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ATOMICS INTERNATIONAL A Division of North American Aviation, Inc.		NAA-SR-MEMO TDR NO. 10446		APPROVALS	
TECHNICAL DATA RECORD		PAGE 1 OF 25		<i>R. L. Galt</i>	
AUTHOR G. E. Berg <i>G. E. Berg</i>		DEPT. & GROUP NO. 726-60		DATE 9-15-64 <i>W. M. Meyer</i>	
TITLE SNAP-10A FSM-4 Performance Analysis - NaK Loading and Thermal Reference Test		GO NO. 7561		S/A NO. 3311 TWR	
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				AUTHORIZED CLASSIFIER SIGNATURE <i>R. L. Galt</i> DATE 9/16/64	
		STATEMENT OF PROBLEM Analyze the performance of the SNAP-10A FSM-4 non-nuclear ground test system during NaK loading and thermal reference testing			
		ABSTRACT: Data taken during NaK loading and thermal reference testing of the SNAP-10A FSM-4 non-nuclear ground test system are presented and analyzed. For purposes of analysis the performance was divided into five categories: 1) system temperatures, 2) system heat losses, 3) converter electrical performance, 4) pump performance, and 5) flight instrumentation performance. In each category emphasis was placed on comparison of measured data to predicted performance and thermal reference performance of the 10FSM-1 and 10FS-1 systems. In almost every case both FSM-4 performance and agreement with predicted values were excellent. An average of 509 watts was produced at a core outlet temperature of 1011°F. The only important problem was a low converter to ground resistance which would have caused a very small decrease in power output if the system had been grounded.			

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I. Introduction

The SNAP-10A FSM-4 system is a non-nuclear ground test unit intended to qualify SNAP-10A for flight testing. With the exception of the reactor, where electrical heaters are substituted for nuclear fuel, the unit is identical to a flight system. (An additional, but temporary, difference is the lack of expansion compensators on FSM-4. Because flight-type compensators were not available, the NaK loading cart was left connected to the system to provide external pressurization. Flight-type expansion compensators will be installed before FSM-4 is subjected to shock and vibration testing. At that time FSM-4 will undergo a second NaK loading and limited thermal reference test).

On August 5, 1964 FSM-4 was loaded with NaK, and on August 24, 1964 the thermal reference test was completed. On August 22 at 14:58 FSM-4 became the first SNAP-10A unit to produce more than 500 watts of electrical power. All hot testing was done in a vacuum environment of 1.0 to .05 microns.

II. NaK Loading

The purpose of NaK loading is to load the SNAP-10A unit with NaK of sufficient purity to prevent plugging of the hydraulic system at 20°F, to verify the purity, and to permanently seal the system.

Figure 1 shows the core outlet temperature history of the FSM-4 system. The system was loaded with NaK at ambient temperature on August 5. Using the NaK loading cart to provide heat and flow, the NaK temperature was raised in several steps to 630°F while watching for indications of plugging in the forty converter legs. No plugging was observed after the system reached 630°F, and the plugging temperature was maintained below 20°F. On August 12 the FSM-4 system was isolated from the NaK loading cart (except for a single pressurization line) and on August 13 NaK loading was completed.

Little performance data was obtained during NaK loading for the following reasons:

1. A work shield covered the converter, limiting the thermoelectric ΔT to less than 50°F and power output to 2 watts at an average NaK temperature of 629°F.
2. Heat and pumping power were provided externally from the NaK loading cart.

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3. Most of the special instrumentation was not installed until after the thermal reference test.

III. Thermal Reference Test

The most important purpose of the thermal reference test is to verify the acceptability of the SNAP-10A unit performance at full operating temperature before launch. In addition on FSM-4 special instrumentation was installed and special tests were conducted to provide more exact information on overall system performance and to provide detailed information on the operation of certain components, especially the converter and the electronic temperature switches.

During the thermal reference test the system temperature was raised in steps to 1010°F (see Figure 1). A portion of the data taken at each plateau was processed using the 10FSM-4 data reduction computer programs. The values quoted in this report are in most cases the output of these programs.

A. FSM-4 Overall Performance Summary

A typical set of FSM-4 performance data at 1010°F is shown in Table I together with predicted values. In almost every case system performance and agreement with predicted values were excellent. The only important problem was a low converter to ground resistance which would have caused a very small decrease in power output if the system had been grounded.

The FSM-4 system met or exceeded every requirement listed in the "FSM-4 Test System Description", NS10FSM4-00-001, June 17, 1964.

