (Figure 5-C).

Elliptic and three-lobe bearings having impressed stability at light loads. (Disadvantage of this design is its somewhat reduced capability to sustain large radial loads. For reference, Figure 5-E shows axial groove bearing (plain).

Each of these latter bearings will be evaluated analytically to determine their applicability to the program. The most promising bearings will be fabricated and tested for stability, load-carrying ability, and flow characteristics. The more promising bearing types will be hot endurance tested on bearing component rigs and incorporated into CRU tests.

(3) Recent Bearing Test Summary

Tests were run in the FRR using cold mercury to evaluate combinations of load, clearance, and minor 3-sector bearing configuration variations

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to realize a stable bearing. No bearing failures occurred in the FRR and no evidences of cavitation-erosion damage were seen as with the plain bearings. Testing in the FRR is continuing to obtain stable bearing operation at loads less than 10 lb per bearing. The next test will be run with the bearing length increased from 0.407 to 0.447 in. The added length has been shown analytically to increase the bearing stability at low loads. Many tests have been conducted in the FRR with the 3-sector journal bearings and the spiral groove thrust bearing. One test was a 100-hr endurance test which was run under severe conditions of load. The first 5 hr were run with 35 lb per bearing unidirectional load and 10 lb per bearing rotating load. When no problems were encountered the unidirectional load was removed and the remaining 95 hr were run with 10 lb per bearing rotating load and under whirling conditions. No decay in performance was noted during the run. During the recently conducted CRU-III-3B test it was noted that the thrust bearing pressure varied during the process of bringing the turbine inlet pressure up to the design point. A test was run in the FRR with the spiral groove thrust bearing to duplicate this occurrence. It was found that with 10 lb/min flow, the bearing pressure drop changed approximately 25 psi when the thrust load increased from 8 to 30 lb. The transient noted during the CRU test is attributed to changing turbine thrust load as inlet pressure changes. The high frequency of reported successes in the FRR, where the operating temperature is the ambient test room temperature, when compared to the continuing series of "foreign article induced" hot operating CRU test failures, points out the need for early use of the hot bearing test rigs to evaluate:

- a) The sensitivity of each bearing configuration to thermal distortion.
- b) The sensitivity of each bearing configuration to foreign particle intrusion.
- c) Operation under "cleaner" mercury flow conditions than are probable in the CRU test rigs in order to obtain long-term bearing endurance operating capabilities.

(4) CRU-Bearings-Test Rig Fabrication

Fabrication of the hot Free Running Rig, while delayed by long delivery time on some items and extensive CRU refabrication activity, has

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progressed to where it is expected to be ready for checkout approximately July 15, 1961. The hot bearing test rig based upon a modified CRU-II with air turbine drive is expected to be ready for checkout August 15, 1961.

A modified hot bearing test fixture using CRU-II is also being evaluated. With this fixture the air turbine drive would be utilized to start the unit and build up to speed and then use 2000 cycle supply to drive the alternator.

The visual flow observation fixture, set back by the higher priority of the two hot bearing test rig installations, is scheduled for completion July 1, 1961. This fixture is expected to be especially valuable in the detection and/or observation of cavitation.

(5) New Departure Subcontract Bearing Material Compatibility Studies

Material samples for wear and scoring resistance evaluation have been sent to New Departure Division of General Motors for their evaluation.

c. Mercury Pump

The test of CRU-III-5A on March 31, 1961 was the first time that the CRU shaft mercury pump supplied the complete mercury loop. During later CRU testing the output of the shaft rotary mercury pump was again dumped. The lubricant and boiler Hg flows were supplied by the Lapp pumps. The output flow and pressure rise across the shaft rotary mercury pump were continually measured during the CRU-III-3B tests and maintained acceptable levels throughout the operating period. When the rotary Hg pump was examined upon disassembly of the CRU after this test, its physical condition was found to be good. This pump configuration is termed a "Number 7" and has an impeller diameter of 0.370 in.

At the present time no serious problems appear to exist in the area of mercury pump development. The No. 7 pump has afforded a design which can be made to satisfy a wide range of system requirements by changing impeller diameter. The problem of leakage past the impeller has been largely eliminated through the use of dynamic sealing. Efficiencies of 50% are to be expected from later variations of this No. 7 pump design. Output pressures required for a useful flow of 42.7 lb/min have dropped from 580 psia to 370 psia. This reduces

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substantially the pressure load upon the CRU piping and the losses through the bearing and boiler flow regulators. Incidentally the TRW test rig (Lapp or Chem) mercury pumps will now have sufficient pressure output to simulate the CRU design Hg pressure and flow.

d. NaK Pump

The rotating magnet form of NaK pump is inherently a very low efficiency device. Pumps for the CRU-III series have efficiencies of 2% and pressure increases of 3.0 psi. A new design called the CRU-IV type has been performance tested at 40,000 rpm, 1000°F NaK and 11.8 gpm NaK flow. It developed 3.5 psi pressure using 765 w for an efficiency of 2.35%. At 14 gpm the power required was 776 w, the ΔP was 3.1 psi, and the efficiency 2.45%. This design has a thinner diaphragm and larger clearance around the rotor. Fabrication of a second CRU-IV type NaK pump has begun for additional performance tests. Figures 6 and 7 show flow vs efficiency % for this CRU-IV No. 7 NaK pump.

