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SNAP 10A FS-3

OPERATIONS

(Title Unclassified)

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ADDENDUM
SNAP REACTOR,
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M-3679 (44th Ed.)

SNAP 10A FS-3

OPERATIONS

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By

R. E. BEDFORD
J. P. BEALL

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ABSTRACT

This addendum, together with the original report, is the final report on the nuclear qualification test of the SNAP 10A Flight System No. 3 (S10 FS-3). This test was terminated after a successful, uninterrupted demonstration at design conditions of 10,000 hr. This was the longest known uninterrupted nuclear reactor operation. This test was conducted for the Atomic Energy Commission by Atomics International at the Santa Susana Nuclear Field Laboratory.

This report details the operational history of the test, and gives an analysis of the behavior of the system components. A more detailed analysis of the reactivity behavior of the reactor is given in NAA-SR-11397, "SNAP 10A Reactor Performance."

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I. INTRODUCTION

The tests described herein represent a continuation of the automatic startup and the 90-day full-power operation tests of the SNAP 10A FS-3 system as described in Sections VI-A and VI-B of NAA-SR-11206, "Preliminary Test Results SNAP 10A FS-3."

The SNAP 10A design objective of 1 year of continuous full-power operation was achieved at 15:02 hr on January 22, 1966, and operation was continued with no intentional change in conditions until February 16, 1966. On February 16, 1966, after 390 days of operation, the fine control drums were inserted to increase the reactor average coolant temperature to near the initial temperature measured at controller deactivation on January 25, 1965. Following the temperature increase active control was maintained for 72 hr. Passive control was then resumed and operation continued at the increased temperature until the system was shut down on March 15, 1966, after 10,000 hr of operation at design conditions. The performance of the test system and test support systems throughout the test was excellent. The fact that the test was conducted for 10,000 hr with no interruption attests to the reliability of all systems. The provision of redundancy for critical components in the test facility and test support systems made it possible to perform maintenance on any malfunctioning equipment without interrupting the test.

The following summary presents the parameters of interest for the 10FS-3 operation:

1) Total critical time (hr) — 10,075
2) Total time above 900°F (hr) — 10,005.5
3) Longest known continuous uninterrupted reactor test (hr) — 10,028
4) Total converter electrical energy release (kwh) — 4038.3
5) Total thermal energy released (kwh) — 382,944.

System performance at 90 days of operation, at the end of 1 year of operation, at stabilization following the temperature increase, and just prior to shutdown are summarized in Table 1. Table 1 also includes, for comparison, the values of the corresponding system parameters observed at controller deactivation on January 25, 1965.

TABLE 1

SUMMARY OF SNAP 10A FS-3 PERFORMANCE

Parameters	Controller Deactivation 1/25/65	End of 90-Day Test 4/22/65	End of 1-Year Test 1/22/66	Stable After Temperature Perturbation 2/19/66	Just Prior to Shutdown 3/15/66
Temperatures (°F)					
Reactor outlet	1032	987	971	1054	1055
Reactor inlet	909	860	843	909	908
Reactor average	971	924	907	982	982
Converter inlet	1025	979	963	1046	1046
Converter outlet	910	861	846	910	910
Converter average	968	920	904	978	978
Radiator inlet	727	708	701	748	744
Radiator outlet	614	579	571	606	605
Mean structure	773	750	739	797	798
Expansion compensator	746	718	708	765	766
Chamber wall	123	124	124	136	134
Reactor Thermal					
Power (kw)	41	37	36	42	42
Flow (gpm)	14.3	12.6	12.1	12.6	12.4
Flow degradation (%)	1.4	11.4	14.3	15.0	15.3
Electrical					
Power output (watts)	512	414	377	482	477
Open-circuit voltage (volts)	57.55	54.82	54.01	62.25	62.43
Closed-circuit voltage (volts)	30.63	28.93	27.77	31.50	33.12
Current (amp)	16.72	14.32	13.56	15.29	14.41
Internal resistance (ohms)	1.61	1.81	1.94	2.01	2.03
Isolation resistance (ohms)	360	242	279	241	236
Efficiencies (%)					
System	1.26	1.11	1.05	1.16	1.13
Converter overall	1.37	1.20	1.13	1.26	1.23
Converter-Carnot	20.8	20.1	19.7	21.1	21.1
Converter-device	6.56	5.98	5.76	5.97	5.84

II. ONE-YEAR ENDURANCE TEST

Following completion of the 90-day test, the system continued to function well throughout the balance of the 1-year test. The downward trend in reactor average coolant temperature observed during the 90-day test continued, at a decreasing rate, well into the 1-year test. Figure 1 shows both the measured and predicted reactor average temperature during the passive control period. The average temperature decreased from the initial 971°F to a minimum of 906°F on October 10, 1965, after 261 days of operation. Subsequently, the average temperature increased slightly to 907°F and remained near this value until the temperature was intentionally increased on February 16, 1966.

Specific reasons for the observed departure from the predicted temperature variation are outlined in NAA-SR-11397, "SNAP 10A FS-3 Reactor Performance." The temperature perturbation test (described in Section III of this report) was undertaken primarily as an effort to provide more insight into the reactivity effects causing the temperature drift.

Figures 2 and 3 show the reactor inlet and outlet coolant temperatures; the same drift as in reactor average temperature is apparent. Reactor thermal power as calculated from system heat balance is shown in Figure 4. System thermal performance during the 1-year test is summarized in the detailed system heat balances of Tables 2, 3, and 4. There are two balance points in the heat balances:

1) At the heat delivered to the converter — at this point there is good agreement;

2) At the heat rejected by the converter radiators — at this point there is a large discrepancy.

This discrepancy could be caused by either high fin emissivity or high fin temperatures. Since the emissivity was not measured following FS-3 thermal reference tests the cause of the discrepancy has not been definitely determined; however, based upon FSM-4 experience, the fin temperatures are suspect. Figures 5 and 6 show converter and component temperatures throughout power operation. System thermal efficiency is shown in Figure 7.

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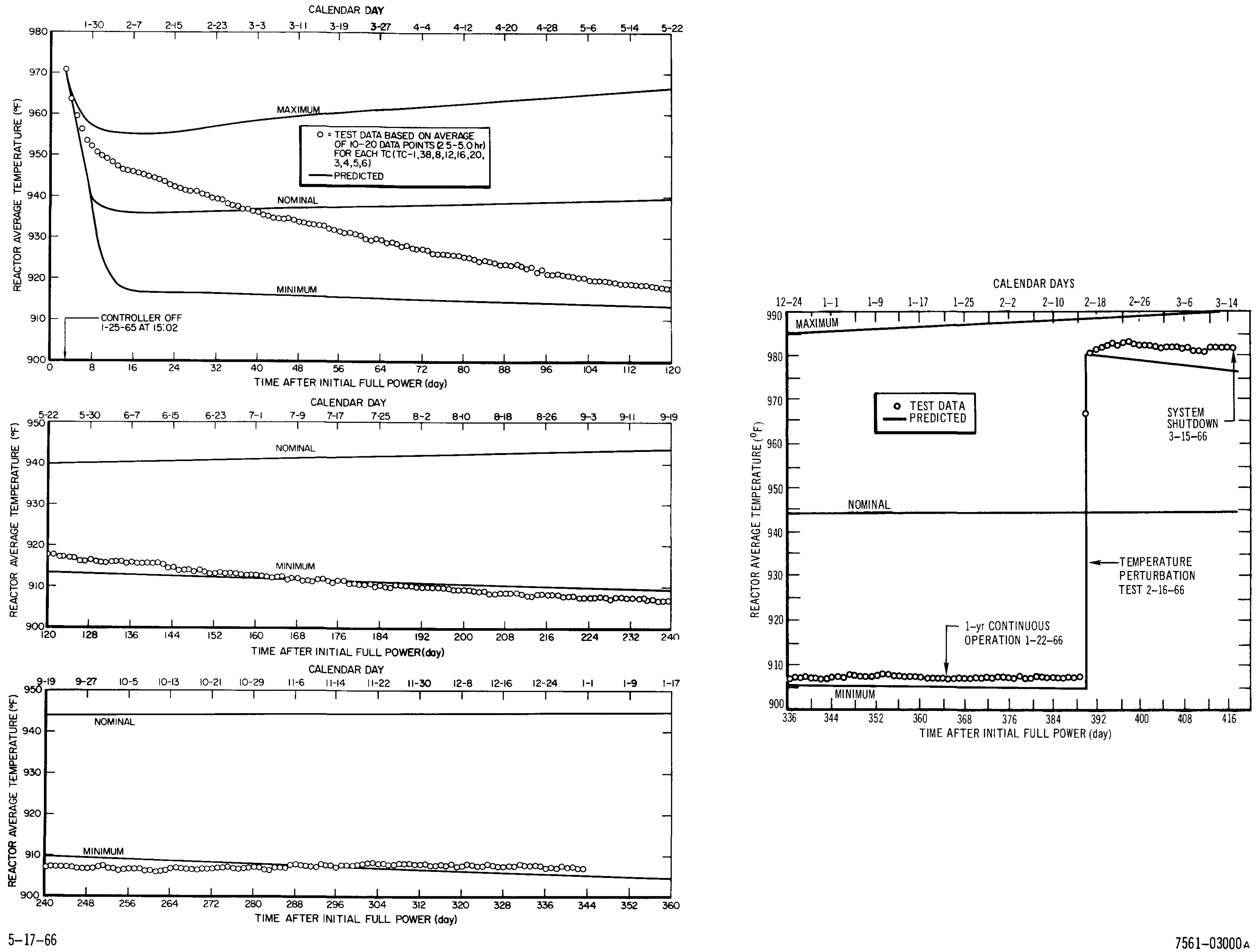

Figure 1. FS-3 Average Temperature

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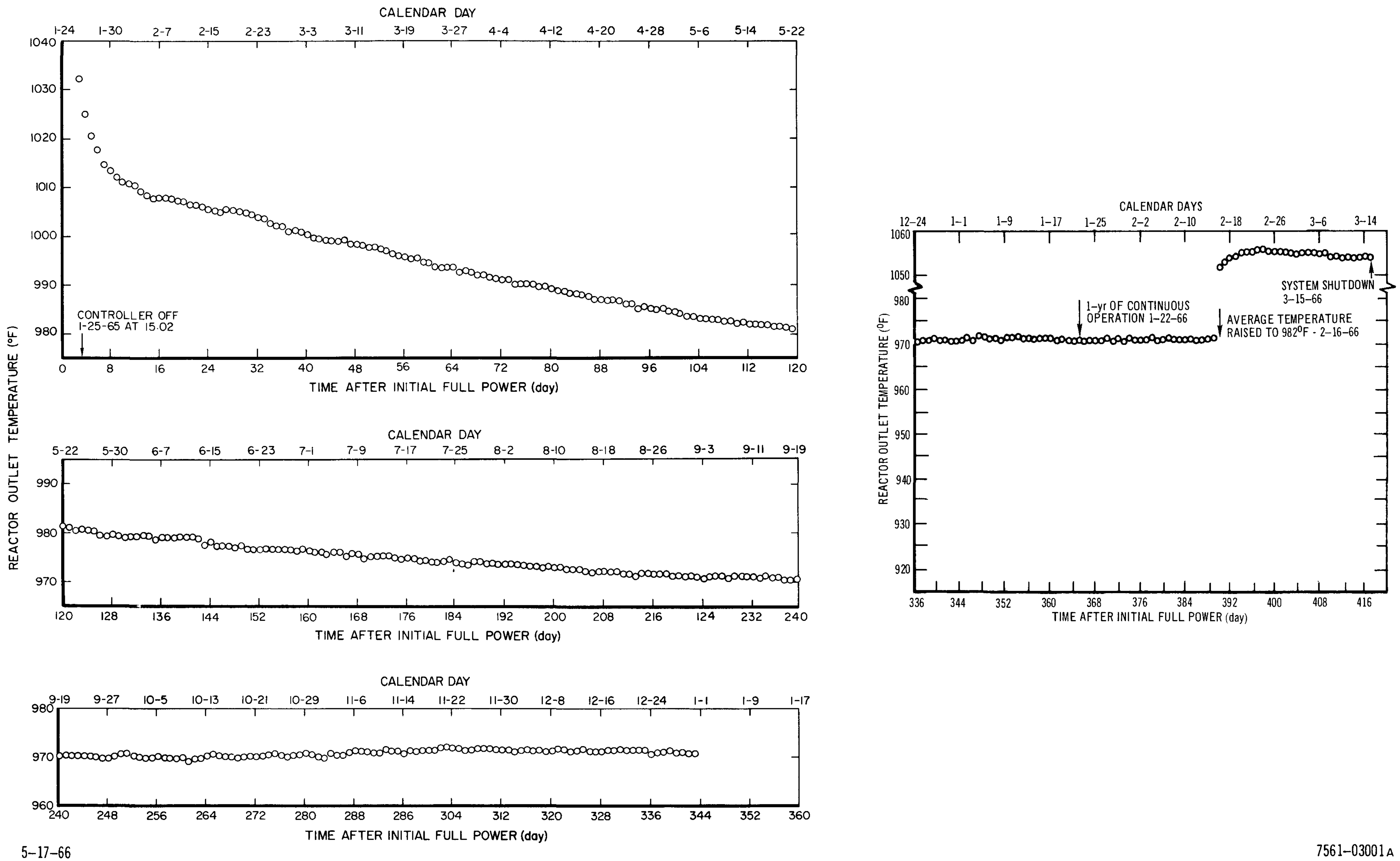

Figure 2. FS-3 Reactor Outlet Temperature

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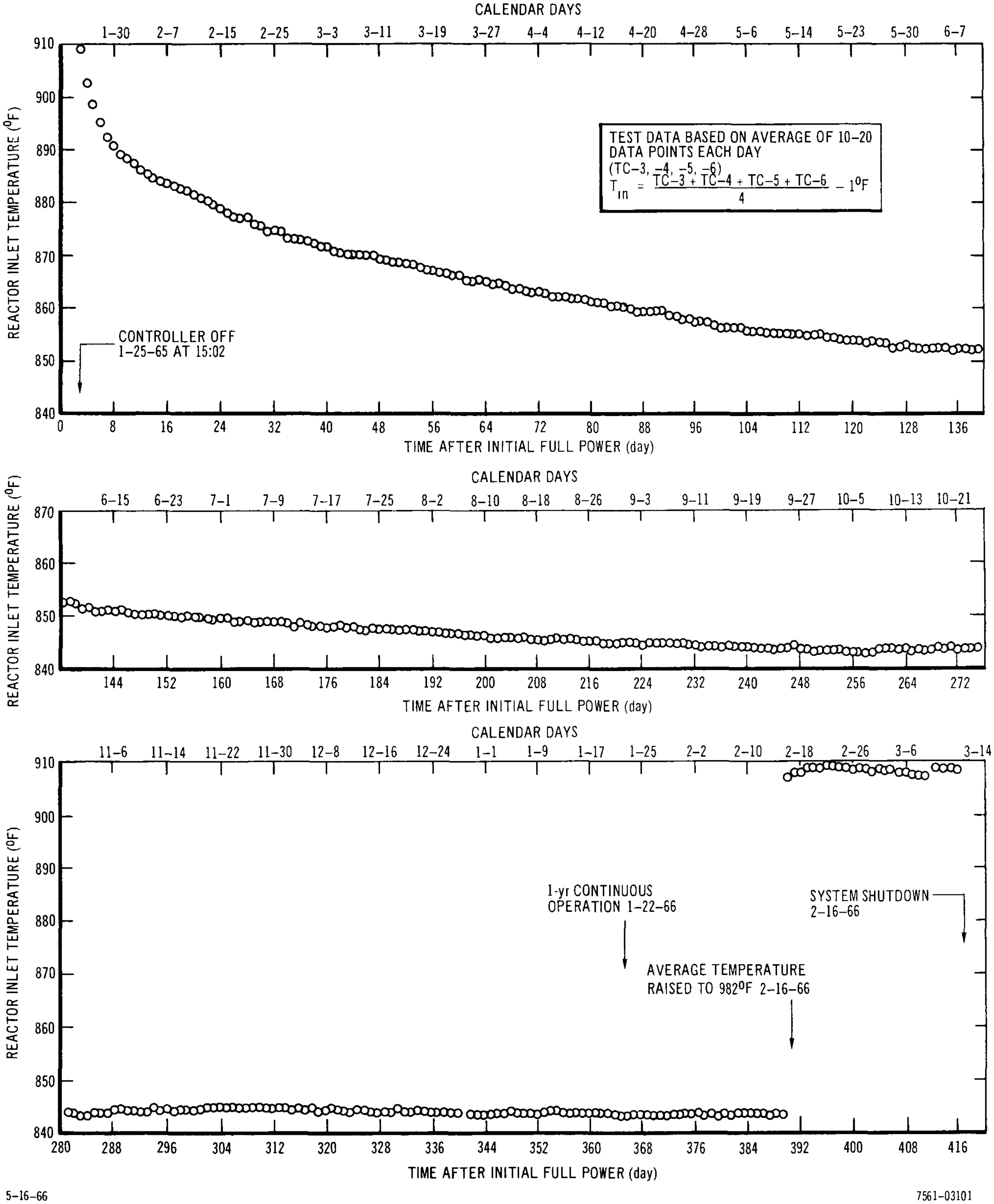