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Table I

10FSM-4 System Performance

	Measured ⁽¹⁾	Predicted ⁽²⁾
Core Outlet NaK Temperature	1011°F	1010°F
Core Inlet NaK Temperature	893°F	878°F
Average Converter NaK Temperature	950°F	944°F
Core Heater Power	41.9 Kw	42.3 Kw
Electrical Power Output	509 Watts	503 Watts
Open Circuit Voltage	57.3 volts	57.2 volts
Converter Internal Resistance	1.61 ohms	1.62 ohms
Flowrate-Based on Heat Balance	14.1 gpm	13.2 gpm
Based on Fringe Flux	13.2 gpm	13.2 gpm
Based on Wall Voltage	12.6 gpm	13.2 gpm
Weighted Average ⁽³⁾	13.5 gpm	13.2 gpm
System Thermal Efficiency	1.25 %	1.19%
Overall Converter Efficiency	1.36%	1.29%
Converter Carnot(Device) Efficiency	21.4%	22.3%
Converter Device Efficiency	6.36%	5.79%

(1) Average of data taken at 17:00 on 8/24/64 and 03:00 on 8/23/64

(2) IL, T.J. Boyle to W.R. Vaughn, "Expected FSM-4 Performance",
May 6, 1964

(3) Weighted average =
$$\frac{\text{fringe} + \text{wall voltage flows} + \text{heat balance flow}}{2}$$

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B. System Temperatures

Important system temperatures are shown in Figure 2. Both the converter outlet and average NaK temperatures were higher than the corresponding temperatures during FSM-1 thermal reference because of the higher flowrate in FSM-4. The expansion compensator and instrument compartment temperatures were close to FSM-1 and were not excessive. (Expansion compensators were not installed in FSM-4, but thermocouples were installed on the position transducers which lay on top of the thermal barrier). The compensators exhibited a hysteresis which was due to holding the system at each plateau for too short a time to reach equilibrium. The equilibrium temperature will be closer to the lower curve.

The converter radiator fin temperatures are substantially higher than those measured during FSM-1 testing. However, the FSM-1 thermocouples were known to be reading low and the corrected readings are close to those measured on FSM-4:

	<u>FSM-1 Corrected</u>	<u>FSM-4 Measured</u>
Average NaK	950°F	950°F
Fin #1	707 ± 11°F	704°F
Fin #72	590 ± 8°F	592°F

These high FSM-4 fin temperatures result in several conflicts which are being investigated:

- 1) The thermoelectric ΔT of 272°F is lower than the 285° which was predicted using T/E module test results (see Table III). However, T/E test data does show significant variation among modules which could affect either module or FSM-4 test results.
- 2) The FSM-4 fin thermocouples were believed to require upward corrections for fin effect, poor thermal contact, and location on low flow legs. These corrections would decrease the thermoelectric ΔT to only 250°F and increase the heat rejected by the converter radiators to 37.6 kw; neither of these values is credible.

C. System Heat Losses

The core heater power requirements and reactor thermal power (core heater power - I²R losses) are shown in Figure 3, together with the reactor thermal power from the FSM-1 thermal reference. It can be seen that the heat input was considerably greater during the first half of the FSM-4 test when the temperature was being increased, e.g., at 557° on August 21 the core heater power was 15.3 kw while on August 23 when temperature was being decreased, it was only 13.4 kw.

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This was expected since the system was not at thermal equilibrium when the data was taken. While the NaK temperature was being increased the neutron shield, reflector, structure, etc., were absorbing substantially more heat than at equilibrium; when the NaK temperature was decreased these components then acted as heat sources reducing the required core heater power. Considering this lack of thermal equilibrium during both the FSM-4 and FSM-1 thermal reference tests, the agreement between the two curves is good.

Table II shows a detailed heat balance of the FSM-4 system. The results of the FSM-1 heat balance are shown for a slightly lower core outlet temperature. The only significant changes from FSM-1 are in the pump and converter radiator losses and the shunt losses. The increased pump and converter losses are due to increased heat rejection efficiency caused by thicker pump fins and the higher emissivity of the FSM-4 converter radiator coating. The shunt losses are lower because the FSM-4 NaK tubes and hot straps are well wrapped with gold foil, whereas about half the gold foil on FSM-1 was missing.