(1) NaK System Thermal Problems

Three major thermal problems are associated with the operation of the NaK system:

- a) The dimensional changes during NaK warmup.
- b) The injection transients upon actual startup.
- c) The long-time high-temperature degradation of magnets.

The entire NaK system warmup timing is dependent upon the rate at which the NaK pump region can adjust itself to increasing temperature in the NaK. Too rapid heating will cause the diaphragm to distort into the clearance space between its normal position and the NaK magnetic rotor. Since current warmup procedures require between 3 and 4 hr to reach 1000°F (at 300°F/hr maximum) with no Hg flow to carry off heat, the CRU housing and shaft absorb much heat and may reach temperatures dangerous to the alternator stator sealing and construction (700°F) limitation. During warmup all dimensions will increase. Clearances may increase or decrease depending upon the net dimensional changes in the surrounding parts.

When the mercury (at a temperature of 150-400°F depending on the squirt-start system design selected) is injected into the system, severe

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Figure 6. NaK Pump Performance, ΔP

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Figure 7. NaK Pump Performance, Efficiency

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thermal shock and thermal transients are developed in the boiler, the NaK loop, the Hg power loop, the coolant passageways, and the bearings, particularly the turbine journal bearing where the shaft may be at 700 to 900°F. To cool the bushings suddenly in both coolant-passage and lubricant region may close up this tight radial clearance. (For this reason 400°F lubricant and coolant Hg has been circulated for a period prior to opening the turbine inlet Hg valve during tests to date.)

The thermal transient induced in the NaK loop (and subsequently at the NaK pump) through the boiler squirt-start Hg injection is predicted to be greatly in excess of the current NaK pump design objective of 600°F/hr. It should be noted that "scram" shutdowns during ground testing also provide similar extreme thermal transient problems.

It has been established that when magnets are operated for long periods of time at high temperatures there is a definite maximum temperature, above which the magnetism rapidly is lost.

With proper pretreatment, magnets can be made stable and repeatable (in strength) between -70°C and 500°C. In one series of tests when magnets were heated up to 500°C (932°F) the magnetic properties increased an average of 4% in the first 200 hr then remained constant for 1000 hr (the duration of the test). However, when heated to 600°C (1112°F) the magnetic properties were drastically reduced in 50 hr and almost entirely lost in 200 hr. Additional experimentation is planned to more accurately determine magnet limitations and optimum magnet pretreatments.

(2) Flow Regulators

The flow regulators are now being built with PH15-7Mo spring and body. Early cracking problems using this material have been corrected by closer

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quality control. This change of material has eliminated the corrosion problem. Satisfactory operation has been achieved at 400°F for times in excess of 150 hr.

It has been found necessary to calibrate the individual units for 400°F operation due to the temperature sensitivity of the design.

Work is continuing on developing an externally adjustable boiler flow regulator. A pilot model may be ready for the PCS-II-1 tests.

e. Turbine

Turbine performance is one of the major areas that requires improvement in order to meet the SNAP 2 system objectives. Previous tests on CRU-III type units (two-stage turbine full admission, axial flow impulse blading) indicate the overall efficiencies of 46-48% vs the required 53-55%. Design activity, initiated last fall, resulted in the CRU-IV turbine which includes modification of five significant parameters from the CRU-III design in order that performance objectives can be met. These modifications include:

<u>Design Change</u>	<u>Predicted Efficiency Increase</u>
Improved velocity ratio, u/c	4%
Improved inlet and exhaust scrolls	1%
Increased rotor solidity	2%
Thinner leading and trailing blade edges	
Converging-diverging nozzles	

The most significant design improvement is the change to a more nearly optimum velocity ratio. In the CRU-II and -III turbine designs it was believed that partial admission losses would reduce turbine performance more than operating at a less than optimum u/c ratio. If the turbine were designed for full admission at the optimum u/c ratio, the blade heights would be reduced to a point where aspect ratio losses are prohibitive. Since the design of the CRU-II and -III turbines, experimental results from SNAP 1 have shown that partial admission losses are not as severe as anticipated. With this additional knowledge it has been possible to design the CRU-IV turbine with a partial admission (33%) first stage and full admission second stage, since partial admission losses can be more accurately predicted. Design velocity ratios for the

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CRU-III turbine first and second stages are 0.327 and 0.353, respectively, resulting in calculated stage efficiencies of 60.3% and 59.2%, respectively. CRU-IV design velocity ratios are increased to 0.448 and 0.523 with a corresponding increase in stage efficiencies to 68% and 61%. The effect of changing from full admission and low u/c ratio to partial admission with a more nearly optimum u/c ratio gives a 4% increase in design efficiency.