Figure 3. FS-3 Reactor Inlet Temperature

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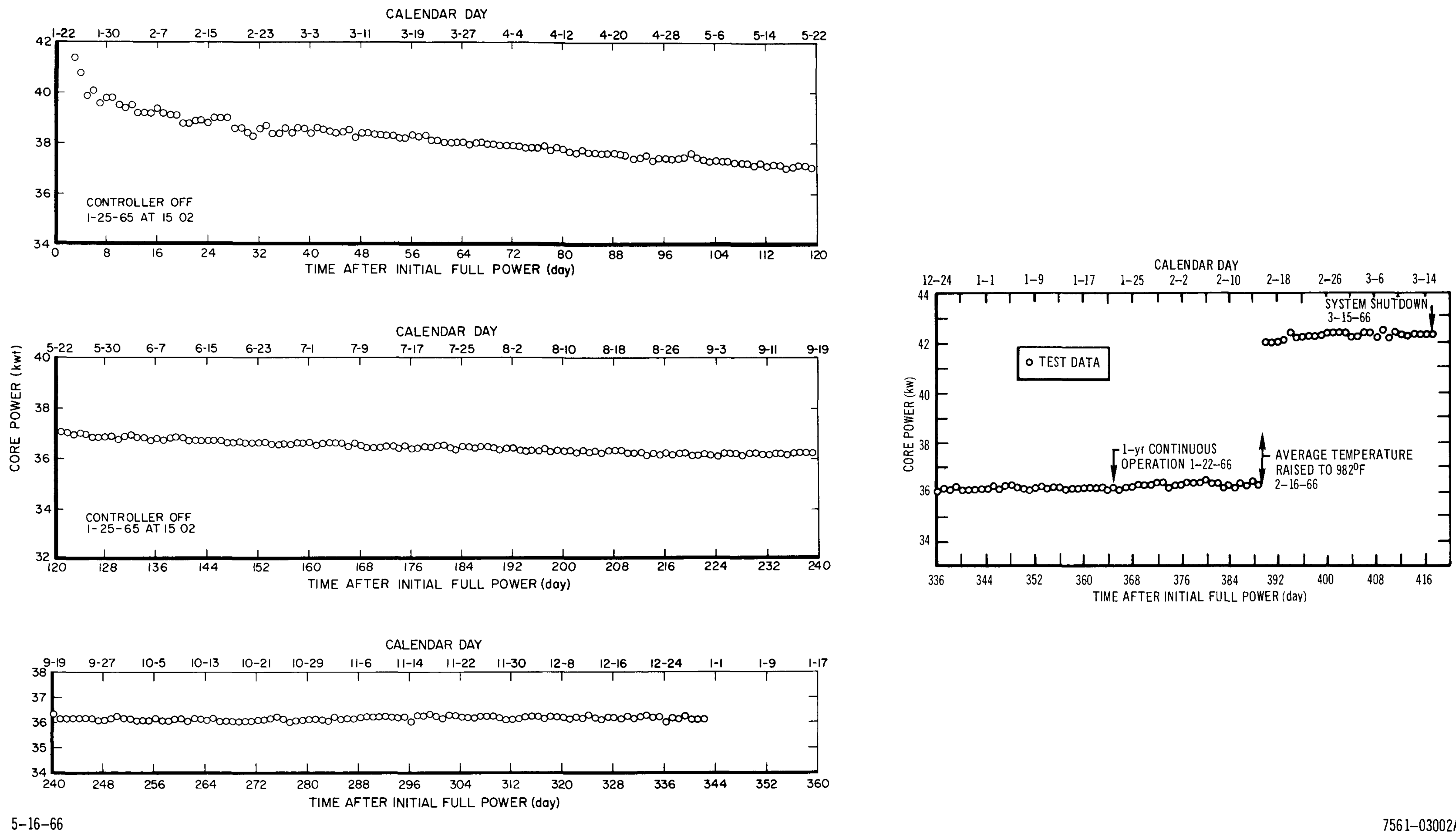

Figure 4. FS-3 Core Thermal Power

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TABLE 2

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
AT CONTROLLER DEACTIVATION (1/25/65)

Calculated Reactor Thermal Power		39.91
Gains — Reflector Internal Heating	0.33	
Losses — Reflector	0.48	
Reactor top	0.29	
Reactor bottom	0.24	
Total	0.68	
Calculated Heat Gain by NaK in Core		39.23
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(39.07)
Gains — Neutron Shield Internal Heating	0.12	
Losses — Pump	1.03	
Supply lines	0.15	
Reactor support legs	0.59	
Neutron shield	(0.83)	
Upper torque box	0.80	
Total	2.45	
Calculated Heat to Converter		36.78
Measured Heat to Converter (Flow Temperature Drop)		(36.92)
Losses — Structure to Neutron Shield	0.16	
Structure to vacuum vessel	1.42	
NaK legs to vacuum vessel	0.33	
Return lines to structure	(0.14)	
Lower torque box	0.80	
Instrument compartment	0.50	
Low-pressure convection	0.15	
Electrical power produced	0.50	
Shunt losses to radiators	(2.86)	
Total	3.86	
Calculated Heat Rejected by Converter Radiator		32.92
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(37.38)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

TABLE 3

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
AT END OF 90-DAY TEST (4/22/65)

Calculated Reactor Thermal Power		37.18
Gains — Reflector Internal Heating	0.43	
Losses — Reflector	0.44	
Reactor top	0.27	
Reactor bottom	0.19	
Total	0.47	
Calculated Heat Gain by NaK in Core		36.71
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(36.85)
Gains — Neutron Shield Internal Heating	0.15	
Losses — Pump	0.95	
Supply lines	0.13	
Reactor support legs	0.51	
Neutron shield	(0.82)	
Upper torque box	0.76	
Total	2.20	
Calculated Heat to Converter		34.51
Measured Heat to Converter (Flow Temperature Drop)		(34.35)
Losses — Structure to Neutron Shield	0.22	
Structure to vacuum vessel	1.32	
NaK legs to vacuum vessel	0.29	
Return lines to structure	(0.10)	
Lower torque box	0.72	
Instrument compartment	0.50	
Low-pressure convection	0.14	
Electrical power produced	0.41	
Shunts losses to radiators	(2.66)	
Total	3.60	
Calculated Heat Rejected by Converter Radiator		30.91
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(33.70)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

TABLE 4

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
AT END OF 1-YEAR TEST (1/22/66)

Calculated Reactor Thermal Power		36.06
Gains — Reflector Internal Heating	0.46	
Losses — Reflector	0.44	
Reactor top	0.26	
Reactor bottom	0.17	
Total	0.41	
Calculated Heat Gain by NaK in Core		35.65
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(35.63)
Gains — Neutron Shield Internal Heating	0.16	
Losses — Pump	0.94	
Supply lines	0.13	
Reactor support legs	0.48	
Neutron shield	(0.80)	
Upper torque box	0.73	
Total	2.12	
Calculated Heat to Converter		33.53
Measured Heat to Converter (Flow Temperature Drop)		(33.01)
Losses — Structure to Neutron Shield	0.22	
Structure to vacuum vessel	1.27	
NaK legs to vacuum vessel	0.27	
Return lines to structure	(0.09)	
Lower torque box	0.70	
Instrument compartment	0.50	
Low-pressure convection	0.14	
Electrical power produced	0.38	
Shunt losses to radiators	(2.51)	
Total	3.48	
Calculated Heat Rejected by Converter Radiator		30.05
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(32.79)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

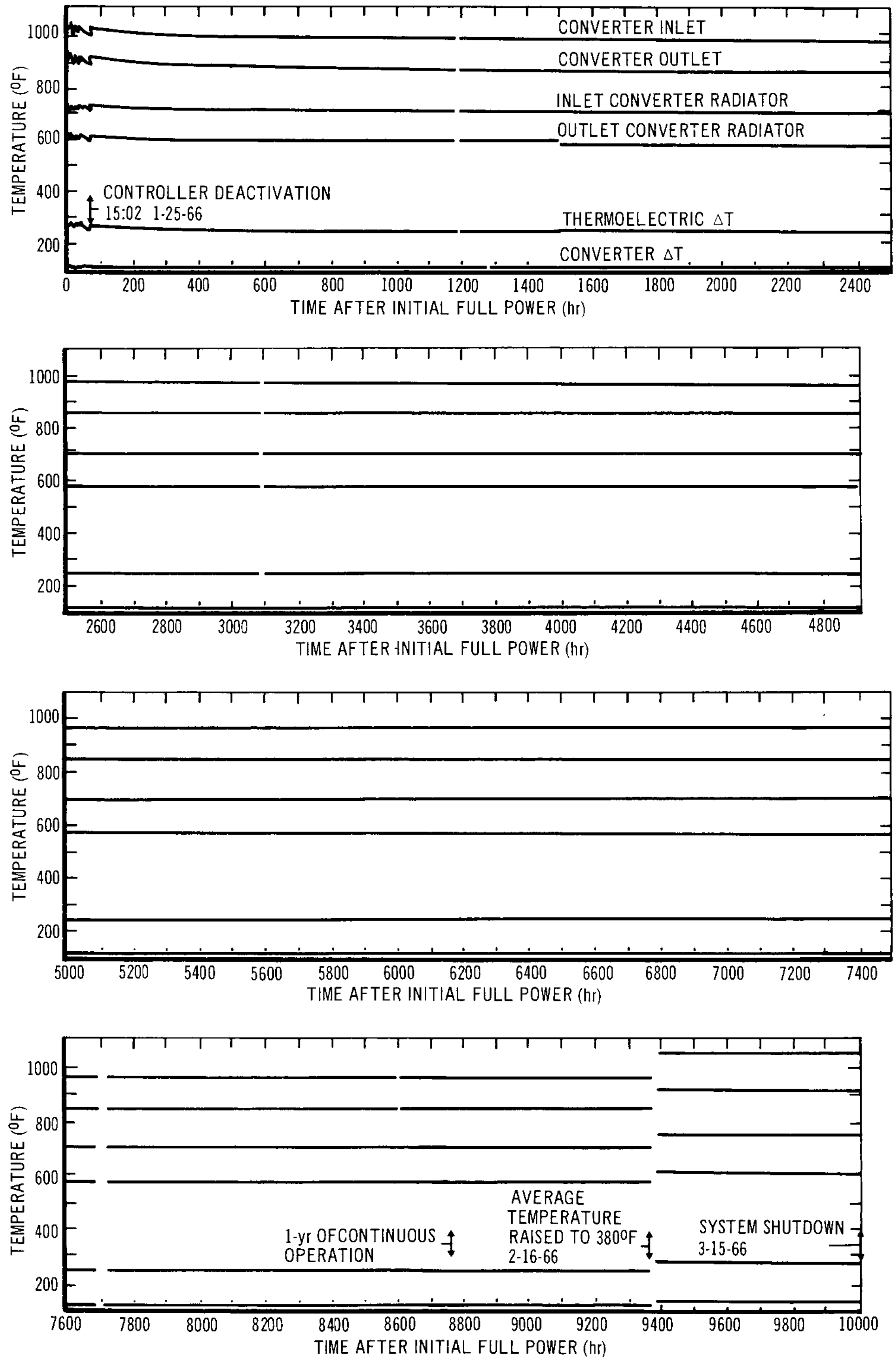

Figure 5. FS-3 Converter Temperatures

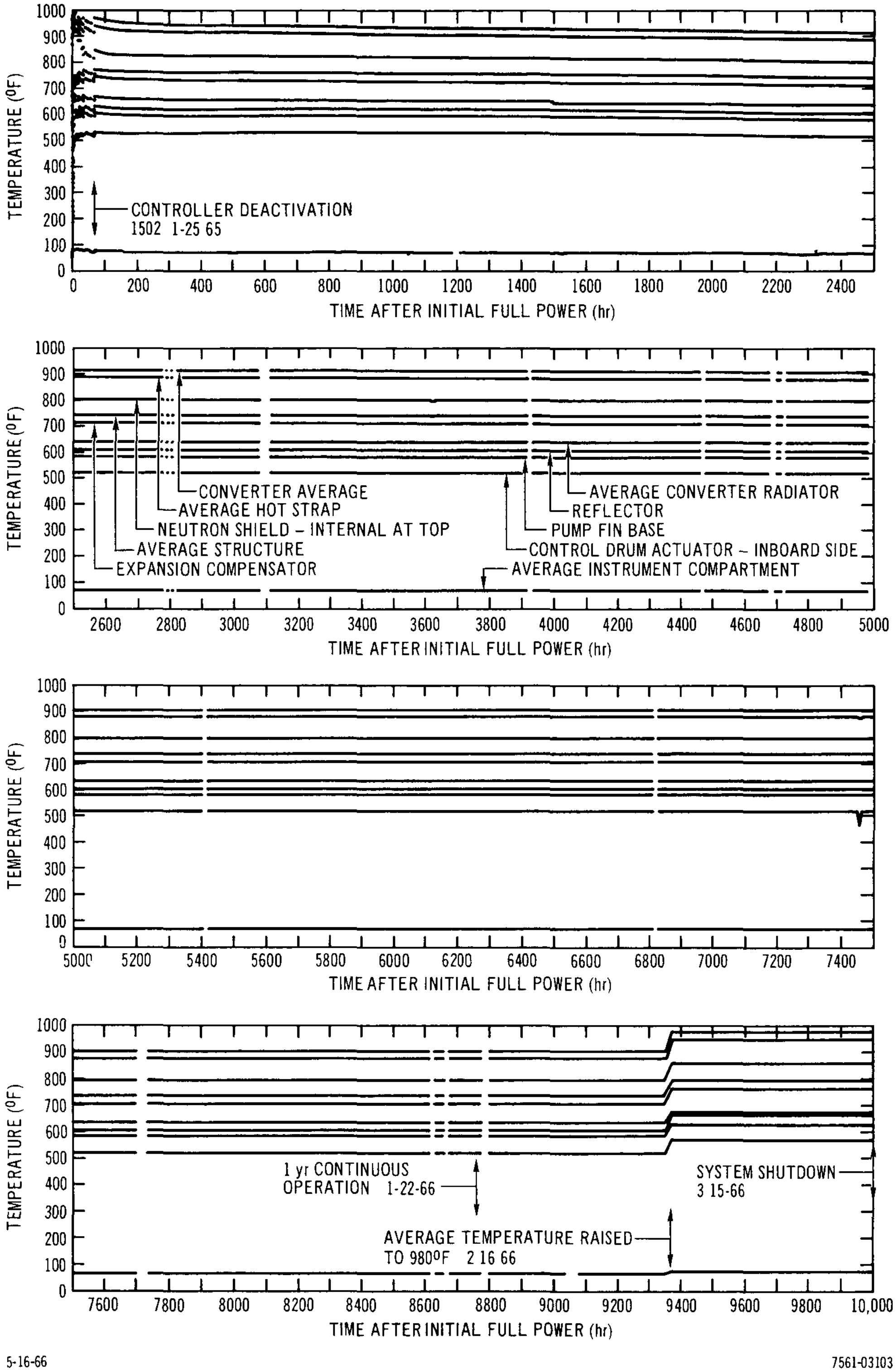

Figure 6. FS-3 Average Component Temperatures

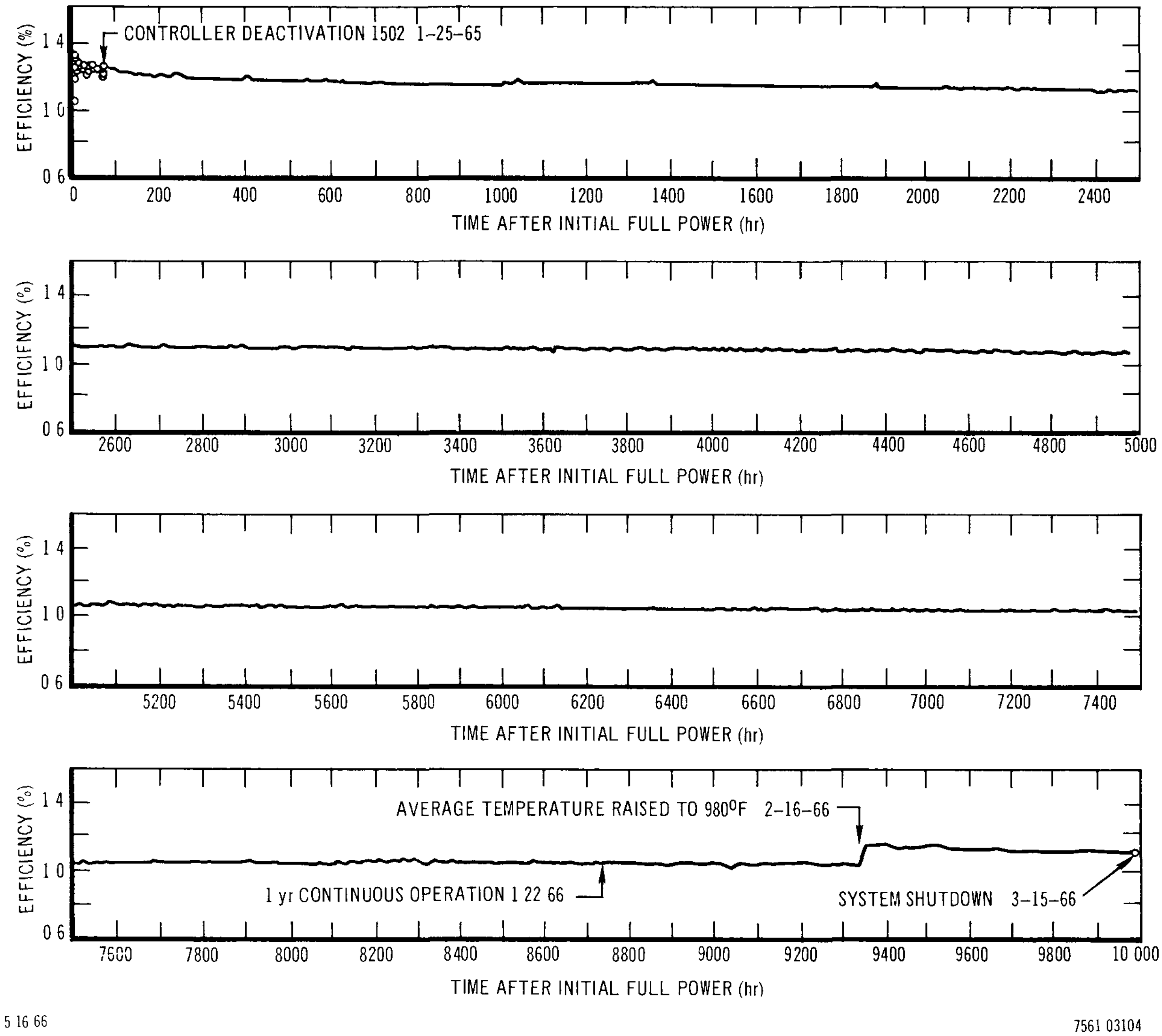

Figure 7. FS-3 System Thermal Efficiency

A. CONVERTER PERFORMANCE

The thermoelectric converter exceeded the predicted performance levels throughout most of the 1-year test. The measured and predicted performance of the converter is best described by reference to Figures 8 through 19. The power output at the end of 1 year of operation was 377 watts, or the equivalent of 420 watts in the space environment.