There are two balance points in the FSM-4 heat balance: 1) At the heat delivered to the converter - At this point there is a large discrepancy which is believed to be due to an error in measured flow. (See Section II.E); 2) At the heat rejected by the converter radiators - At this point there is good agreement. However, as mentioned in Section III.B the radiator fin temperatures have not been corrected, and the corrections would increase the heat loss to 37.5 kw which is much too high. This could be caused by using either an emissivity or fin temperature which is too high. Since the emissivity value was confirmed by measurement after NaK loading, the fin temperatures are suspect.

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Table II
System Heat Losses

		FSM-4 ⁽¹⁾	FSM-1 ⁽²⁾
Core Outlet Temperature, °F		1010°	995°
Average Converter NaK Temperature, °F		950°	927°
Measured Core Heater Power, kw		42.2 ^{±1}	39.8 ± 0.4
Losses - I ² R	1.1	1.1 ± 0.2	
Heat to Reactor (Reactor Thermal Power)		41.1	38.7 ± 0.4
Losses - Reflector Sides	0.9	0.9	
Reactor & Reflector Top	0.6	0.5	
Pump	1.0	0.7	
Reactor Outlet Lines	0.1	0.1	
Reactor Support Legs	0.4	0.4	
Neutron Shield Case Top	0.5	0.6	
Total	3.5	3.2	
Heat Delivered to Converter		37.6 ± 1.1	35.5
Measured Heat Delivered to Converter		(34.3)	(34.2)
(Q = mGAT) ⁽³⁾			
Losses - Upper Torque Box	0.5	0.5	
Lower Torque Box	0.7	0.7	
Structure to Vac.Ves.	1.3	1.2	
NaK Tubes to Vac.Ves.	0.3	0.3	
Instrument Compartment	0.5	0.5	
Low Pressure Convection	0.2	0.1	
Total	3.5	3.3	
Electrical Power Output	0.5	0.4	
Total	4.0	3.7	
Heat Rejected by Converter Radiator		33.6	31.8
Heat Rejected by Converter Radiators			
(Based on Fin Temp.)		34.6	30.6 ± 1.2
Losses - Unaccounted for		-1.0	-1.2
Shunt Losses from Structure, Pellets,			
NaK Tubes & Hot Straps to Radiator	2.6	3.0	

(1) Based on data taken at 03:00 on 8/23/64.

(2) L.L. Bixson, "Evaluation of the Thermal Reference Test of the 10FSM-1 NNPU", TDR 9707, to be published

(3) The flowrate used is the average of the fringe flux and wall voltage only.

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D. Converter Electrical Performance

Figure 4 shows the electrical power output as a function of average converter NaK temperature. Data from FSM-1 and FS-1 thermal reference tests are also plotted. As expected the FSM-4 power output was improved due to increased thermoelectric materials efficiency and heat rejection capability. The power output of FSM-4 was 9-10% greater than FSM-1 and 15% greater than FS-1. The increased power at 1010°F was in good agreement with the predicted values; however the measured thermoelectric ΔT was significantly lower than predicted. If the measured ΔT is correct then the predicted power output would be substantially lower. This is shown in Table III.

Two possible reasons for this discrepancy are being investigated: 1) the radiator fin thermocouples may be in error on the high side, resulting in a thermoelectric ΔT which is too low, or 2) the average value of 0.4 watts/couple and .085 volts/couple @ 305° ΔT may not apply to the couples used in the FSM-4 converter.

Figure 5 shows the FSM-4 open and closed circuit voltages and the FSM-1 open circuit voltage as a function of average converter NaK temperature. As with power output, the performance is improved over FSM-1 and very close to the predicted value.

Figure 6 shows the converter current as a function of average NaK temperature.

Figure 7 shows the FSM-4 and FSM-1 converter internal resistance determined by the open circuit voltage technique as a function of average NaK temperature. The FSM-4 resistance is very close to the predicted value, slightly above that measured during FSM-1 thermal reference, and substantially below FSM-1 after the 90-day test. The FSM-1 internal resistance was more dependent on the temperature above 850°F. The apparent lower FSM-1 resistance during thermal reference may not be real because of the inadequate technique in use for measuring open circuit voltage at that time. The ambient resistance of the FSM-4 converter increased from 1.00 ohms before the test to 1.08 ohms afterward. This degradation in resistance can also be seen at 550°, 850° and 950° where the higher point in each case was taken during cool-down of the system.