Turbine efficiency is quoted as based on flange-to-flange conditions and the losses incurred in the inlet and exit scrolls are charged to the turbine. It is, therefore, essential that the scrolls be designed as efficiently as possible. The increase in wheel diameter and the incorporation of partial admission in the CRU-IV turbine allows more freedom in the scroll design from a package standpoint. The CRU-IV inlet scroll has been designed for constant inlet velocity with minimum pressure drop. The exhaust scroll is a split volute diffuser with the most nearly optimum expansion consistent with package design considerations. These improvements result in an additional 1% efficiency gain.

To provide the proper guidance for the working fluid through the rotor blades, the rotor solidity, $\frac{\text{axial chord}}{\text{pitch}}$ ratio should be approximately 3.0. A value less than about 3 does not provide good control of the flow causing separation losses, while a value greater than about 3 results in increasing skin friction losses. The CRU-IV turbine design incorporates a more nearly optimum solidity ratio than CRU-III. Trailing edge mixing losses and expansion losses are significant in very small turbines since $\frac{\text{trailing edge thickness}}{\text{exit channel width}}$ ratio is relatively large. This loss can be minimized by maintaining trailing edge thickness at a minimum. Leading edge thicknesses should be maintained as small as possible to insure that the rotor inlet relative Mach number is less than 1 to prevent rotor choking and shock losses. But in a mercury turbine for long-life applications, erosion may influence the minimum leading edge thicknesses. Long-term testing of SNAP 1 indicated that erosion was not as serious as was thought. Based on the above considerations the leading and trailing edge thicknesses of the CRU-IV rotors are 0.008 and 0.006 in., respectively. This compares to 0.017 and 0.010 in. for the CRU-III first-stage leading and trailing edges and 0.020 and 0.010 in. in the CRU-III second stage.

The high pressure ratios employed in the SNAP 2 turbines result in supersonic spouting velocities in both stages. In the CRU-III turbine it was

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assumed that in the first stage the expansion necessary for supersonic velocities took place in the axial clearance between the nozzle exit and rotor inlet. This expansion was abrupt since the throat of the nozzle was designed at the nozzle exit. CRU-IV uses converging-diverging nozzles in both stages to achieve controlled expansion. These three factors - rotor solidity ratio, thinner leading and trailing edges, and the use of convergent-divergent nozzles - combine to enable much better flow control and reduced flow losses in the CRU-IV turbine compared to CRU-III. These factors combine to provide a predicted 2% improvement in turbine efficiency.

Recent CRU-IV performance analyses, conducted both by Atomics International and TRW, indicate the possibility of large interstage pressure losses resulting from inadequate collector area prior to entering the second stage nozzle blade ring.

In order to minimize these losses, the interstage collector of CRU-IV-0 is being "hogged-out" to provide approximately twice the initial design flow passage area. Furthermore, in view of the difficulty in accurately predicting such losses by analytical methods, interstage instrumentation is being provided on the CRU-IV-0 test unit.

Incorporation of the leakage bypass duct in the CRU-IV labyrinth design will result in decreased heat input in the turbine area and minimize the thermal problems which have arisen in CRU-III operation. The effect of this addition has been shown analytically, but will not be known definitely until CRU-IV testing is accomplished.

Because the performance of the new turbine design will not be proven experimentally until CRU-IV is tested, it has been decided to proceed with an alternate design (CRU-IV-2). This design will maintain the same concept and envelope, but incorporate minor changes which affect turbine performance in areas where analysis methods are not completely accurate.

5. Summary of Principal Changes Between CRU-IV and CRU-III

- a. Castings are used throughout (as opposed to machined billets) for the inlet scroll, alternator housing, and exhaust scroll.
- b. Basic turbine design changes:
 - 1) Nozzle and rotor mean diameters increased from 1.400 in. to 2.300 in.