The converter power output is shown in Figure 8; also shown are the predicted converter power output and power output extrapolated to space conditions. The

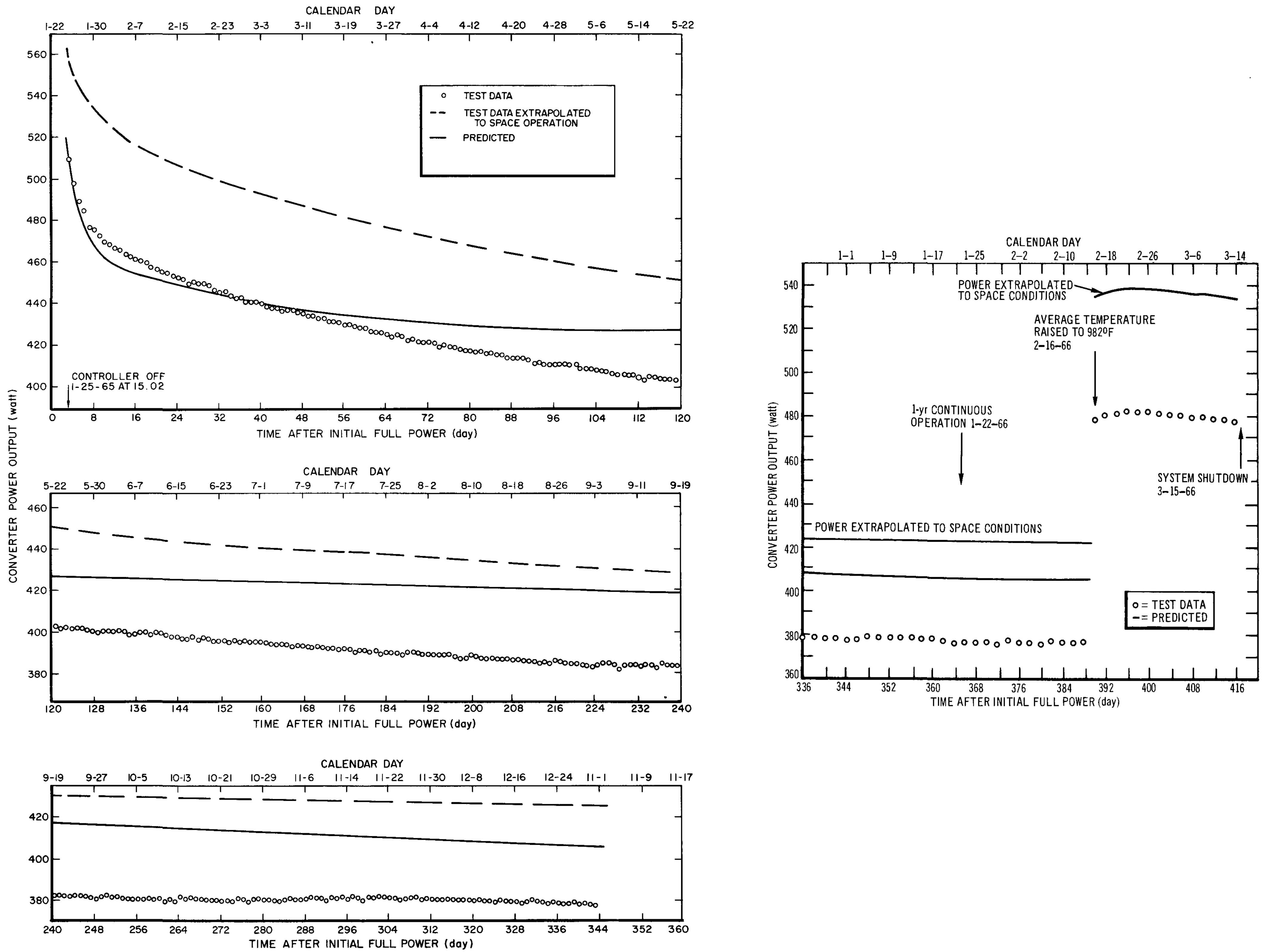

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Figure 8. FS-3 Converter Power Output

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predicted power is based upon the nominal predicted reactor average temperature shown in Figure 1 and the predicted converter degradation shown in Figure 10. As apparent from Figure 8, the electrical output was, during most of the power operation, considerably lower than predicted. The difference between the measured and predicted power is primarily a result of average temperature variation from the nominal predicted temperature.

Figure 8 is not, therefore, an accurate appraisal of converter performance. To remove the effect of decreasing temperature on the converter power, the data presented in Figure 9 have been normalized to an average converter NaK temperature of 920°F. With the temperature effect thus removed, it is apparent from Figure 9 that FS-3 converter performance was considerably better than predicted during most of the 1-year test.

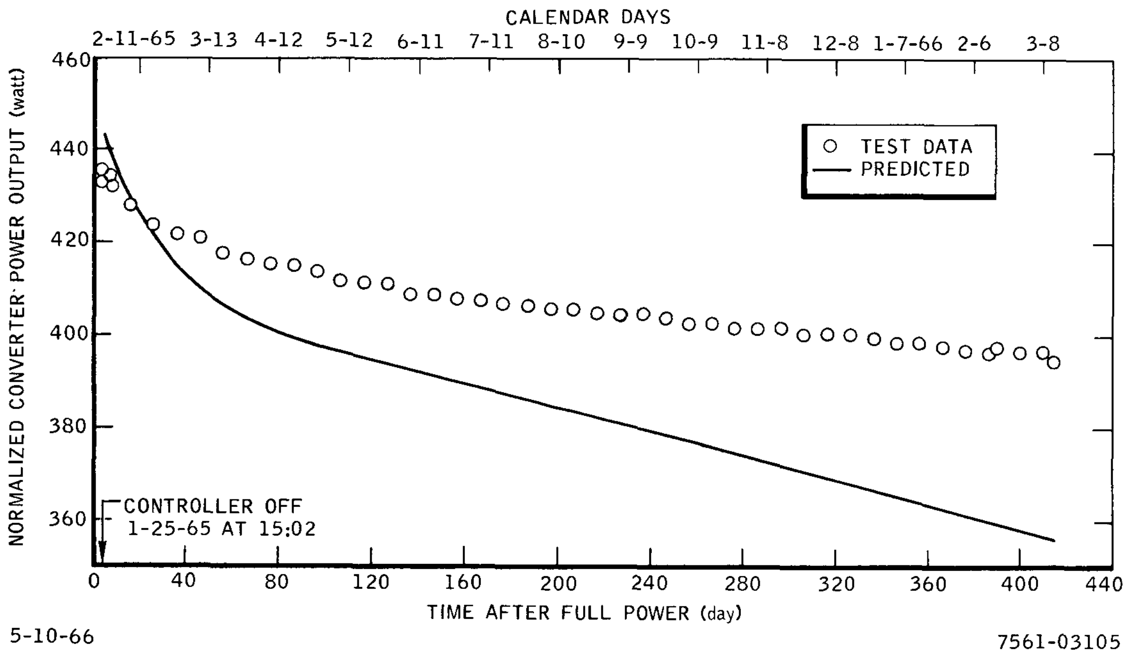

Figure 9. FS-3 Converter Power Output Normalized to Average Converter NaK Temperature of 920°F

It should be noted that the normalized power data of Figure 9 differ slightly from the data of Figure 27 of NAA-SR-11206. The difference is due to a change in the method of normalization of the power data based upon data taken during the temperature perturbation test (see Section III). During this temperature perturbation test the converter power output at matched load was observed to follow the relationship:

$$P_{mL} = g(t)T^{4.65}$$

where

P_{mL} = matched load converter power output (watts)

$g(t)$ = coefficient which is time dependent due to converter degradation

T = absolute average reactor coolant temperature (°R).

The data shown in Figure 9 were normalized using the preceding relationship, whereas earlier normalizations were based upon the relationship $P_{mL} = g(t)T^{4.9}$.

The extrapolation to space conditions was accomplished by adjusting the measured converter power output to account for the effects of (1) heat reflected from the vacuum chamber wall back to the converter radiator due to the departure of the chamber wall from the black-body conditions, and (2) the change in heat sink temperature, i.e., from a chamber wall temperature of 125°F to the equivalent space temperature of 0°F in the sun.

The adjustment to account for chamber wall reflectivity was made in the following manner: the net heat rejection from the converter radiator to the chamber wall is given by the expression:

$$q_{R-C} = A_R \mathcal{F}_{R-C} \eta_f \sigma (T_R^4 - T_{CH}^4) \quad \text{Btu/hr}$$

where

A_R = radiator area (ft^2)

$\mathcal{F}_{R-C}$ = gray-body shape factor, or effective emittance from radiator to chamber wall

η_f = radiator fin effectiveness

σ = Stefan-Boltzmann constant (0.1714×10^{-8} Btu/hr-ft^2-°R^4)

T_R = representative average radiator temperature = 1110°R

T_{CH} = average FS-3 chamber wall temperature = 585°R.

The effective emittance, $\mathcal{F}_{R-C}$, is defined by the following well-known expression:

$$\mathcal{F}_{R-C} = \frac{1}{\left(\frac{1}{\epsilon_R} - 1\right) + \frac{1}{F_{R-C}} + \frac{D_R}{D_C}\left(\frac{1}{\epsilon_C} - 1\right)}$$

where

ϵ_R = actual radiator emissivity (0.9)

D_R = average conical-shaped radiator diameter (2.9 ft)

D_C = average chamber diameter (8 ft)

ϵ_C = chamber wall emissivity (0.85)

F_{R-C} = geometric factor from radiator to chamber wall (0.99)

Therefore, the effective FS-3 radiator emissivity is

$$\mathcal{F}_{R-C} = 0.85.$$

The radiator heat rejection in space, with the sink temperature equal to T_{CH}, is

$$q_{R-S} = A_R \epsilon_R \eta_f \sigma (T_R^4 - T_{CH}^4).$$

In the region of the SNAP 10A converter design point (near 20% Carnot efficiency) converter power output is directly proportional to the radiator heat-rejection capability. Therefore, the adjustment to FS-3 power output to account for chamber wall emittance is

$$F_\epsilon = \frac{q_{R-S}}{q_{R-C}} = \frac{\epsilon_R}{\mathcal{F}_{R-C}} = \frac{0.90}{0.95} = 1.06,$$

which represents a 6% increase in power in the space environment.

The adjustment for the change in heat sink temperature from the average FS-3 chamber wall temperature of 125°F to the equivalent space temperature of 0°F was calculated by the following expression, which compares the heat-rejection capability of the radiator in space to that in the FS-3 test chamber:

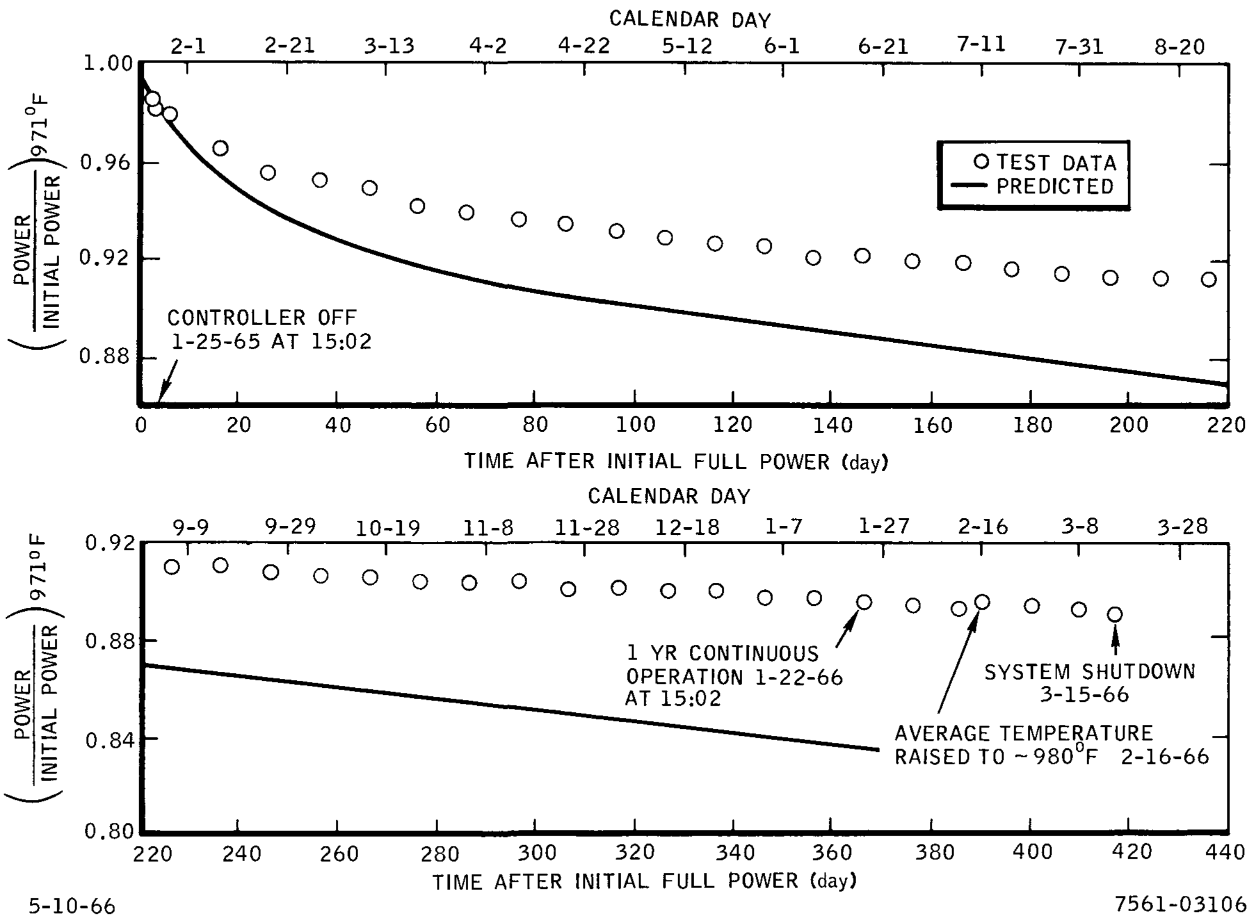

Figure 10. FS-3 Converter Degradation

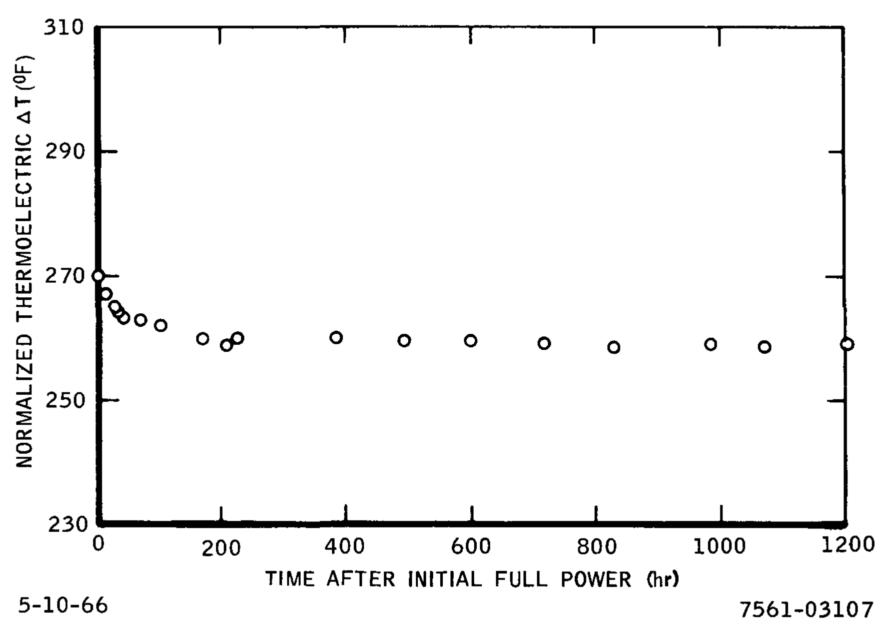

Figure 11. FS-3 Thermoelectric ΔT Normalized to 920°F

$$F_{ST} = \frac{(T_R^4 - T_{SP}^4)}{(T_R^4 - T_{CH}^4)}$$

where

T_R and T_{CH} are as defined previously

F_{ST} = power output correction for heat sink temperature

T_{SP} = equivalent space temperature (sun) = 460°R.

On substitution in this expression,

$$F_{ST} = 1.051,$$

indicating an additional 5.1% power output increase in space. This method of extrapolation avoids a complete converter heat balance but is accurate only for converters operating near 20% Carnot efficiency, such as the FS-3 converter. The total adjustment for extrapolation to space is, therefore,

$$F_T = F_{ST}F_\epsilon = 1.114.$$

Converter degradation, as shown in Figure 10, was obtained by normalizing converter power to 971°F, the core average temperature at the end of the 3-day control period, using the same method as used for the discussed normalization to 920°F. The degradation shown in Figure 10 differs from that in Figure 28 of NAA-SR-11206 due to the new normalization and the method of computing converter power output at initial full power, as discussed in the following paragraph. The predicted degradation curve of Figure 10 is based upon FSM-4 and early module test data.