The most serious problem observed during the FSM-4 thermal reference test was the severe decrease in converter resistance to ground shown in Figure 8. (No decrease in power output was observed, probably because the converter and load were ungrounded). Although the

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Table III
Converter Temperatures and Power

	<u>Measured</u> ⁽¹⁾	<u>Predicted</u>
Average Converter NaK Temperature	950°F	944°F
Average Converter Radiator Temperature	648°F ⁽²⁾	630°F
Average Thermoelectric ΔT	272°F	285°F
Power Output, watts		
Calculated (3)	458	503
Measured	509	-
Open Circuit Voltage		
Calculated (3)	54.5	57.2
Measured	57.3	-

(1) Based on average of two computer runs.

(2) No corrections have been made for TC location on low flow legs, fin effect, or poor thermal contact.

(3) IL, L.L. Lepisto to J.J. Gill, "Expected Initial Steady State Performance Characteristics of FSM-4 SNAP-10A T/E Converter", May 1, 1964

$$\text{Power} = (0.4 \text{ watts/couple})(1440 \text{ couples}) \left(\frac{\Delta T_{T/E}}{305^\circ\text{F}} \right)^2$$

$$\text{Open Circuit Voltage} = (.085 \text{ volts/couple})(720 \text{ couples in series}) \times \left(\frac{\Delta T_{T/E}}{305^\circ\text{F}} \right)$$

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resistance of the alumina resistors would be expected to decrease by about four orders of magnitude in going from ambient to 950°F, the initial ambient converter resistance was about two orders of magnitude less than calculated assuming the alumina resistors were the only path to ground. This indicates that the alumina is not the sole determinant of resistance and that it may not be correct to assume that the converter will show the same temperature dependency. Figure 8 also shows that the resistance to ground did not return to its original value as the temperature decreased. However, the resistance did increase to about 10K as a function of time after ambient temperature was reached:

<u>Time</u>	<u>Isolation Resistance, Ohms</u>
Before thermal reference test(8/17/64)	$1.2-1.5 \times 10^6$
Just after thermal reference test	1×10^3
2 days after	5×10^3
7 days after	10×10^3
10 days after	8×10^3

The FS-1 resistance to ground data shown in Figure 8 also shows a strong temperature dependency. The step change in resistance was caused by several shorts which also decreased converter power output. During the test shown the resistance did not recover because of the NaK leak; however, in previous thermal tests, the shorts disappeared as temperature decreased and the resistance to ground returned to several hundred K within a few days after hot testing.

No information is yet available on the cause or mechanism of the decrease in FSM-4 resistance to ground. An intensive investigation is underway.

E. Pump Performance

The FSM-4 NaK flowrate is in question because of discrepancies between the flow as indicated by a heat balance, fringe flux, wall voltage, NaK to pump fin base ΔT . This is shown in Table IV.

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Table IV
NaK Flowrate at 1010°F

<u>Method</u>	<u>Flowrate, gpm (1)</u>
Heat Balance	14.1 ± 0.6
Fringe Flux	13.2
Wall Voltage	12.6
Weighted Average (2)	<u>13.5</u>
NaK to Pump Fin Base ΔT	12.9

(1) Based on the average of two computer runs.

(2) Weighted average =
$$\frac{\text{Fringe} + \text{wall voltage} + \text{heat balance}}{2}$$

Although this is the same sort of discrepancy as occurred in the FSM-1 test, there are important differences:

- 1) The FSM-1 discrepancies were much larger - up to 3.5 gpm difference compared to 1.5 gpm for FSM-4.
- 2) The quality of the acceptance test data for recent pumps (including FS-1 and FSM-4) is greatly improved over FSM-1.
- 3) The acceptance test loop flowmeters have been recalibrated since the testing of the FSM-1 pump.
- 4) New millivolt to flow correlations have been developed so that acceptance test data is no longer used directly, but is modified to account for differences between SNAP unit and test loop pressure drop characteristics. These correlations make the wall voltage much more accurate and also improve the fringe flux.

The FS-1 wall voltage and fringe flux, using the new correlation, indicated almost identical flows at all temperatures during thermal reference testing of FS-1. This indicated flow in turn agreed very closely with the flow predicted from NaK to fin base ΔT. In addition the heat delivered to the converter (calculated from $Q = m\dot{C}\Delta T$) agreed to within 0.4 kw of the value calculated from the FSM-1 heat balance. This excellent agreement obtained with the FS-1 pump indicates that the acceptance loop flowmeter calibration and the correlation methods are valid and that the FSM-4 problem may be specific to the FSM-4 system or acceptance test data. A detailed investigation of the problem is underway. For the present the weighted average flow shown in Table IV will be used.