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- 2) First-stage admission reduced from full (360°) to partial (120°).
 - 3) Blade quantities increased from 39 first stage and 47 second stage to 107 each stage.
 - 4) Number of nozzles changes from 20 each stage to 12 first stage and 36 second stage.
 - 5) Nozzle inlet angle second stage increased from 49° to 96° (first stage still 138°).
 - 6) Nozzle exit angle now 15° for each stage (second stage on CRU-III was 20°).
 - 7) Rotor inlet and exit angles now the same (30° first stage, 33° second stage).
 - 8) Nozzle and rotor blade heights have been increased.
 - 9) Second-stage nozzle and rotor axial chords have been changed to 0.225 in. from 0.28 in. and 0.20 in., respectively.
 - 10) Nozzle and rotor exit throat widths have all been reduced on both stages.
 - 11) The high pressure turbine seal has been lengthened.
 - 12) Three bypass tubes are provided to route most of the residual high pressure leakage back to the turbine exhaust.
 - 13) A thermal shield was installed to prevent direct impingement of the turbine high pressure seal leakage upon the turbine-bearing journal-bearing block.
 - 14) The nozzles of both stages have been changed to a convergent-divergent design.
- c. The leads from the alternator now exit through a radial tube terminating in a "cannon-type" plug. This eliminates disassembly seal breakage and maintains alternator winding hermetic seal.
- d. New housing design requires only three weld cuts for disassembly involving removal of the shaft. This both improves the fabrication of the unit and facilitates the maintenance and repairs of items under test. Capability for 5 reweld operations on these CRU flanges has been achieved.
- e. The alternator and turbine bearing OD of the CRU-IV shaft is 0.625 in. compared to 0.500 in. on the CRU-III.

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- f. The shaft is largely hollow.
- g. As a result of "e" and "f" the shaft critical speed is now in excess of 65,000 rpm compared to slightly over 40,000 rpm for CRU-III.
- h. The thinner housing walls result in a better thermal profile across the unit.
- i. Leakage on the mercury pump has been reduced by the use of a "slinger" on the pump rotor.
- j. The coolant flow of mercury around the alternator has been fed into parallel grooves in the alternator housing.
- k. The alternator rotor is now welded to the shaft at both ends.
- l. The design of the alternator stator has been revised to provide more vibration damping.

6. Control

It has been the goal of the SNAP 2 Combined Rotating Unit speed control program to develop a control compatible with the complete APU environment. The most difficult environmental condition imposed on the control is the 600°F ambient temperature. The development efforts to date have resulted in confidence that this temperature requirement can be attained by all control components except one. The present inability to meet this requirement is due to a lack of diodes which will function reliably at this temperature. TRW was recently informed by their only remaining supplier that they are discontinuing efforts to manufacture 600°F diodes. Development activities now being conducted by other transistor and diode manufacturers may well result in the capability to produce reliable 600°F diodes in the future.

In view of these considerations, TRW has recommended that the CRU speed control development program be directed to produce a fully flight-capable control with a 400°F ambient temperature limitation. Diodes presently available will permit reliable operation at this temperature. When 600°F diodes become available, the control can be modified to uprate the 400°F limitation. The 400°F control will be approximately the same weight and size as the 600°F controller.

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Diode life tests are continuing with a total of 49 days at 400°F. During this test, two units out of nine have failed. Little or no change due to aging has been noted on the surviving seven units. The diodes are operated only periodically during data taking and are soaked at 400°F non-operative between data points. To rectify this, a continuously operating life test rig is now being designed. The design and construction of a diode life-test test rig is nearing completion and testing of twenty 400°F diodes will be initiated. Effort will be accelerated on the system breadboard, and preliminary packaging studies will be undertaken. The design efforts toward high temperature breadboard components have been concentrated on reducing the size of the power stages, hence reducing losses within the control.

Harmonic distortion tests were run on the output voltage wave of an alternator while being loaded by various combinations of system and parasitic loads composed of two stages per phase. All tests resulted in distortion within specification (7%) ranging from 3.5 to 6%. These tests were significant in that data was acquired which should permit a more sophisticated power stage design.

A study of possible locations within the power conversion system for the parasitic load resistors is being made. The NaK pump discharge line would provide a likely location for installation of high temperature wrapped resistors and would be capable of providing the necessary heat rejection.

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VII. NON-NUCLEAR DEVELOPMENT SYSTEM

A. PSM-1 DEVELOPMENT SYSTEM

The primary objective of the PSM-1 system (see Figure 8) is to design, fabricate, install, and operate a non-nuclear package system test of the flight test configuration. The specific objectives are as follows:

- 1) To obtain design, fabrication, and installation information for the flight package configuration.
- 2) To obtain non-nuclear performance data for the flight package configuration. This includes both design and transient conditions.
- 3) To test and develop orbital startup techniques and startup equipment.
- 4) To prove the suitability of NaK system cleanup, loading, and sealing techniques for a void-free system.
- 5) To obtain performance information for the radiator-condenser in a simulated heat transfer environment.