The initial power used in computing the degradation (520 watts) is based on the power output at controller deactivation plus 1.5%. This approach was taken because of system temperature transients in the first 72 hr of full-power operation. To illustrate these transients, Figure 11 shows the average thermoelectric element temperature difference normalized to a constant average NaK temperature. The data show an abnormally high thermoelement ΔT during the first few

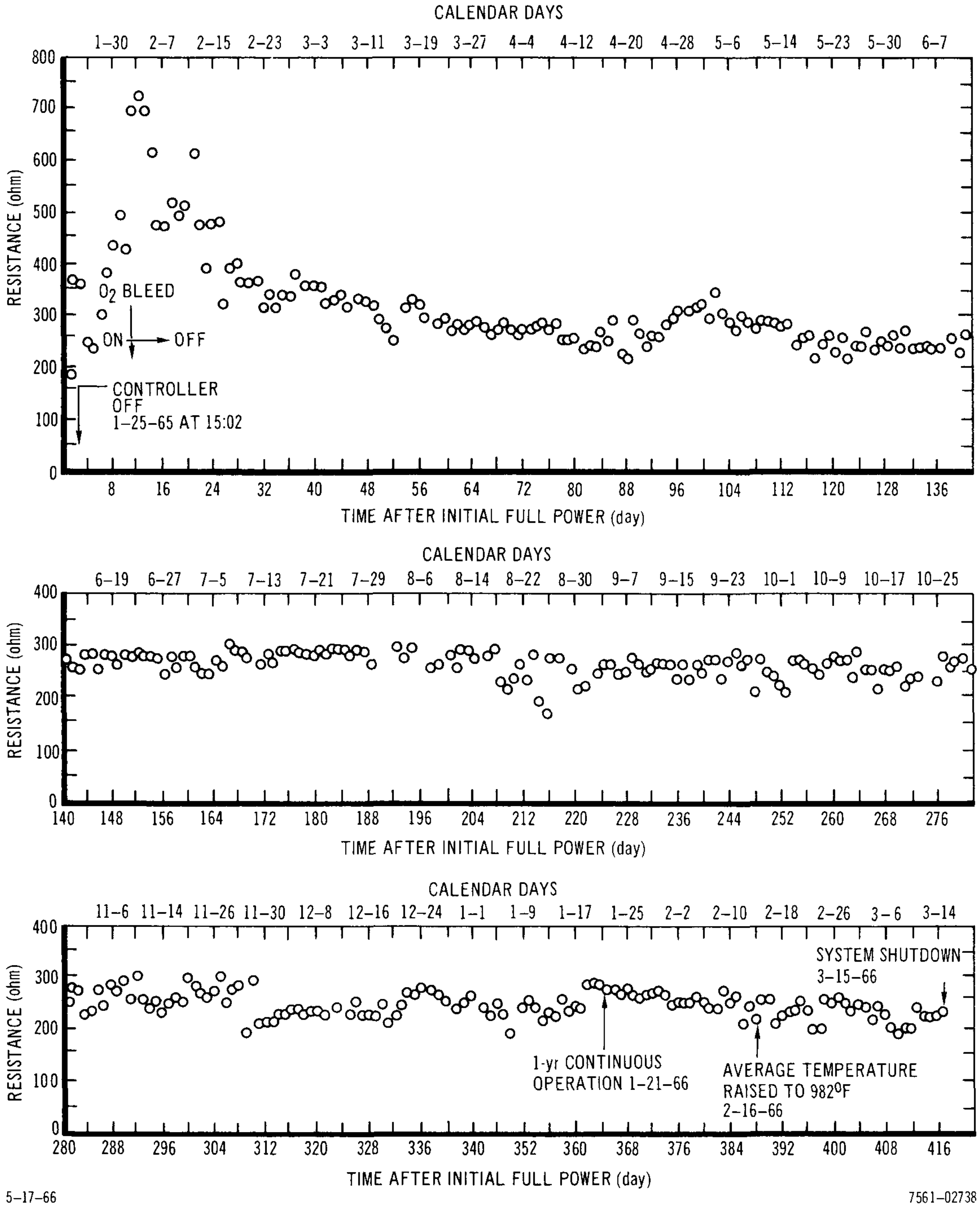

Figure 12. FS-3 Converter Resistance to Ground

days of operation, which was not observed during module qualification testing. Since power output is proportional to the square of thermoelectric ΔT, power output was also abnormally high during the first few days of operation. The high initial ΔT occurred because of the high heat capacities of the radiation shield and the test chamber. Approximately 50 hr were required to achieve radiation shield equilibrium and the chamber wall temperature increased from 113°F at initial full power to 123°F at controller deactivation 72 hr later. Both of these factors tended to increase the initial average thermoelement ΔT and initial power output. Since thermoelectric module qualification tests did not exhibit such initial ΔT variations, it is reasonable to base converter initial power on the relatively stable 72-hr data plus 1.5%, which was the observed degradation in the first 72 hr of module qualification tests.

Following the rapid initial converter degradation, the rate of degradation decreased steadily and stabilized at a long-term degradation rate of 0.45 ± 0.03%/1000 hr following the 125th day of operation.

Figure 12 is a continuation of Figure 25 in NAA-SR-11206 and shows the behavior of the converter resistance to ground throughout FS-3 power operation. Despite the scatter in the date of Figure 12, a long-term downward trend in resistance to ground is detectable. Assuming a linear decrease from the 56th to the 390th day of operation, the rate of change is -0.54 ± 0.21 ohm/week at the 99% confidence level. Resistance data for the period from the 390th day to the end of the test were not used in determining the rate of decrease because of the large increase in average temperature introduced during the temperature perturbation test. The resistance to ground remained high enough at all times to have a negligible effect on the converter power output.

Converter open- and closed-circuit voltages and load current are plotted in Figure 13. The same parameters are shown also in Figures 14 and 15 normalized to an average converter NaK temperature of 920°F. The open-circuit voltage is that measured instantaneously upon opening of the converter load circuit. Measurement of the instantaneous open circuit voltage permits calculation of the converter internal resistance without the influence of Peltier effects.

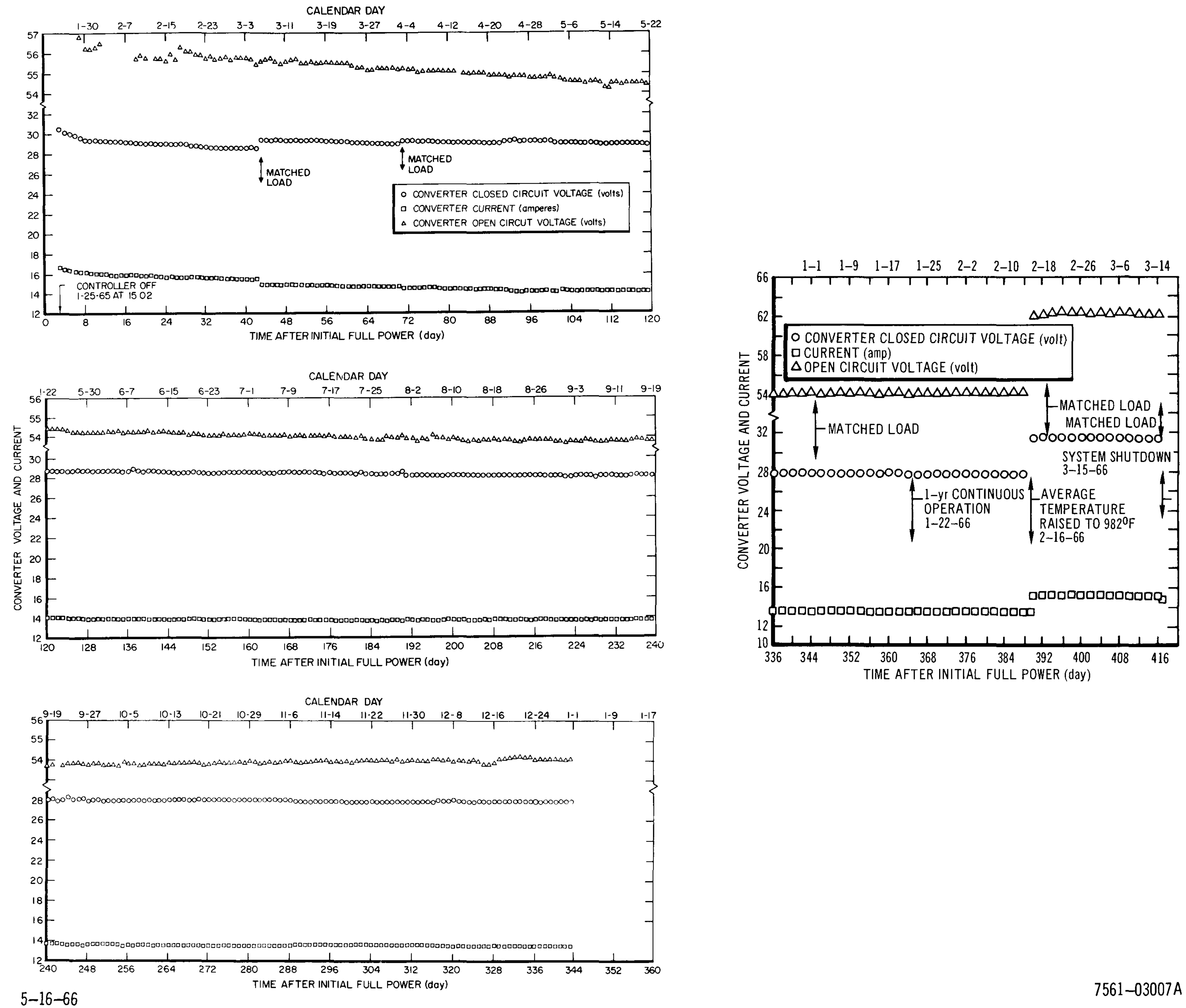

Figure 13. FS-3 Converter Voltage and Current

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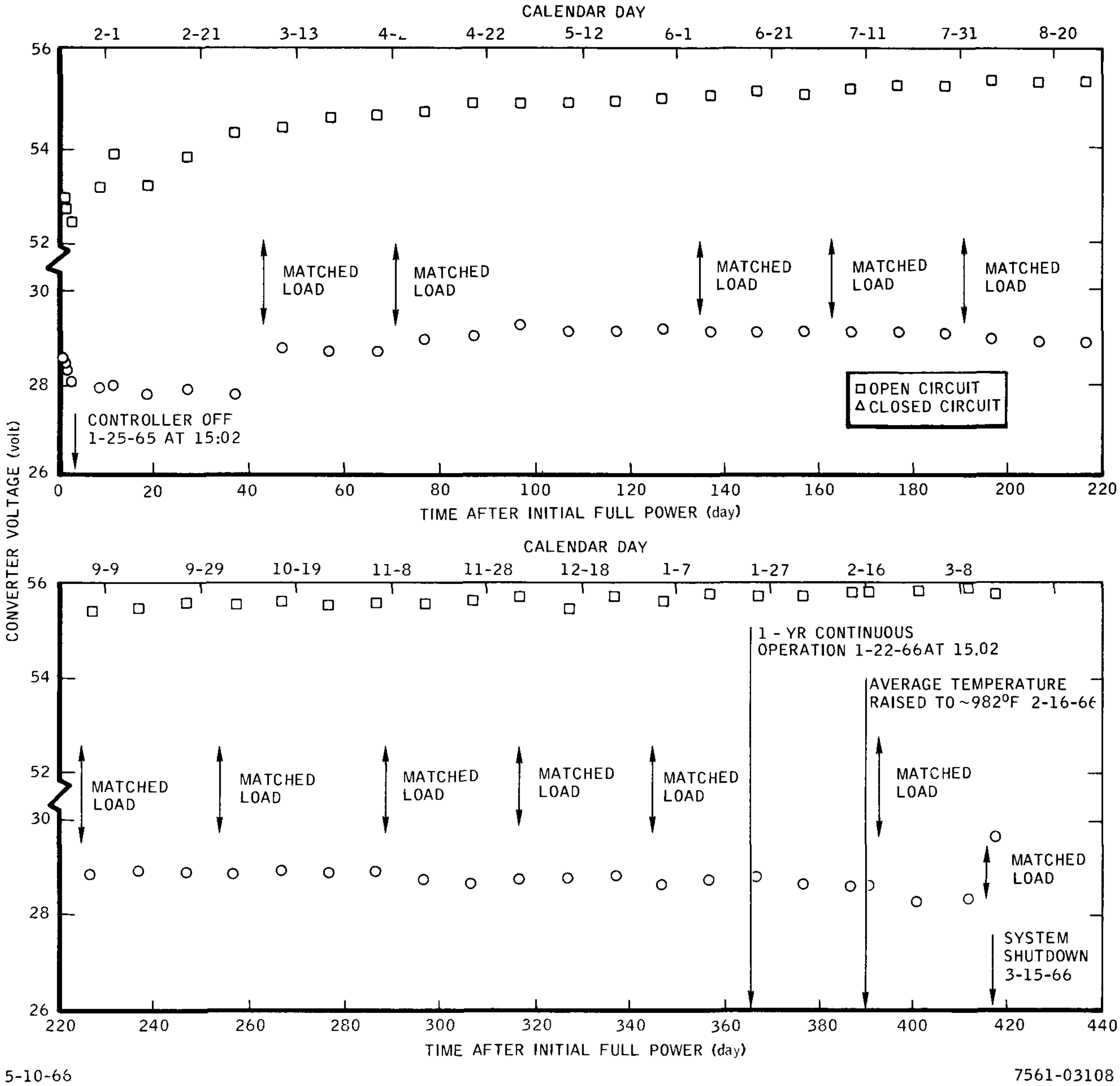

Figure 14. FS-3 Converter Voltage Normalized to 920°F

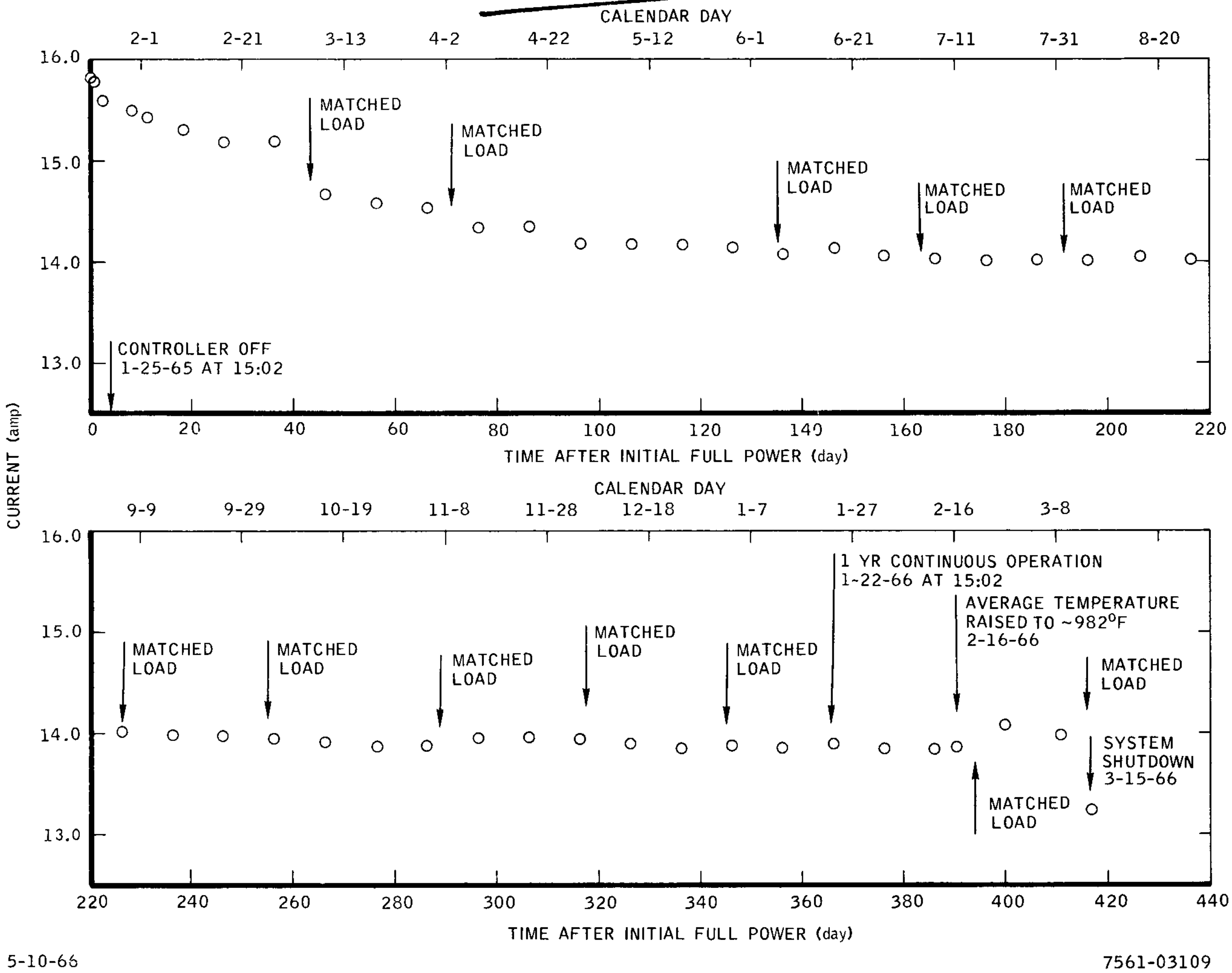

Figure 15. FS-3 Converter Current Normalized to 920°F

Load matching tests were performed at approximately 30-day intervals during power operation. The effect on closed-circuit voltage and load current can be seen in Figure 13. The perturbations in converter power following each load matching test were negligible, thus indicating that near matched load operation was maintained throughout FS-3 power operation.