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Figure 9 shows the flowrate based on fringe flux and wall voltage as a function of core outlet temperature. Pump acceptance test data (at the calculated FSM-4 system pressure drop) and several heat balance flow values are also shown. As expected, the acceptance test data rises above the system data as temperature increases. This happens because the NaK to pump fin base ΔT (the thermoelectric driving force) in the system is less than during acceptance test due to the presence of the hot reactor below the pump. Figure 10 shows this. The average installed ΔT is even lower than the measured values plotted because the fin thermocouples are located at the top of the fin, farthest away from the hot reactor. (FSM-1 data indicated the bottom was as much as 80°F hotter at 1010°F for an old style pump with thin fins). In Figure 11 the average system flow (based on the average of fringe flux and wall voltage flow) has been replotted as a function of measured NaK to fin base ΔT . The discrepancy in flowrate is again apparent since the system curve would be expected to fall below the acceptance test data (because the actual average NaK to fin base temperature is lower than the measured ΔT).

F. Flight Instrumentation Performance

Most of the flight instrumentation performed satisfactorily. Thermocouples and resistance thermometers in particular showed a vast improvement over FSM-1 and a significant improvement over FS-1. Only one of 29 TC's and one of 16 RT's failed. (However, it should be noted that FSM-4 has not yet undergone shock and vibration). Thermocouples at the same locations on the NaK tubing showed a scatter of $\pm 2^\circ\text{F}$ from the average at 1010°F. The installations were good enough to detect the 5° ΔT from the pump outlet to the upper manifold. The TABRD stud was within 10° of the NaK temperature - so close that it is doubtful that this TC serves any useful purpose. Those converter radiator fin TC's which should have been indicating the same temperature showed a $\pm 5^\circ\text{F}$ scatter and appeared to be reading about the right temperature (see Section III.B). There was no apparent converter shorting caused by the radiator fin TC's. All other TC's performed satisfactorily except for one reflector TC. (This is the second failure out of six reflector TC's tested). The four heat shield TC's were not tested.

Only one of sixteen resistance thermometers failed (RT-3). For the eleven RT's which could be compared to TC's, the maximum difference between the TC's and an RT (in its operating range) was only 6°F.

The converter voltage and current taps performed satisfactorily, but the converter degradation device indicated too high an internal resistance (see Table V) and should be investigated.

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Table V
Converter Internal Resistance, Ohms

Average NaK Temperature, °F	$\frac{E_{oc} - E_{cc}}{I}$	CZ-1	% Difference
557°	1.32	1.48	+ 12%
950°	1.61	1.93	+ 20%

The output of the flow transducers seemed satisfactory, but the conversion from millivolts to flow is questionable (see Section III.E).

The control drum and expansion compensator position transducers operated satisfactorily. The control drum transducers undergo a significant shift in calibration with increasing temperature. This will be taken into account for the nuclear systems using component test and FSM-4 thermal reference data. The expansion compensator transducers are slightly temperature dependent, but this effect is no greater than the scatter in calibration data.

The performance of position switches, status indications, and nuclear detectors was not investigated.

IV. Problem Areas and Further Work

1. The only major FSM-4 system problem is the low converter to ground resistance. A large number of tests are being performed on the converter to determine the cause and cure.
2. As a result of this preliminary analysis, several conflicts with either predicted or other measured results have been uncovered. They concern system flowrate, radiator fin temperatures, power output/couple, and the converter degradation device. A special effort should be given to resolving these conflicts.
3. The data reduction computer program will be revised to take advantage of the results of this preliminary analysis. The nine reference runs used as a basis for this report will then be reprocessed. Two additional runs at each plateau and six additional runs at 1010° will also be processed.

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FIGURE 1-10FSM-4 CORE OUTLET
TEMPERATURE HISTORY

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FIGURE 2
10 FSM-4 SYSTEM
TEMPERATURES

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FIGURE 3

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FIGURE 4 - IOFSM 4
CONVERTER ELECTRICAL
OUTPUT

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FIGURE 6 - OFSM-4 CONVERTER
CURRENT

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FIGURE 8 OFSM-4 CONVERTER
RESISTANCE TO GROUND

K-E
SEMI-LOGARITHMIC 359-91
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

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FIGURE 11-10FSM-4 PUMP PERFORMANCE

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