The PSM-1 design points have been established as follows:

Turbine efficiency	0.45 (CRU-III design)
Turbine flow	20.8 lb/min
Turbine leakage	0.6 lb/min
NaK flow rate	76 lb/min
Reactor (electrical heater) power	58.2 kw
Alternator output	2.53 kw

The instrumentation requirements were finalized. The instrument block diagram, panel layouts, and wiring diagrams are completed. The instrumentation includes the electrical control for the CRU, and the NaK and mercury process instruments.

The specification for the simulated reactor (electrical heater) control system was released for purchase. The control system design is such that the heater can be controlled by an analog computer to simulate the reactor during startup conditions or by heater outlet temperature during steady-state operation. The control system will allow a peak power input of 100 kw to the heater during transient conditions.

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Figure 8. S-2-PSM-1 System Piping and Instrumentation Diagram

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The APU assembly drawing was completed. This drawing shows all major components of the APU including the power conversion system (PCS-II-1), the radiator-condenser (RC-6), the simulated reactor (electrical heater), the in-line ground start electrical heater, the simulated orbital startup pump, the NaK expansion compensator, the load ring, upper support structure, and the NaK and mercury piping configuration.

The APU NaK and mercury piping spool drawings have been completed for fabrication. The system test piping layout drawings were completed. These drawings show the piping routing between the APU and the equipment and instrumentation located outside the APU vacuum tank, the vacuum system and cooling water system for the APU vacuum tank, and the nitrogen system for the mercury injection equipment. These drawings will be used for installation of the system test in Building 032 at the AI Nuclear Development Field Lab area, Santa Susana.

Work was initiated on establishing the requirements for sun-shade heat lamps. These lamps will also be used to simulate insulation during startup of the APU.

The integration points between the TRW-supplied power conversion system (PCS-II-1) and the remainder of the system were finalized. All mercury systems integration points are through-welding type flanges to facilitate removal of the CRU, if required.

Design of PCS-II-1 was completed at TRW. This includes the NaK-to-mercury boiler, the CRU-III, the support structure, and the interconnecting piping. Design of the breadboard mercury injection equipment which will accompany the PCS was also completed.

Work was initiated on preparing the system test procedures. These will include startup, shutdown, steady-state, and off-design conditions. A study was initiated to determine modifications to the system test and additional components which would be required if boiler conditioning or operation without the CRU is required at Atomics International.

A study was initiated to determine the requirements of a refrigeration system for the APU vacuum tank to maintain the tank walls as low as 0°F. The requirement for the low wall temperature is based on recent tests and calculations which indicate the radiator-condenser outside coating has an emissivity

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of approximately 0.85 rather than the earlier design value of 0.90. Consequently with the APU located in the vacuum tank, a radiator-condenser surface area of 110 ft², and a tank-wall design temperature of 100°F, the mercury level in the radiator-condenser (subcooler portion) during design point operation would be 2 to 3 in. below the centerline of the CRU mercury pump. Thus, on a ground test it would be necessary to overcome this static mercury head by increasing the condensing pressure in the radiator-condenser 1 to 1-1/2 psi, resulting in off-design steady-state operation. Lowering the vacuum tank temperature to about 0°F results in a mercury level 1 to 2 in. above the CRU mercury pump centerline, allowing the system to be operated at design point.

The following major components of the PSM-1 system test have been fabricated: the APU vacuum tank, the breadboard mercury injection system, the mercury boiler, and the NaK expansion compensator. Components currently in construction are: the combined rotating unit CRU-III, the electrical heater which will simulate the reactor heat source, system structural support members including the load ring and the reactor support structure, a dc induction pump which will simulate the orbital startup pump, the in-line ground startup heater, and the radiator-condenser with steel honeycomb and steel tubes. Orders have been placed for all the major equipment, instrumentation, and material required for assembly and operation of the PSM-1 system. The building which will house the PSM-1 system test is being constructed and is scheduled for completion August 1, 1961. Installation of the test assembly will be initiated at that time.

The APU vacuum tank is a carbon steel vessel 8 ft in diameter and 16 ft high, which will contain the APU in a simulated spatial heat transfer environment. The tank pressure will be maintained at about 10^{-3} mm Hg to essentially eliminate convective heat transfer from the APU. The mercury condenser will be cooled by radiation to the tank wall which will be maintained as low as 0°F by circulation of refrigerant through copper coils attached to the outer surface of the tank. The breadboard mercury injection system consists of two nitrogen pressurized tanks having steel bellows between the mercury and the nitrogen and associated piping with solenoid valves to allow system pressurization and depressurization. This equipment will be used for filling and draining of the circulating mercury loop and for pressurization of the CRU mercury pump suction as may be required for APU startup. The mercury is contained in the bellows which are connected through valves to the APU mercury loop.

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The PSM-1 mercury boiler is a counterflow NaK shell-to-mercury-tube heat exchanger having seven Haynes-25 tubes within a 316 stainless steel shell in a coil configuration.