Converter internal resistance is shown in Figure 16. Figure 17 shows internal resistance normalized to an average converter NaK temperature of 920°F. The scatter and blank periods in the earlier data reflect defective instrumentation, which was corrected at approximately 1000 hr after initial full power. As

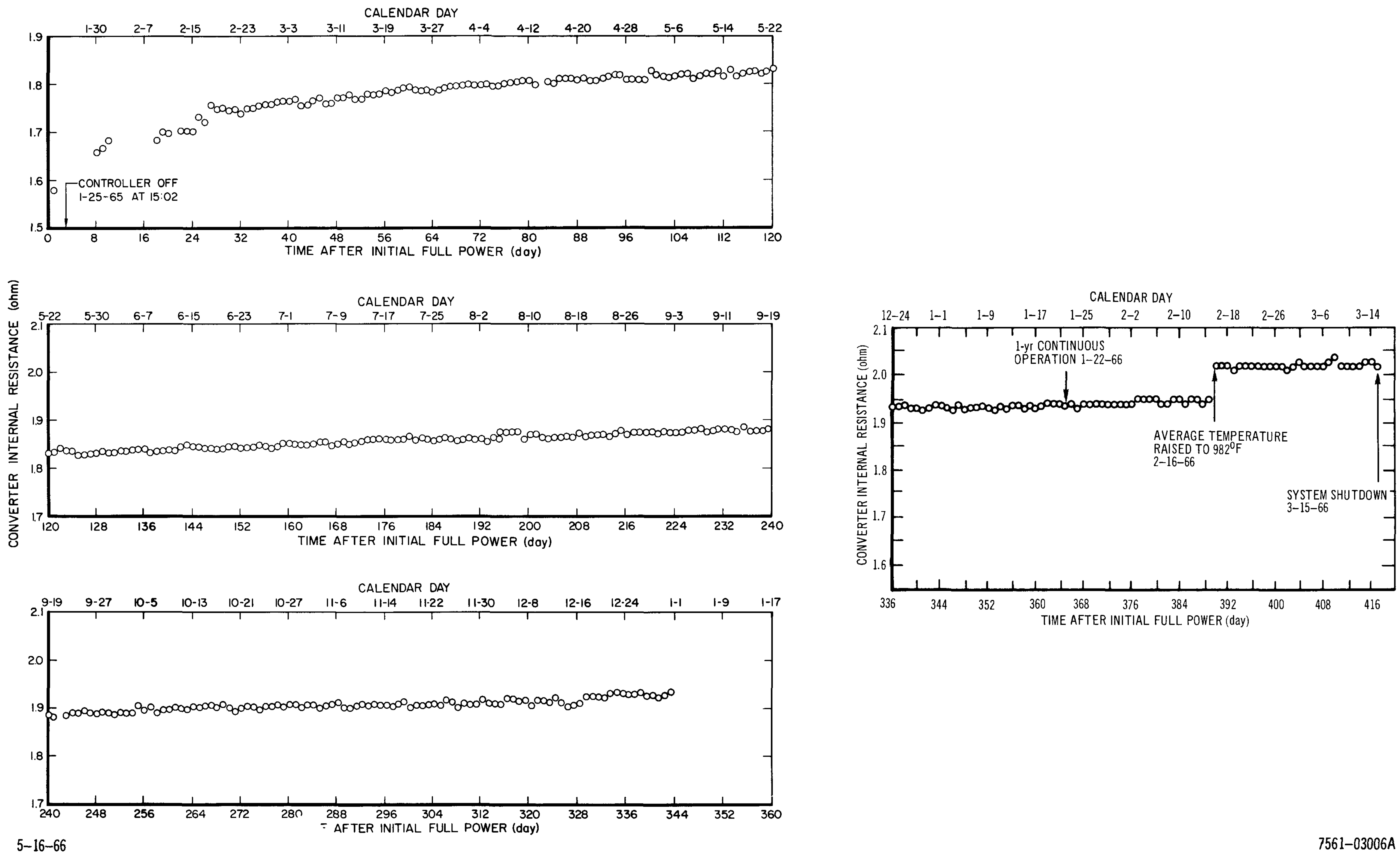

Figure 16. FS-3 Converter Internal Resistance

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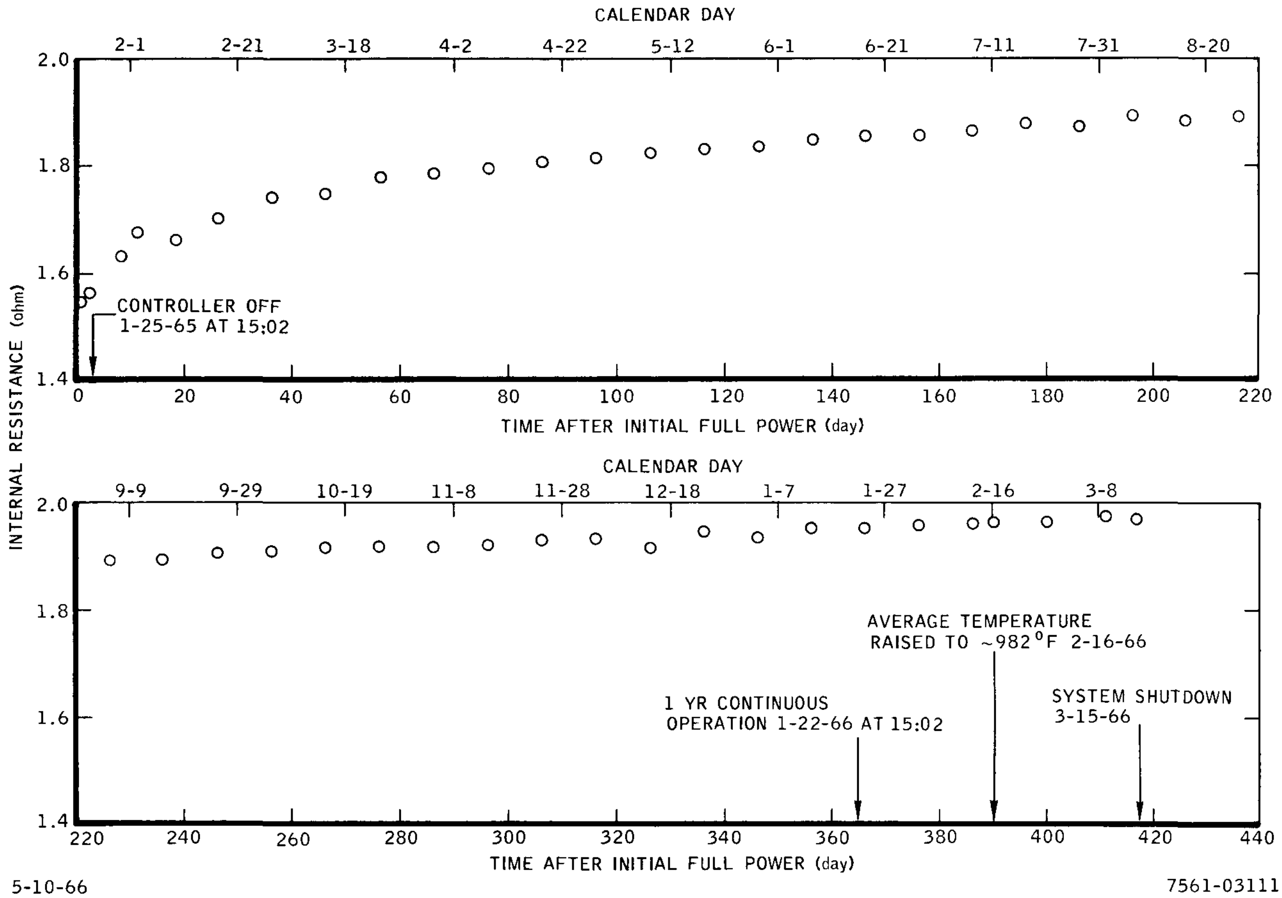

Figure 17. FS-3 Converter Internal Resistance Normalized to 920°F

apparent from Figure 18, which shows converter internal resistance degradation, the behavior of the FS-3 converter internal resistance was typical of that observed in previous module qualification tests.

Converter temperatures are given in Figure 5 and converter efficiencies are shown in Figure 19.

B. PUMP PERFORMANCE

Figure 20 is a history of the thermoelectric NaK pump flow rate. The flow rate shown is that measured by the pump flowmeter, FT-2. Pump degradation is shown in Figure 21. The flow rates used in determining the degradation have been normalized to a reactor outlet temperature of 1030°F. The degradation at the end of 1-year of operation was 14.3%. Also shown in Figure 21 is the

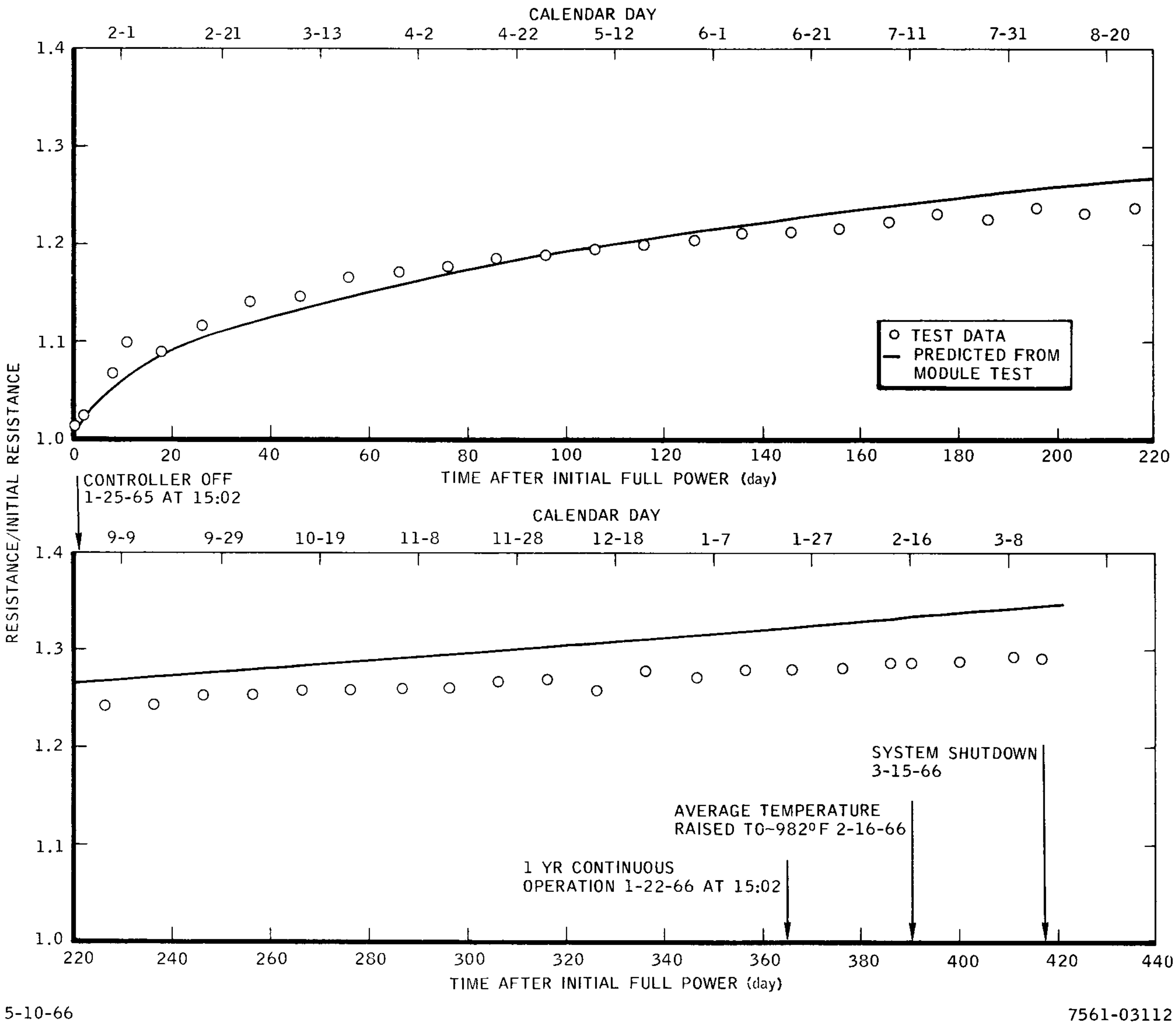

Figure 18. FS-3 Converter Internal Resistance Degradation

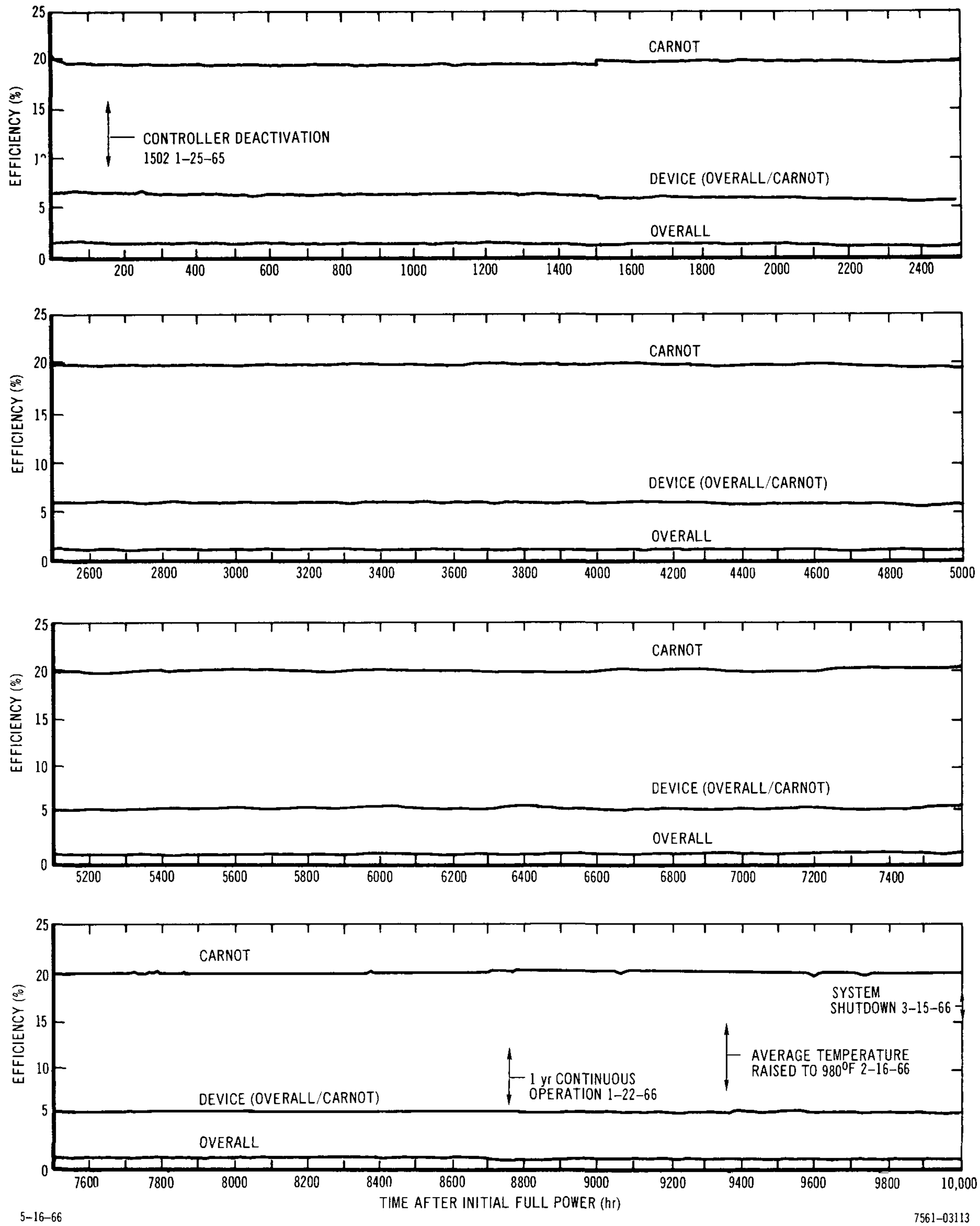

Figure 19. FS-3 Converter Efficiencies Normalized to 920°F

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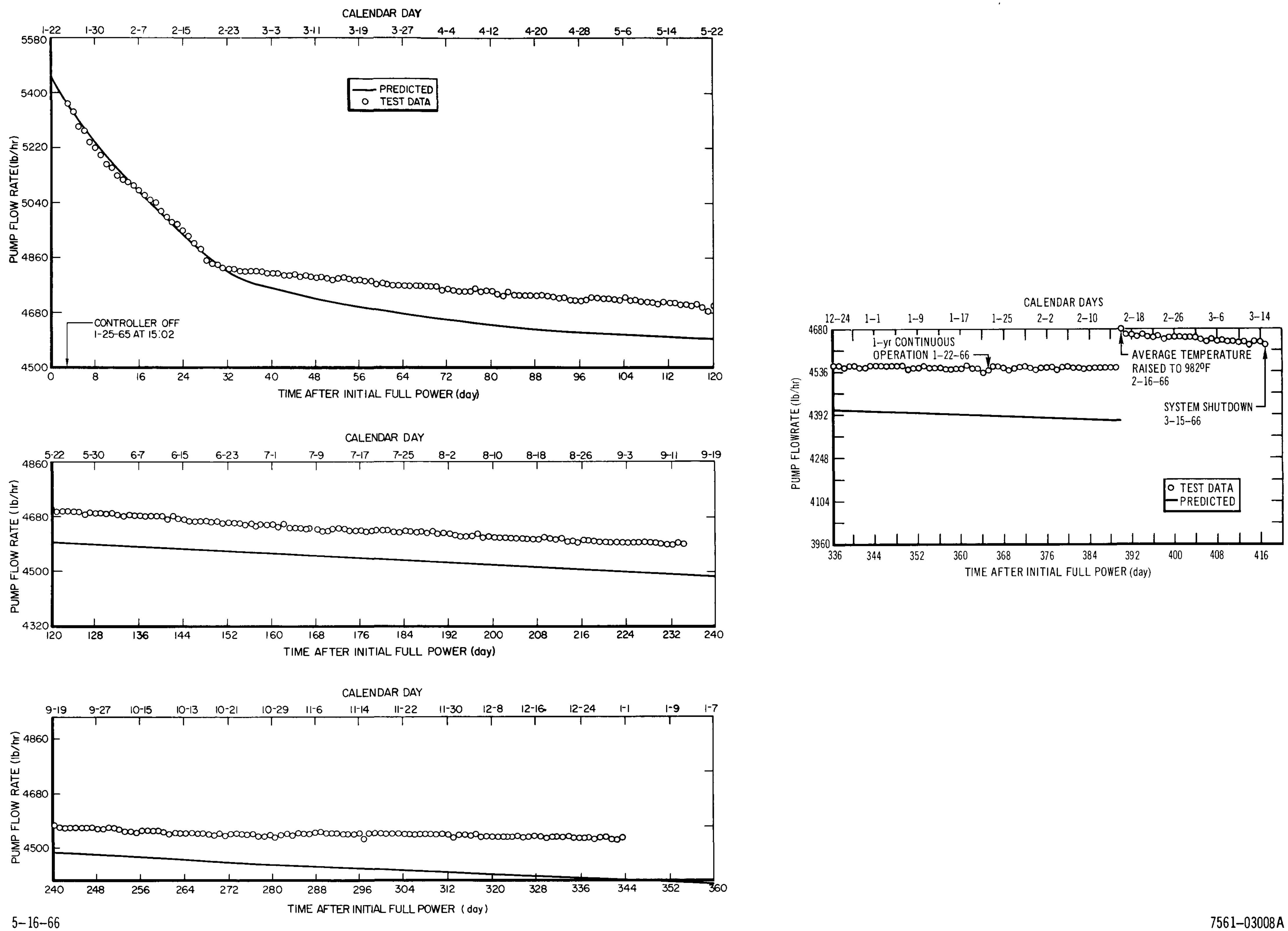