The electrical heater which will be used to simulate the reactor heat source is an immersion type heater utilizing high watt density cartridge resistance heaters. The heater size and flow area were based upon matching of the NaK residence time and pressure drop in the reactor. The heater is rated at 75-kw continuous operation and is capable of maintaining 100-kw transients.

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VIII. OPERATION ANALYSIS

A. SYSTEM FLIGHT SAFETY

The operational sequence from shipment to re-entry has been under investigation. The sequence of procedures plus the procedures themselves are being studied to insure maximum safety.

In order to examine the magnitude and probability of anticipated hazards, digital computer codes and analog computer studies are being developed into an inclusive theoretical analysis of normal and abnormal hazard situations. A particle deposition digital code has been completed to be used in conjunction with the AIREK, FIRE, and INSTANT codes reported earlier. Codes predicting fission product diffusion from the core; direct, organ, and deposition doses; cloud rise; and fallout and rainout deposition are proposed to complete the theoretical analysis.

Experimental studies which will provide range of applicability of the theoretical data are presently in the proposal stage. Included in the more immediate proposals are a fission-product-release study and launch-abort study. The fission-product-release study is anticipated to determine type and quantity of fission products released. The results attained by the SNAP 2 safety-evaluation study will be summarized in the following reports:

- 1) SNAP 2 Flight Safety Criteria
- 2) SNAP 2 Preliminary Flight Safety
- 3) SNAP 2 Accident Study (Hazards)
- 4) Final SNAP 2 Safeguards

A preliminary safety film titled "Nuclear Reactors for Space," NAA-SR-5800, has been completed.

B. RELIABILITY

1. Reliability Apportionment

The reliability apportionment of the SNAP 2 system goals have been re-apportioned in greater detail among the major components of the system. Four phases of unattended operation are included in the apportionment: survival of

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launch conditions, successful orbital startup, endurance for 1 year of operation, and shutdown of nuclear operation at end of life. The reliability goal for each of the above phases is 0.99, 0.96, 0.895 and 0.995 respectively. This yields a total SNAP 2 reliability goal of 0.84 which is in the range of values indicated as optimum goals from a prior economic analysis which included the costs of missile launching and reliability improvement program costs. For the purpose of apportionment the reliability goal for each phase was converted to failure rate F , where $F \approx 1 - \text{Reliability}$. The failure rate was then apportioned among the individual system components in proportion to estimated relative difficulty in achieving reliability as shown in Table III. Indicated apportionments were based on individual judgment and may be adjusted readily as knowledge accumulates.

The goals allotted to safety components require additional comment. Safety components have a function or mission which is quite different from the mission of the power-producing system components. However, the malfunctioning of safety components may influence the primary power-producing mission by inadvertently destroying the system when it is not required or called for. Thus the safety component failure rate allotments refer to the permitted frequency of malfunctions which shut down a safe system. The reliability goals for safety components for shutting down an unsafe system have not yet been estimated. This requires an evaluation of potential danger to the operating personnel and general public and what amount of risk of this danger is acceptable.

The reliability goals for the telemetry equipment for the SNAPSHOT's also constitute a separate mission in which the risk is inadequate feedback of launch and orbital performance information.

2. Estimate of SNAPSHOT Reliability

For purposes of evaluating SNAP 2 development program plans in terms of expected reliability, a reliability learning process must be estimated. Such an estimate is of necessity on a very approximate basis and the results should be treated merely as indications of possible results which may be useful in comparing projected program modifications in terms of reliability.

The general shape of reliability growth has been observed and correlated with effort in the field of rocket engine development at Rocketdyne, Division of North American Aviation, Inc., which yielded the following equation:

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TABLE III
SNAP 2 FAILURE RATE APPORTIONMENT TO COMPONENTS

	Failure per Launch	Failure per Startup	Failure per Year	Failure per Shutdown
<u>Reactor Components</u>				
Reactor Vessel	0.0001	0.0001	0.0003	--
Reactor Fuel Loading	0.0005	0.0010	0.0100	--
Reflector Assembly and Drums	0.0002	0.0010	0.0005	0.0010
Long Term Controls Minus Actuators	0.0001	--	0.0100	--
Control Drum Actuator	0.0001	0.0003	0.0052	--
Shield Assembly	0.0001	0.0001	0.0015	--
Subtotal	0.0011	0.0025	0.0275	0.0010
<u>Safety Components</u>				
Launch Destruct Inaction	0.0001	0.0001	--	--
Launch Destruct Jettison	0.0001	0.0002	--	--
Reflector Ejection and Sensors	0.0001	0.0001	0.0002	0.0020
Re-entry Parts Dispersal	0.0001	0.0001	0.0001	0.0020
Subtotal	0.0004	0.0005	0.0003	0.0040
<u>Primary Components</u>				
Volume Compensator	0.0001	0.0001	0.0001	
Separate Source Pump	0.0001	0.0006	--	
Closure Seal	0.0001	0.0001	0.0001	
Subtotal	0.0003	0.0008	0.0002	
<u>Power Conversion Components</u>				
CRU				
Turbine	0.0005	0.0010	0.0020	
Alternator	0.0010	0.0020	0.0050	
Bearings	0.0020	0.0200	0.0250	
Hg Pump	0.0002	0.0005	0.0050	
NaK Pump	0.0004	0.0005	0.0020	
CRU Subtotal	0.0040	0.0240	0.0390	
Parasitic Load Control	0.0005	0.0010	0.0050	
Boiler	0.0005	0.0005	0.0050	
Radiator Condenser	0.0010	0.0025	0.0250	
Subtotal	0.0060	0.0280	0.0740	
<u>System Startup Components</u>				
Batteries	0.0001	0.0005	--	
Startup Programmer	0.0001	0.0002	--	
Startup Sensors	0.0002	0.0020	0.0001	
Startup Squibs	0.0001	0.0005	--	
Startup Drum Actuators	0.0002	0.0010	--	
Injection Tanks	0.0001	0.0005	0.0001	
Startup Valves	0.0002	0.0010	0.0008	
Nose Cone Ejection	0.0001	0.0005	--	
Subtotal	0.0012	0.0080	0.0010	
<u>Assembly</u>				
Primary Piping and Connections	0.0003	0.0001	0.0010	
Secondary Piping and Connections	0.0004	0.0001	0.0010	
Structure	0.0003	--	--	
Subtotal	0.0010	0.0002	0.0020	
TOTAL	0.0100	0.0400	0.1050	0.0050
Reliability	0.99	0.96	0.895	0.995
Net Reliability Goal - 84%				

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$$R = \exp \left[\frac{-1.3}{x^{1.5} + 1.3} \right]$$

where

R = achieved reliability

x = number of engine test lots (groups of 20 tests)

A similar equation with reliability improvement effort in the denominator has been proposed for improvement of SNAP reliability, as follows:

$$R = \exp \left[\frac{-1}{\frac{m}{3} t + 0.3} \right]$$

where

R = achieved reliability

m = number of simultaneous systems under test development

t = years of life-test development effort on a SNAP system or equivalent level of component effort

The constants were estimated so that the initial 1-year reliability of the first ground-test hardware is $R_0 = 0.05$. The major estimate relating to growth was a relation of 3 years of system development testing required to yield an increase of 1 year in mean time between failures.

With the above estimated equation the SNAP 2 program was evaluated as shown on Figure 9. Each major performance or life test was evaluated in terms of estimated length of actual operation and what fraction of the complete system was represented in the test. The nuclear tests appearing in the SNAP 10A program were also included since the reactor subsystems are similar. The total equivalent number of systems under test is shown in a summary chart in the middle of Figure 9. From this summary of system effort the learning curve was used to obtain the projected reliability growth estimated for the SNAP 2 program. At the date of SNAPSHOT the curve indicates an expected reliability of $R = 0.4$ with a confidence level of about 50%.

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Figure 9. SNAP 2 Present Program Expected Reliability Growth

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3. Optimum Apportionment of SNAP 2 Reliability Development Test Program

The maximum rate of increase of reliability is obviously achieved by directing the majority of improvement effort in the areas which contain largest contribution to system failure rate. The costs of such directed efforts must be balanced against potential reliability gains to quantitatively assess the proper magnitude of such an apportionment of effort.

An economic analysis for the simple case of a two-subsystem apportionment of SNAP 2 into the nuclear reactor subsystem and the non-nuclear power-conversion subsystem was made. The results are shown on Figure 10. A basic parameter to be estimated is the fraction of the total system failure rate that is due to the reactor subsystem. From Table III the fraction is about $1/4$ for SNAP 2, so a set of lines was prepared in this region and appears on Figure 10. The ratio of reactor subsystem test cost per year to the non-nuclear subsystem test cost per year is about $C_1/C_2 = 4$. This yields an optimum apportionment of effort of about $b = 1.9$ for the ratio of non-nuclear subsystem development test time to reactor subsystem development test time. Thus the SNAP 2 power-conversion effort should be about twice as large as the reactor effort in order to obtain maximum rate of increase of reliability within any particular budget constraint.

C. FLIGHT INSTRUMENTATION AND TELEMETRY

1. Instrumentation and Telemetry System

The flight instrumentation and telemetry system will function to transmit command signals to the APU and transmit back data from the APU representing its performance. Telemetered command signals to the APU are needed in order to:

- a) Start up the APU after a suitable long-life orbit has been verified; a stored program and internal control system within the APU will then take all subsequent actions necessary to complete the startup sequence, once this initial command has been received.
- b) Initiate the necessary safety actions to destruct the core and/or scram the reflectors if necessary during launch and initial orbital phases.