Figure 20. FS-3 Pump Flowrate

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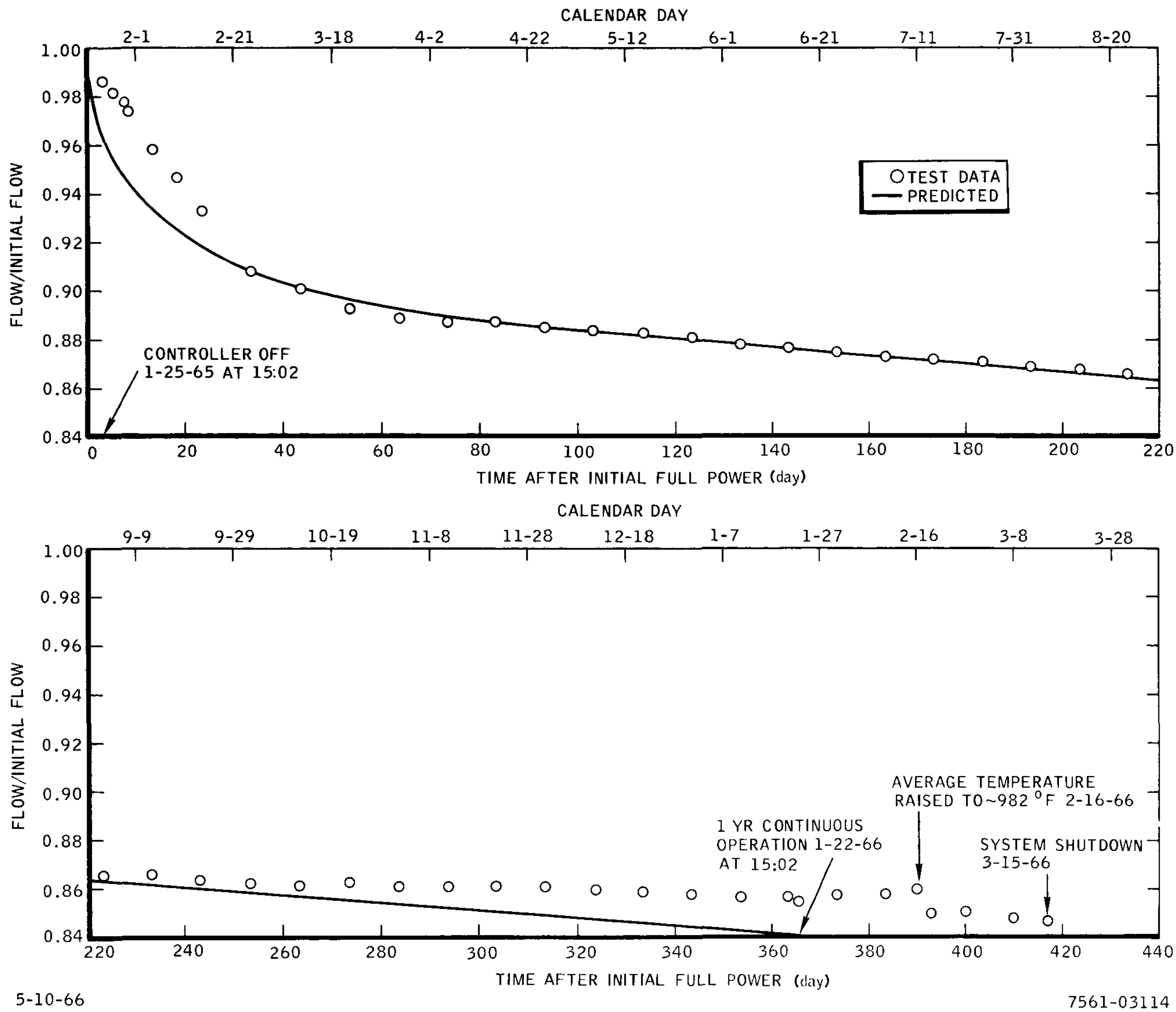

Figure 21. FS-3 Pump Degradation

degradation expected based upon the average degradation obtained from several qualification test pumps. The long-term rate of degradation of the FS-3 pump (i.e., the rate established after the rapid, initial degradation during the first 60 days of operation) was 0.58%/1000 hr as compared to the expected 0.67%/1000 hr.

C. EXPANSION COMPENSATOR

Figure 22 shows the expansion compensator unit (ECU) position normalized to a reactor average temperature of 950°F. The apparent position shift shown in

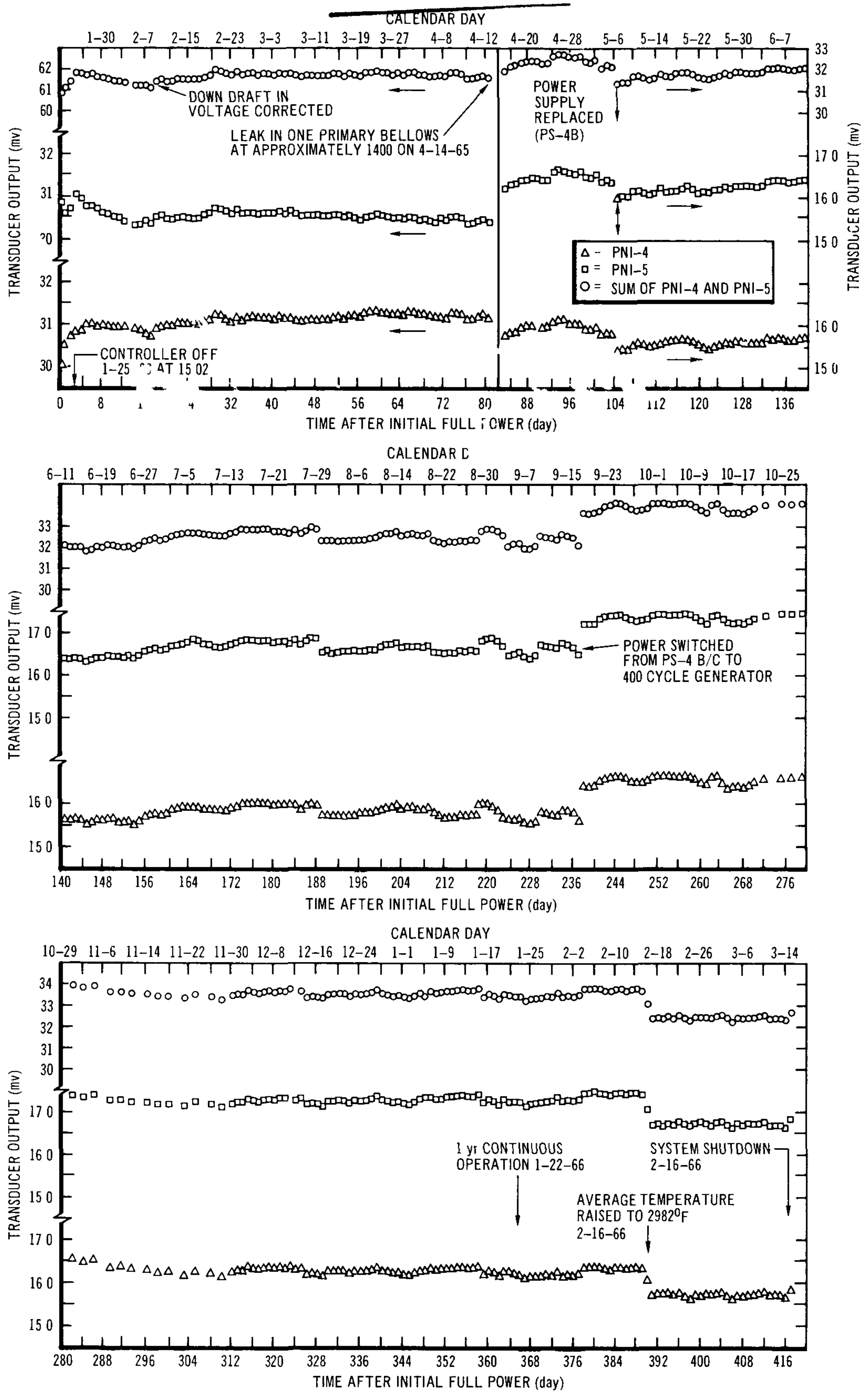

Figure 22. FS-3 Expansion Compensator Position (Millivolt)

Figure 22 after the temperature increase of February 16 is due to the normalization technique used. Shown are the millivolt outputs of each position transducer and their combined outputs. No significant sustained drift in position was observed following the primary bellows leak on April 14, 1965, indicating satisfactory performance throughout the remainder of power operations. A detailed description of the bellows leak is given in Section VI-B-3 of NAA-SR-11206. ECU position expressed in inches of displacement is shown in Figure 23. ECU temperature is plotted in Figure 6.

D. DIAGNOSTIC INSTRUMENTATION

The system diagnostic instrumentation performed satisfactorily throughout the 1-year endurance test. The status of the instrumentation at the end of the 1-year test was the same as reported at the completion of the 90-day test in

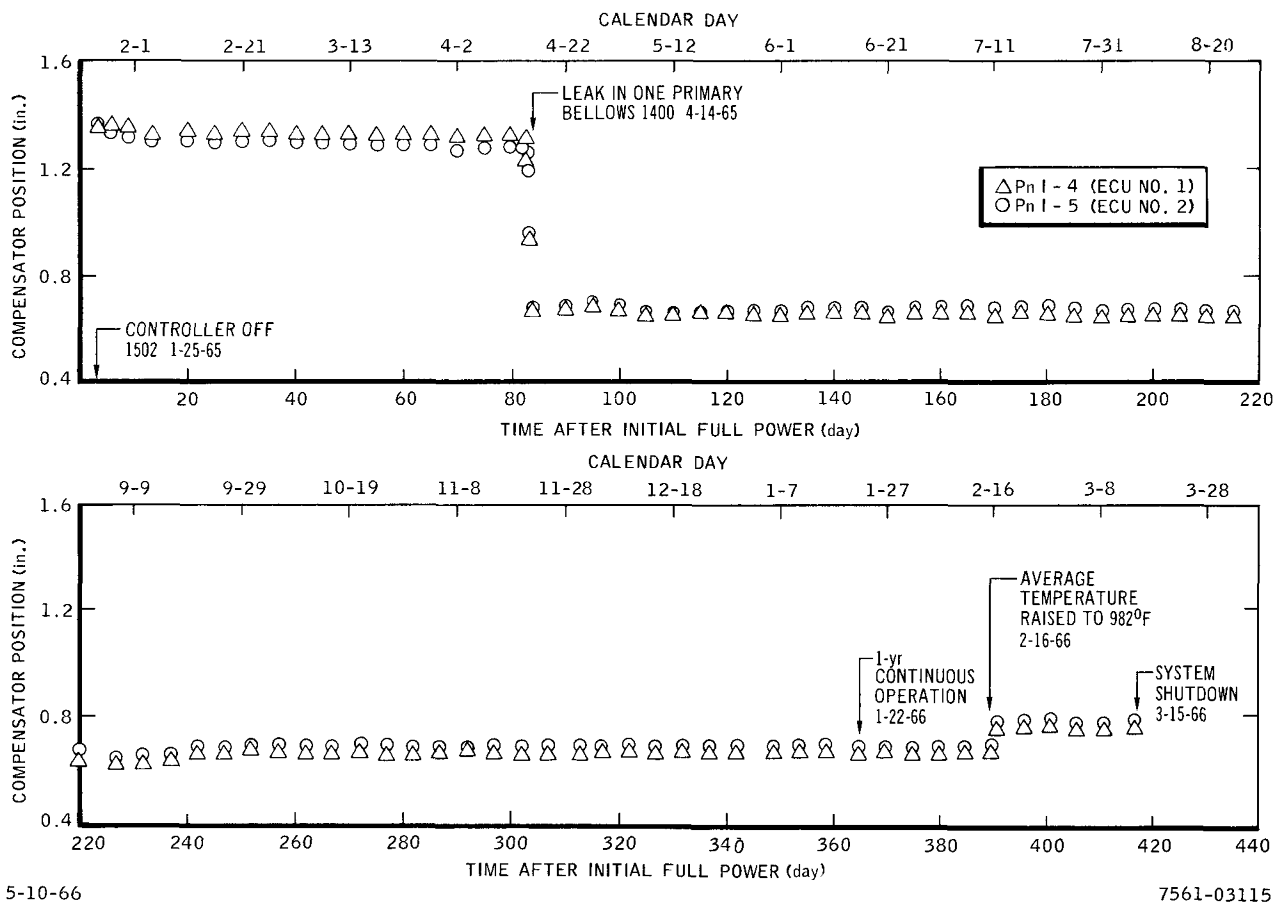

Figure 23. FS-3 Expansion Compensator Position (Inches)

NAA-SR-11206. Of the 120 total channels, 56 were still operating properly, 19 were reading off-scale, 34 were not programmed to function during this phase of the test and 11 had failed. Similar operation of the instrumentation system during flight would have enabled full evaluation of system performance.

Failure of ND-1, ND-3, and RD-1 was expected because the reflection of radiation from the walls of the test vault subjected these instruments to radiator doses approximately 100 times greater than the free space condition, for which they were designed. A summary of instrumentation status is shown in Table 5.