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Figure 10. Optimum Apportionment of SNAP 2 Reliability Development Test Program

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Telemetered data from the APU is necessary, starting from the time of launch, in order to:

- a) Evaluate the response of critical APU components and structures to launch shock, vibration, and aerodynamic heating.
- b) Determine critical APU system temperatures prior to startup, in order to evaluate the adequacy of the methods used to prevent NaK freezing.
- c) Evaluate the transients incurred during orbital startup and diagnose the causes of possible failure to start. This is one of the most important functions of the telemetry data, since no amount of ground testing can exactly simulate the effects of zero gravity on the startup method used.
- d) Determine the safety status of the reactor at all times. The status of the control drums, reflectors, nose cone, destruct charges, and other equipment important to the APU safety must be known at all times during launch and early orbital operation.
- e) Determine steady-state design point in the space environment and changes in this design point due to short-term transients such as sun shade, so that off-normal performance can be recognized and corrected.
- f) Determine long-term transients and aging effects so that reliability in the space environment can be estimated and this data fed back into design improvements.
- g) Determine the cause of possible APU failures at any time during the mission. This failure data will be the sole means of providing design corrections to subsequent SNAP 2 flight systems in the event of an APU failure in space.

For these reasons, the importance of a reliable, well instrumented telemetry system cannot be emphasized enough. The philosophy used in the engineering of this system will be to provide as much instrumentation as possible within the weight and power consumption limitations.

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2. Description of System

Engineering of the flight instrumentation system has been initiated. Preliminary meetings with Lockheed Missile and Space Company (LMSC) have defined the broad areas of responsibilities with respect to instrumentation and telemetry components. The APU will contain all the transducers and the signal conditioning equipment (amplifiers, bridges, demodulations circuitry, etc.) necessary to convert the signal to a dc voltage proportional to the variable being measured. Dc signal level ranges varying from 10 mv to 5 v full-scale can be handled by LMSC input circuitry. The dc amplifiers, reference junctions, multiplexers, transmitters, tape recorders, calibration signals, etc., necessary to telemeter the dc signals to ground stations are provided in the Agena. Figure 11 is a functional block diagram indicating how the various type APU measurements are transmitted to the LMSC portion of the system.

A preliminary instrument list summarizing all transducers required for SNAPSHOT has been prepared and is being resolved with TRW and LMSC. Table IV is a summary of the number of measurements of each type required.

TABLE IV
TYPE OF FLIGHT MEASUREMENTS REQUIRED

Measurement Type	Number Required
Temperatures	75
Pressures	8
Flow	5
Position	7
Electrical parameters	7
On-Off (operational events)	25
Shock and vibration	19
Radiation level	3
Differential temperature	5
Differential pressure	2
Miscellaneous	5
Spares	10
Total Number Required	171

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Figure 11. Diagram of Typical Flight Instrumentation Channels

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The following command signals are needed: APU start, reactor destruct, and reflector scram. Several additional command channels may be necessary for redundancy and spares.

The functions of the data portion of the telemetry system have been broken down into several subsystems: ascent data subsystem, stored data subsystem, and real time subsystem.

The ascent subsystem will supply the data necessary from the time of launch until following the second Agena burn. This consists primarily of high frequency shock and vibration data; however, some slower responding signals such as temperatures, primary system pressure, and reactor safety status will also be telemetered.

The stored data subsystem will contain the tape recorder and other equipment necessary to collect data while in orbit and out of range of tracking stations. Adequate storage time will be provided to allow continuous data collection during the APU startup phase and will be determined based on the maximum expected time between tracking stations. Data from the tape recorder can be read out rapidly over the tracking stations. Following initial startup, the stored data subsystem will be used as an APU failure-monitoring system and will be capable of collecting data for a minimum of 45 min before and 45 min after an APU malfunction (as indicated by loss of alternator output). Thus the tape need not be read out unless a failure occurs and diagnosis of what occurred before and after the failure is required. All APU transducers with the exception of shock and vibration will be fed into the stored data system.

The real time subsystem is for the purpose of reading out data from all transducers in the APU into the tracking station without going into storage first. This subsystem is used following the ascent phase and will indicate events in the APU as they are happening over the tracking station.

This subsystem will be used for several purposes: Data will be read out from this system during APU startup over every available tracking station so that no transient data is missed while the stored data is read out. At less frequent intervals following startup this data will be read out to evaluate the steady-state design point and short and long term shifts in the design point. The system will provide the only means of assessing APU status and performance following tape recorder failure.