TABLE 5

FS-3 INSTRUMENTATION STATUS

Tag	Channel	Function	Readings				Remarks	
			Expected 1-25-65	Actual 1-25-65	Actual 1-22-66	Actual 3-15-66		
Ac-1	-	X accelerometer	-	(1)	-	-	OK	O
Ac-2	-	Y accelerometer	-	(1)	-	-	OK	O
Ac-3	-	Z accelerometer	-	(1)	-	-	Pickup ok, cable failed open	F
CZ-1	04-14	Conv. Degradation	1.6 Ω[2]	14 + Ω[2]	-	-	Reads very high	F
FT-1	01-08	Pump Wall Voltage	13.4 gpm	13.4 gpm	11.4 gpm	11.6 gpm	OK	
FT-2	01-04	Pump Fringe Flux	13.4 gpm	13.9 gpm	12.1 gpm	12.4 gpm	OK	
IT-1	04-15	0-50A Shunt	16.2A	16.22A	13.57A	14.43A	OK	
IT-2	04-16	0-30A Shunt	16.2A	16.19A	13.54A	14.39A	OK	
IT-3	07-19	Pump Current	~40A	38.46A[3]	-	-	OK	O
ND-1	07-02	High n Flux	3×10^{10} nv	2.7×10^{10} nv	-	-	Failed	F
ND-3	07-04	Low n Flux	Zero shift, followed transient				Failed	F
PnI-1	07-15	+Z Drum (0-135)	23.4°	27°	26.4°	24.2°	(4)	
PnI-2	07-16	-Z Drum (0-135)	23.4°	27°	25.5°	22.1°	(4)	
PnI-3	07-18	-Z Drum (0-30)	23.4°	28°	26 1°	21.0°	(4)	
PnI-4	03-14	ECU No. 1 Pos.	1.46 in.	1.33 in.	0.67 in.	0.76 in.	(5)	
PnI-5	03-15	ECU No. 2 Pos.	1.46 in.	1.32 in.	0.70 in.	0.79 in.	(5)	
PnI-6	07-17	+Z Drum (0-30)	23.4°	25.5°	23.9°	21.6°	(4)	
RD-1	07-06	Gamma Detector	Zero shift, lost sensitivity after 24 hours					F
RT-1	05-05	Reactor Outlet	1007°F	1022°F	1006°F	1098°F	Reads high	F
RT-2	07-07	Reactor Inlet	890°F	891°F	854°F	924°F	OK	
RT-3	06-02	Converter Inlet	1000°F	1001°F	962°F	1045°F	OK	
RT-4	06-03	Converter Outlet	878°F	880°F	831°F	898°F	OK	
RT-5	05-18	Tube 25 Inlet	319°F	319°F[3]	-	-	Failed March 1, 1965[6]	F
RT-6	05-12	Tube 45 Inlet	319°F	317°F[3]	-	-	OK, off scale. Performed normally during shutdown	O
RT-9	05-20	Tube 26 Outlet	255°F	-	-	-	Failed open[7]	F
RT-10	05-23	Tube 16 Outlet	255°F	250°F[3]	-	-	OK, off scale. Performed normally during shutdown	O

TABLE 5 (Continued)

Tag	Channel	Function	Readings				Remarks	
			Expected 1-25-65	Actual 1-25-65	Actual 1-22-66	Actual 3-15-66		
RT-11	05-14	Tube 46 Outlet	255°F	255°F(3)	-	-	OK, off scale. Performed normally during shutdown	O
RT-12	05-24	Tube 36 Outlet	255°F	255°F(3)	-	-	OK, off scale. Performed normally during shutdown	O
RT-13	06-22	Inst. Comp. Bay G	65-100°F	79°F	70°F	86°F	OK	
RT-14	06-23	Inst. Comp. Bay B	65-100°F	64°F	51°F	69°F	OK	
RT-15	06-24	Inst. Comp. Bay H	65-100°F	101°F	91°F	108°F	OK	
RT-16	07-23	Inst. Comp. Bay D	65-100°F	76°F	63°F	80°F	OK	
RT-17	05-08	Pump Radiator No. 1	170°F	171°F(3)	-	-	OK, off scale. Performed normally during shutdown	O
RT-18	05-10	Pump Radiator No. 2	188°F	185°F(3)	-	-	OK, off scale. Performed normally during shutdown	O
TC-1	01-02	Reactor Outlet	1005°F	1007°F	969°F	1052°F	OK	
TC-2	-	Reactor Outlet	Used for scram initiation					N
TC-3	01-03	Reactor Inlet	890°F	890°F	843°F	909°F	OK	
TC-4	01-07	Reactor Inlet	890°F	894°F	847°F	913°F	OK	
TC-5	05-06	Reactor Inlet	890°F	890°F	843°F	908°F	OK	
TC-6	05-07	Reactor Inlet	890°F	890°F	842°F	908°F	OK	
TC-7	-	Reactor Outlet	Used for scram initiation					N
TC-8	05-17	Tube 27 Inlet	1002°F	1001°F	962°F	1045°F	OK	
TC-9	05-21	Fin (Tube 27) Inlet	716°F	712°F	714°F	741°F	OK	
TC-10	05-19	Tube 27 Outlet	878°F	860°F	810°F	872°F	OK	
TC-11	05-22	Fin (Tube 27) Outlet	596°F	584°F	563°F	598°F	OK	
TC-12	01-18	Tube 17 Inlet	1002°F	1002°F	964°F	1046°F	OK	
TC-13	01-20	Fin (Tube 17) Inlet	716°F	715°F	710°F	759°F	OK	
TC-14	01-19	Tube 17 Outlet	878°F	888°F	852°F	918°F	OK	
TC-15	01-21	Fin (Tube 17) Outlet	596°F	621°F	580°F	616°F	OK	
TC-16	05-11	Tube 47 Inlet	1002°F	1005°F	965°F	1048°F	OK	
TC-17	05-15	Fin (Tube 47) Inlet	716°F	717°F	697°F	746°F	OK	
TC-18	05-13	Tube 47 Outlet	878°F	863°F	815°F	877°F	OK	
TC-19	05-16	Fin (Tube 47) Outlet	596°F	587°F	567°F	601°F	OK	
TC-20	01-22	Tube 37 Inlet	1002°F	1002°F	961°F	1044°F	OK	
TC-21	05-25	Fin (Tube 37) Inlet	716°F	719°F	700°F	746°F	OK	
TC-22	01-23	Tube 37 Outlet	878°F	899°F	851°F	918°F	OK	
TC-23	06-01	Fin (Tube 37) Outlet	596°F	592°F	575°F	606°F	OK	
TC-24	01-09	Pump Radiator No. 1	595°F	592°F	580°F	630°F	OK	
TC-25	05-09	Pump Radiator No. 2	595°F	601°F	589°F	632°F	OK	
TC-31	06-04	-Z Reflector	620°F	614°F	604°F	664°F	OK	
TC-38	01-06	Reactor Outlet	1005°F	1004°F	967°F	1052°F	OK	
TC-39	-	Heat Shield	-	-	-	-	Heat shield not installed	N

TABLE 5 (Continued)

Tag	Channel	Function	Readings				Remarks	
			Expected 1-25-65	Actual 1-25-65	Actual 1-22-66	Actual 3-15-66		
TC-40	06-05	+Z Reflector	620°F	623°F	610°F	673°F	OK, low resistance to ground	N
TC-41	-	Heat Shield	-	-	-	-	Heat shield not installed	N
TC-42	-	Heat Shield	-	-	-	-	Heat shield not installed	N
TC-43	-	Heat Shield Squib	-	-	-	-	Heat shield not installed	N
TC-44	02-06	TABRD Temp.	984°F	987°F	948°F	1032°F	OK	
TS-1	-	Temp. Control No. 1	Reset	Actuates	-	-	OK, series connection original set point	O
TS-2	-	Temp. Control No. 2	1004°F	1007°F	-	-	1030°F	O
TS-3	-	Low Temp. Malf.	-	-	-	-	Not installed	N
TS-4	-	High Temp. Malf.	-	-	-	-	Not installed	N
TS-5	-	Heat Shield Ejection No. 1	300°F	307°F(8)	-	-	OK, see EvM-1, actuated at 298°F during shutdown	O
TS-6	-	Heat Shield Ejection No. 2	-	-	-	-	Not recorded	N
VT-1	04-11	Voltage	29 v	29.2 v	27.78 v*	33.11 v*	OK	
VT-2	04-12	Normal Voltage	29 v	28.9 v	27.80 v*	33.13 v*	OK	
VT-3	04-19	Legs 15-12	2.9 v	2.7 v	2.62 v*	3.14 v*	OK	
VT-4	04-20	Legs 11-48	2.9 v	3.0 v	2.84 v*	3.39 v*	OK	
VT-5	04-21	Legs 47-44	2.9 v	2.9 v	2.73 v*	3.27 v*	OK	
VT-6	04-22	Legs 43-40	2.9 v	3.0 v	2.90 v*	3.46 v*	OK	
VT-7	04-23	Legs 39-36	2.9 v	3.0 v	2.84 v*	3.38 v*	OK	
VT-8	04-24	Legs 35-32	2.9 v	2.9 v	2.68 v*	3.21 v*	OK	
VT-9	04-25	Legs 31-28	2.9 v	2.9 v	2.75 v*	3.28 v*	OK	
VT-10	05-01	Legs 27-24	2.9 v	2.9 v	2.73 v*	3.27 v*	OK	
VT-11	05-02	Legs 23-20	2.9 v	3.0 v	2.87 v*	3.43 v*	OK	
VT-12	05-03	Legs 19-16	2.9 v	3.0 v	2.79 v*	3.26 v*	OK	
VT-13	-	C-1 Sensor Status	-	-	-	-	Not recorded	N
VT-15	-	C-1 Freq. Div. Volt	-	-	-	-	Not recorded	N
VT-17	-	A&A' Motor Coil	-	-	-	-	Not recorded	N
VT-18	-	B&B' Motor Coil	-	-	-	-	Not recorded	N
VT-19	-	C&C Motor Coil	-	-	-	-	Not recorded	N
VT-20	-	D&D Motor Coil	-	-	-	-	Not recorded	N
EvM-1	1	Heat Shield Squib Fire	300°F	307°F(8)	-	-	OK (contact on K14A) 298°F during shutdown	O
EvM-2	2	Startup	Closed	Closed(9)	-	-	On command	O
EvM-3	3	Malf. Enable	-	-	-	-	Circuit modified	N
EvM-5	5	Low Temp. Malf. Stat.	-	-	-	-	Switch not installed	N
EvM-8	8	ECU Squibs Fire	Closed	Closed(9)	-	-	On command	O
EvM-9	9	Drum Squib Fire	Closed	Closed(9)	-	-	OK	O
EvM-16	6	High Temp. Malf. Stat.	-	-	-	-	Switch not installed	N

TABLE 5 (Continued)

Tag	Channel	Function	Readings				Remarks	
			Expected 1-22-65	Actual 1-25-65	Actual 1-22-66	Actual 3-15-66		
EvM-17	-	BRH Energize	-	-	-	-	Not monitored	N
EvM-18	-	Override (KOR) Stat.	-	-	-	-	Not monitored	N
EvM-19	-	Malf. Bus Status	-	-	-	-	Not monitored	N
EvM-20	-	CZ Status	-	-	-	-	Not monitored	N
PnS-1	-	+Z Coarse Drum In	Closed	Closed	Closed	Closed	(13)	
PnS-2	-	+Z Coarse Drum Out	Open	Open	Open	Open	(13)	
PnS-3	-	-Z Coarse Drum In	Closed	Closed	Closed	Closed	(13)	
PnS-4	-	-Z Coarse Drum Out	Open	Open	Open	Open	(13)	
PnS-5	-	+Z Fine Drum In	Open	Open	Open	Open	(13)	
PnS-6	-	+Z Fine Drum Out	Open	Open	Open	Open	(13)	
PnS-7	-	-Z Fine Drum In	Open	Open	Open	Open	(13)	
PnS-8	-	-Z Fine Drum Out	Open	Open	Open	Open	(13)	
PnS-9	-	ECU No. 1 Bellows	385°F	435°F(8)	-	-(12)	OK, actuated at average core temp. of 808°F during shutdown	O
PnS-10	-	ECU No. 2	385°F	442°F(8)	-	-(12)	OK, actuated at average core temp. of 819°F at shutdown	O
PnS-11	16	Heat Shield No. 1 Pos.	-	-	-	-	Shield not installed	N
PnS-12	17	Heat Shield No. 2 Pos.	-	-	-	-	Shield not installed	N
PnS-15	12	+Z Reflector Pos.	Open	Closed-Reopened(8)	-	Open	(10)	
PnS-16	13	-Z Reflector Pos.	Open	Closed(8)	-	Open	(10)	F
PnS-17	-	Band Status No. 1	-	-	-	-	Not monitored	N
PnS-18	-	Band Status No. 2	-	-	-	-	Not monitored	N
Sw-5A	10	Low Volt. Sensor No. 1	Open	Intermittent Closing(9)	Closed	Closed	Apparently failed about 1-30-65	F
Sw-5B	-	Low Volt. Sensor No. 2	Open	-	-	-	Apparently failed(11)	F

(1) Frequency response acceptable. Readings taken during structural qualification, about 8-20-64.
(2) Calculated converter resistance, measurement is not direct since AI inductor not installed.
(3) Readings taken at start of test, 1-22-65.
(4) 500-gm downward preload on sensor shaft was omitted during final installation of sensor.
(5) Reduced deflection attributed to (a) inaccurate zero setting of transducer, (b) deficiency in total quantity of NaK in system, since PnI-4 and -5 were used to measure bellows deflection at system seal-off. Accuracy poor in low range. The large decrease in position between 1-25-65 and 1-22-66 is due to the primary bellows leak which occurred on 4-14-65.
(6) RT-5 failed on March 1, 1965. Measured output indicates a shorted detector.
(7) Performance of RT-9 during startup indicated an open detector. Performance during shutdown on 3-16-66 was normal.
(8) Reading taken at start of test, 1-22-65, 1 16 p.m., or shortly thereafter.
(9) Reading taken at start of test, 1-22-65.
(10) To permit remote handling at test conclusion, reflector installation was modified and eccentric pins omitted, allowing differential movement at switch locations not anticipated in flight.
(11) Not monitored. Coils of Sw-5A and 5B are in parallel, one set of DPDT contacts in series. Status checks of unused contacts on 3-11 and 3-17 showed Sw-5B open, but checks at applicable test points with K12 closed, on 1-25, 2-12, and 3-17, indicated both Sw-5A and 5B closed.
(12) Operation of PnS-9 and PnS-10 at the high average temperatures indicated in the "Remarks" column is a result of the primary bellows leak which occurred on April 14, 1965.
(13) All drum limit switches actuated at normal positions during shutdown.

*VT-1 through VT-12 recalibrated 3-5-65. O: Off Scale, F: Failed, N: Not Recorded

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III. TEMPERATURE PERTURBATION TEST

On February 16, 1966, after 390 days of continuous operation, the FS-3 system was subjected to a controlled change in temperature during which the reactor average temperature was increased from 907 to 982°F. Following the temperature increase active control was maintained for 72 hr before passive control was resumed for the remaining FS-3 power operation.

The primary purpose of changing the temperature was to provide additional information for use in the analysis of the reactor temperature behavior shown in Figure 1. The observed reactivity effects the temperature perturbation were slightly different than expected. Based on an analysis of the observed 66°F temperature drift of FS-3 during the 1-year test, it was estimated that a total of 22¢ of reactivity was lost due to all reactivity effects. Using the same effective temperature coefficient (0.334¢/F°) for the proposed 73°F temperature increase of the temperature perturbation test, it was predicted that 24.4¢ of reactivity would be required to stabilize at the new operating conditions. A portion of this total (xenon 3.5¢ and part of the reflector heating effect) was expected to occur during the 72-hr control period following the temperature increase. With a 30 F° increase in reflector temperature, it was expected that 20.3¢ would be required to reach the new initial full power condition.

The actual reactivity insertions totaled 17.4¢, which indicates an apparent coefficient of -0.29¢/°F would be appropriate during power level changes. It also indicates that an isothermal temperature coefficient of -0.25¢/°F would be applicable. There is an uncertainty of about ±0.02¢/°F in these coefficients due to uncertainty in the reflector coefficient for FS-3.

The reactivity losses during the active control period following the temperature increase also differed considerably from the predicted. The predicted (with a correction for actual reflector heating) was 4.3¢ as compared to the measured loss of 1.3¢.

The reactivity effects summarized in the preceding paragraph are discussed in detail in NAA-SR-11397.

Table 1 summarizes the performance of the system after stabilization at the increased temperature following the temperature perturbation. Reactor coolant temperatures during the temperature perturbation are shown in Figures 24 and 25.

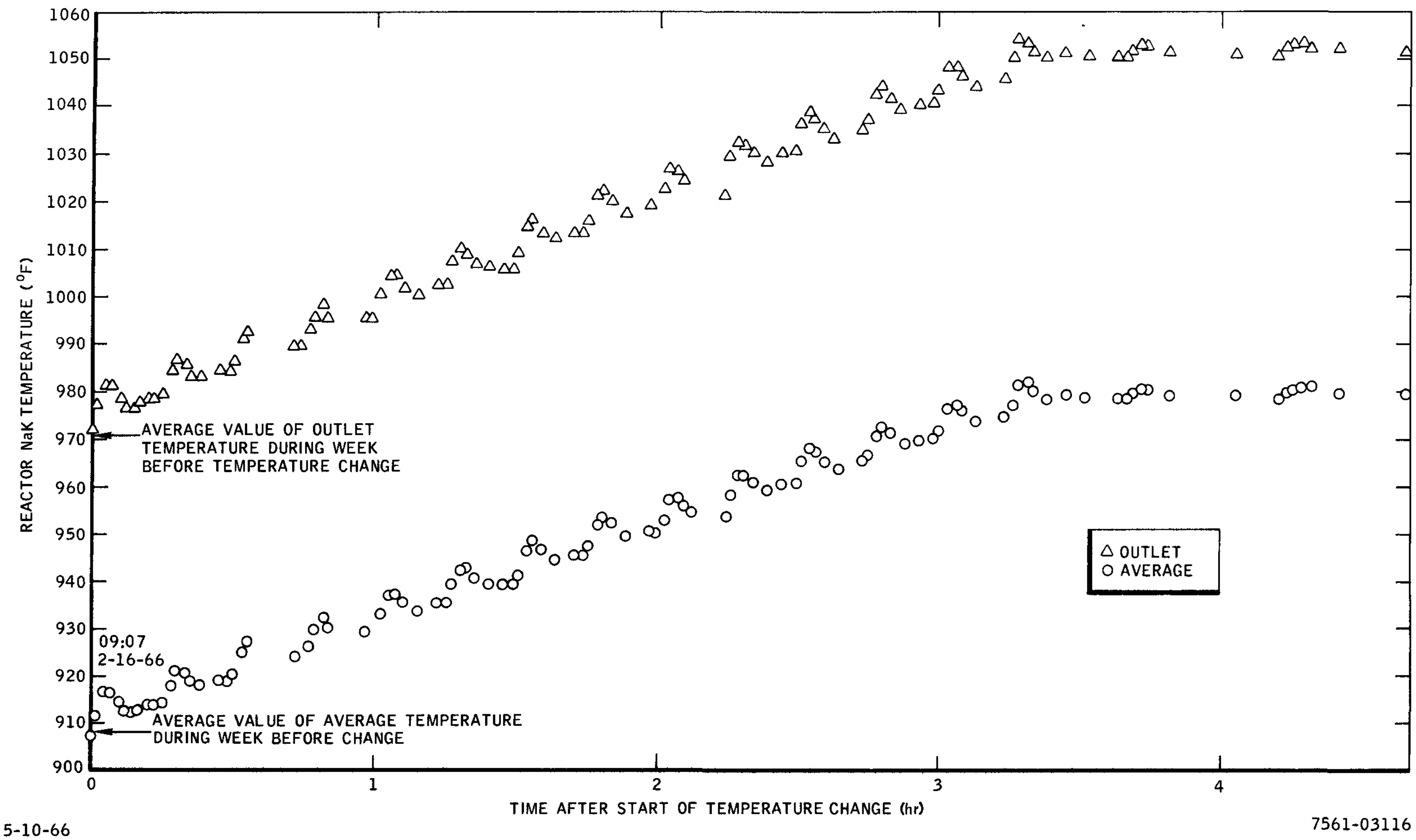

Figure 24. FS-3 Temperature Perturbation Test — Reactor NaK Temperatures

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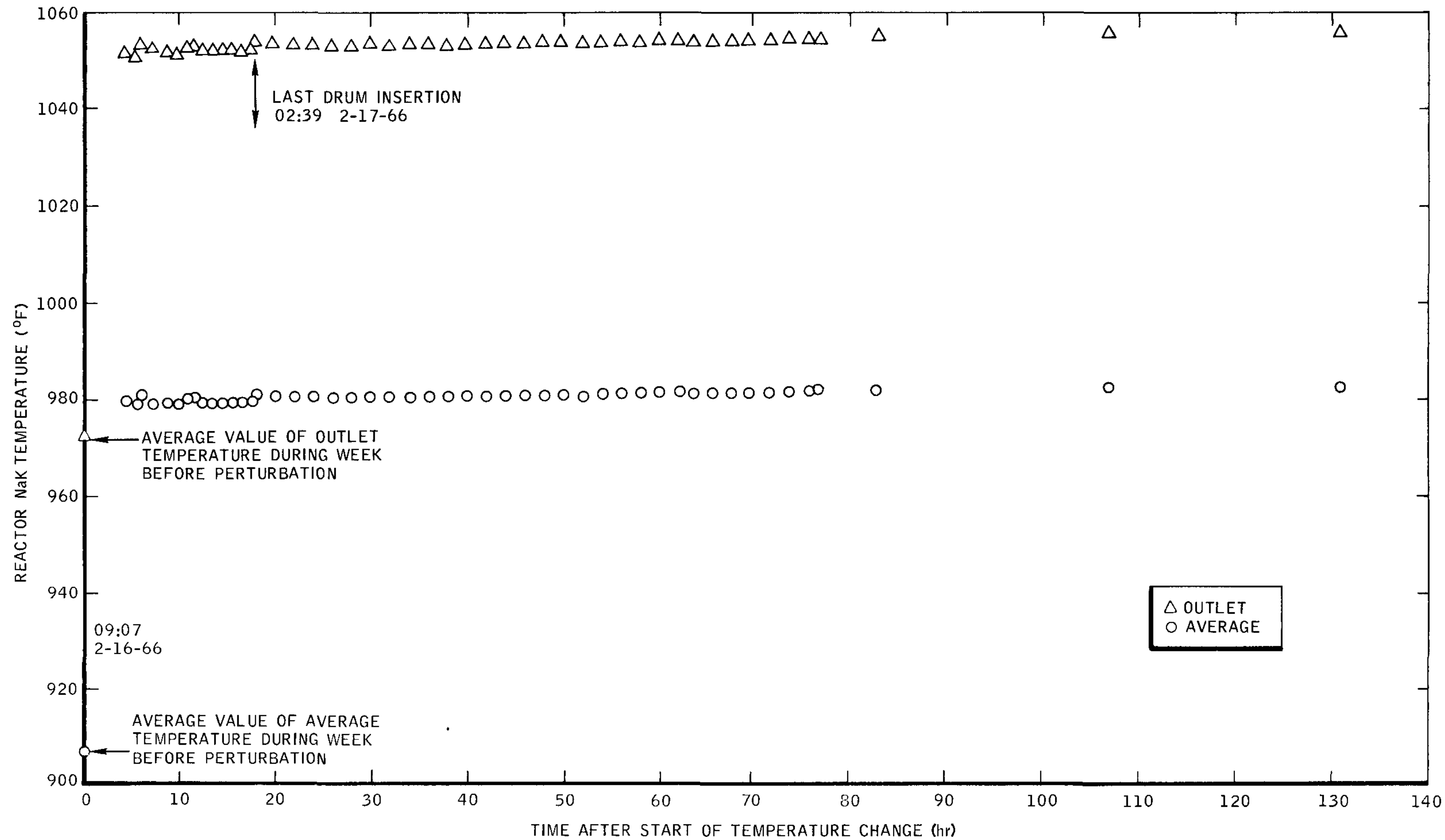

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Figure 25. FS-3 Temperature Perturbation Test — Reactor NaK Temperatures

Reactor temperatures during passive control after stabilization are shown in Figures 1, 2, and 3. Tables 6 and 7 are detailed system heat balances at the beginning of passive control and just prior to shutdown.

The converter performance during the temperature perturbation experiment is shown in Figures 26 and 27. Figure 27 shows converter power output as a function of converter average NaK temperature and provides the basis for normalization of converter power to a constant temperature. The data in Figure 27 may be approximated by a relationship of the form:

$$P \sim T^{4.65}$$

where

P = the converter power output (watts)

T = average converter NaK temperature (°R)

In determining the relationship proportionality, only power data taken under stable temperature conditions were considered. Therefore, the intermediate data points between 904 and 979°F, which were taken during temperature transients, would be expected to fall slightly above the curve based on $P \sim T^{4.65}$ as illustrated in Figure 27. Furthermore, the proportionality $P \sim T^{4.65}$ includes the effect on converter power of the FS-3 test chamber wall-temperature variation with increasing average converter NaK temperature and therefore is applicable only to the FS-3 test system. When the effect of chamber wall-temperature variation is removed the proportionality becomes $P \sim T^{4.8}$.

Converter power degradation, as determined by the method outlined in Section II-A was 10.5% upon stabilization at the increased temperature (9431 hr total operating time). The degradation just prior to system shutdown was 11.0% for an overall average degradation rate of 1.1%/1000 hr.

Converter performance for the time period between stabilization at the increased average temperature and system shutdown is shown in Figures 8 through 19.

TABLE 6

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw) STABLE AFTER TEMPERATURE PERTURBATION (2/19/66)

Calculated Reactor Thermal Power		41.35
Gains — Reflector Internal Heating	0.51	
Losses — Reflector	0.55	
Reactor top	0.33	
Reactor bottom	0.22	
Total	0.59	
Calculated Heat Gain by NaK in Core		40.76
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(41.03)
Gains — Neutron Shield Internal Heating	0.16	
Losses — Pump	1.11	
Supply lines	0.16	
Reactor support legs	0.61	
Neutron shield	(0.95)	
Upper torque box	0.93	
Total	2.63	
Calculated Heat to Converter		38.13
Measured Heat to Converter (Flow Temperature Drop)		(37.86)
Losses — Structure to Neutron Shield	0.22	
Structure to vacuum vessel	1.54	
NaK legs to vacuum vessel	0.34	
Return lines to structure	(0.12)	
Lower torque box	0.85	
Instrument compartment	0.50	
Low-pressure convection	0.15	
Electrical power produced	0.48	
Shunt losses to radiators	(3.30)	
Total	4.08	
Calculated Heat Rejected by Converter Radiator		34.05
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(37.71)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

TABLE 7

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
JUST PRIOR TO SHUTDOWN (3/15/66)

Calculated Reactor Thermal Power		42.06
Gains — Reflector Internal Heating	0.51	
Losses — Reflector	0.55	
Reactor top	0.33	
Reactor bottom	0.22	
Total	0.59	
Calculated Heat Gain by NaK in Core		41.47
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(41.74)
Gains — Neutron Shield Internal Heating	0.18	
Losses — Pump	1.11	
Supply lines	0.16	
Reactor support legs	0.60	
Neutron shield	(0.96)	
Upper torque box	0.94	
Total	2.63	
Calculated Heat to Converter		38.84
Measured Heat to Converter (Flow Temperature Drop)		(38.57)
Losses — Structure to Neutron Shield	0.23	
Structure to vacuum vessel	1.55	
NaK legs to vacuum vessel	0.34	
Return lines to structure	(0.11)	
Lower torque box	0.86	
Instrument compartment	0.50	
Low-pressure convection	0.15	
Electrical power produced	0.48	
Shunt losses to radiators	(3.33)	
Total	4.11	
Calculated Heat Rejected by Converter Radiator		34.73
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(37.67)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

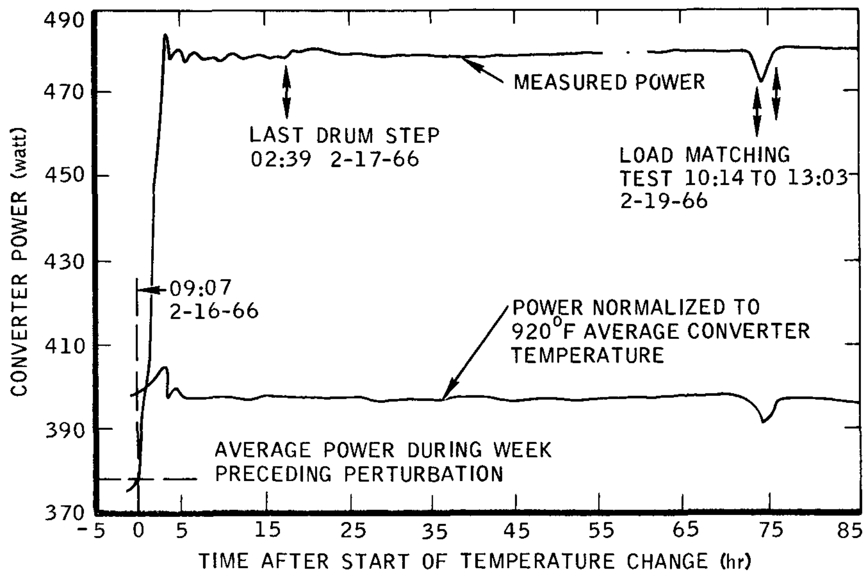

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Figure 26. FS-3 Temperature Perturbation Test — Converter Performance

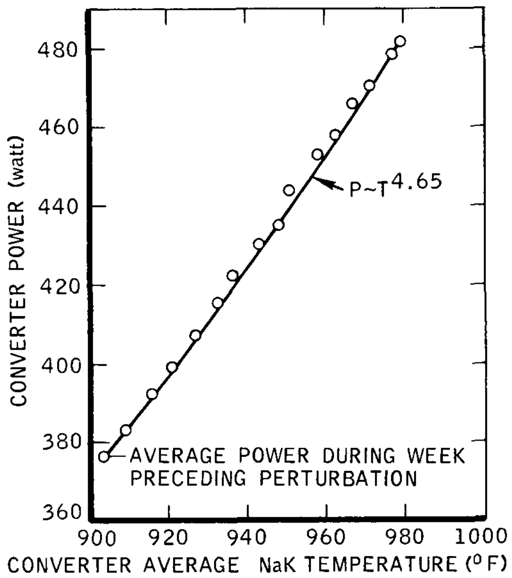

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Figure 27. FS-3 Temperature Perturbation Test — Converter Power

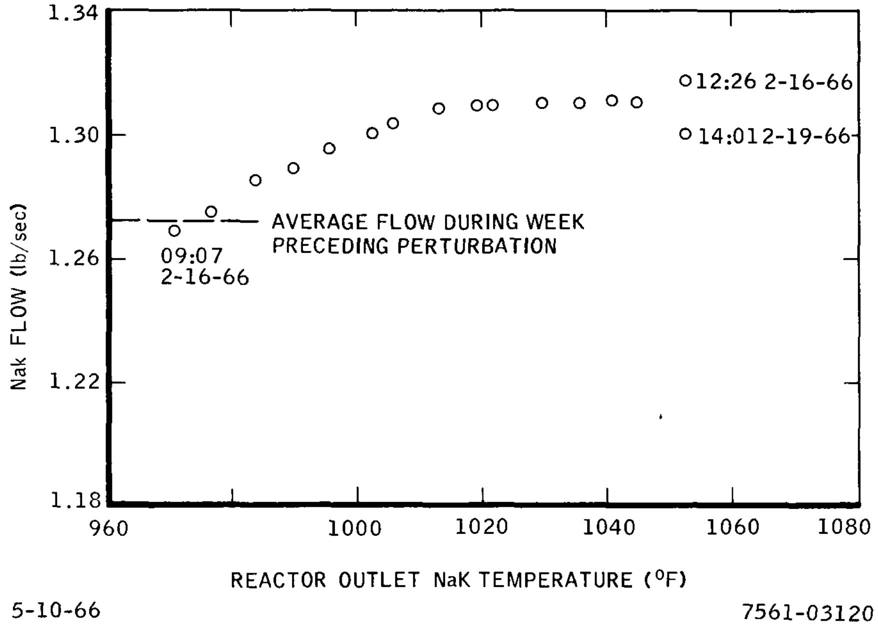

Figure 28. FS-3 Temperature Perturbation Test — Pump Performance

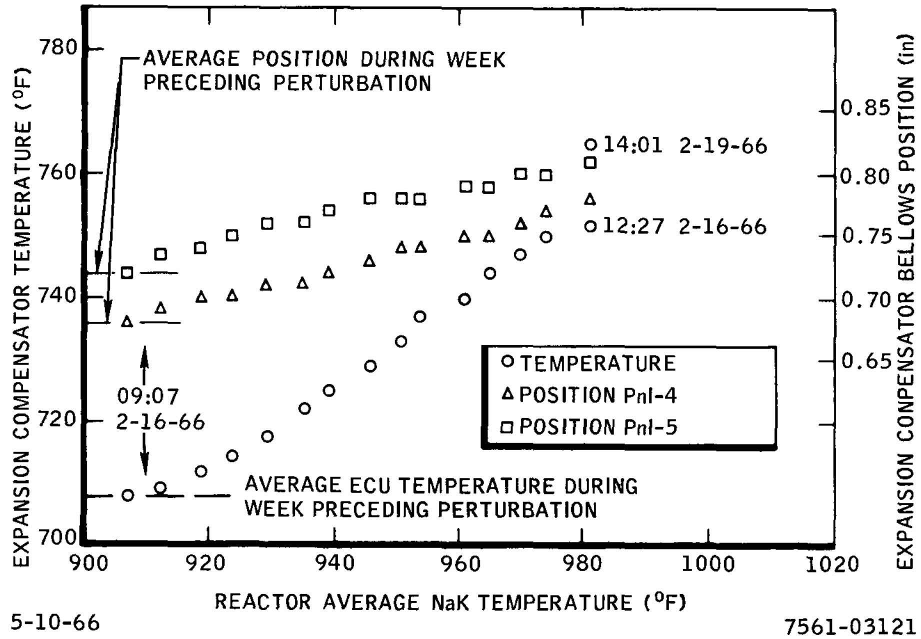

Figure 29. FS-3 Temperature Perturbation Test — Expansion Compensator Performance

Figure 28 shows the variation in pump flow rate as a function of reactor outlet temperature during the temperature perturbation. Pump performance while stabilized at the increased temperature is shown in Figure 20. Total pump degradation upon first reaching the 1053°F outlet temperature was 14.3%, followed by an additional 1% during the stabilization period. The degradation just prior to shutdown was 15.3%.

ECU performance during the temperature change is shown in Figure 29. Performance was near that expected except that the ECU temperature reached 765°F as compared to the predicted 755°F. The maximum operating limit for the compensator is 775°F.

Performance of system diagnostic instrumentation was satisfactory. The only anomaly observed was the failure of TS-3 and TS-4 to operate during the temperature increase due to improper connections in the switch circuits.

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IV. SYSTEM SHUTDOWN

On March 15, 1966, the shutdown of FS-3 was initiated following the completion of 10,000 hr of full-power operation. During the shutdown, the average reactor coolant temperature was leveled at 906 ± 5°F for 4 hr and at 760 ± 5°F for 8 hr. The reactor was shut down at an average temperature of 558°F at an indicated 0.1-in. deflection on ECU No. 1. Total operating time and energy release for the FS-3 are summarized as:

Total critical time (hr)	10,075
Total time at full power (hr), $T_{average} \geq 900°F$	10,005.5
Total thermal energy release (kwt)	382,944
Total electrical energy release (kwe)	4038.3
Average electrical power output (watts)	402.4
Average electrical power (watts), space equivalent	450.7

Table 8 is a summary comparison of FS-3 performance during system shutdown with the performance during thermal acceptance tests in January 1965.

Figure 30 is a history of reactor temperatures during the shutdown operation. Figure 31 shows the converter inlet and outlet NaK and radiator temperatures and temperature drop across the converter thermoelectric elements. Figure 32 shows the average NaK, structure, ECU hot strap, control actuator, reflector, converter radiator, neutron shield, instrument compartment, and pump fin-base temperatures. With the exception of the neutron shield the thermal performance of system components was as expected. As apparent in Figure 32 the indicated neutron shield temperature responded rapidly to changes in average NaK temperature, overshot at each plateau, and then increased while the average NaK temperature remained constant. This behavior is contrary to that expected for the shield with its high heat capacity and to observed temperature behavior in previous system tests. Since internal shield temperature data were also erratic during FS-3 startup, this anomaly is attributed to faulty thermocouples. It is noted, however, that the shield case temperature plotted in Figure 32, exhibits the expected time lag.

TABLE 8

COMPARISON OF FS-3 PERFORMANCE DURING SHUTDOWN TO PERFORMANCE DURING THERMAL ACCEPTANCE TESTS

	Thermal Acceptance	Shutdown
Thermal Performance		
Temperatures (°F)		
Converter inlet NaK	800	803
Converter outlet NaK	720	713
Converter average	760	758
Converter ΔT	80	90
ECU*	702	603
Maximum structure*	740	664
Heater power input (kw)	29.5	0
Reactor thermal power (kw)	0	25.1
Electrical Performance		
Power output (watts)	237	213
Open circuit voltage (volts)	36.2	39.9
Internal resistance (ohms)	1.41	1.85
Thermoelectric ΔT	187	184
Pump Performance		
Flow rate based on fringe flux (gpm)	11.4	11.3

*The high ECU and structure temperatures during thermal acceptance tests result from use of electrical ground test heaters mounted on NaK return lines.

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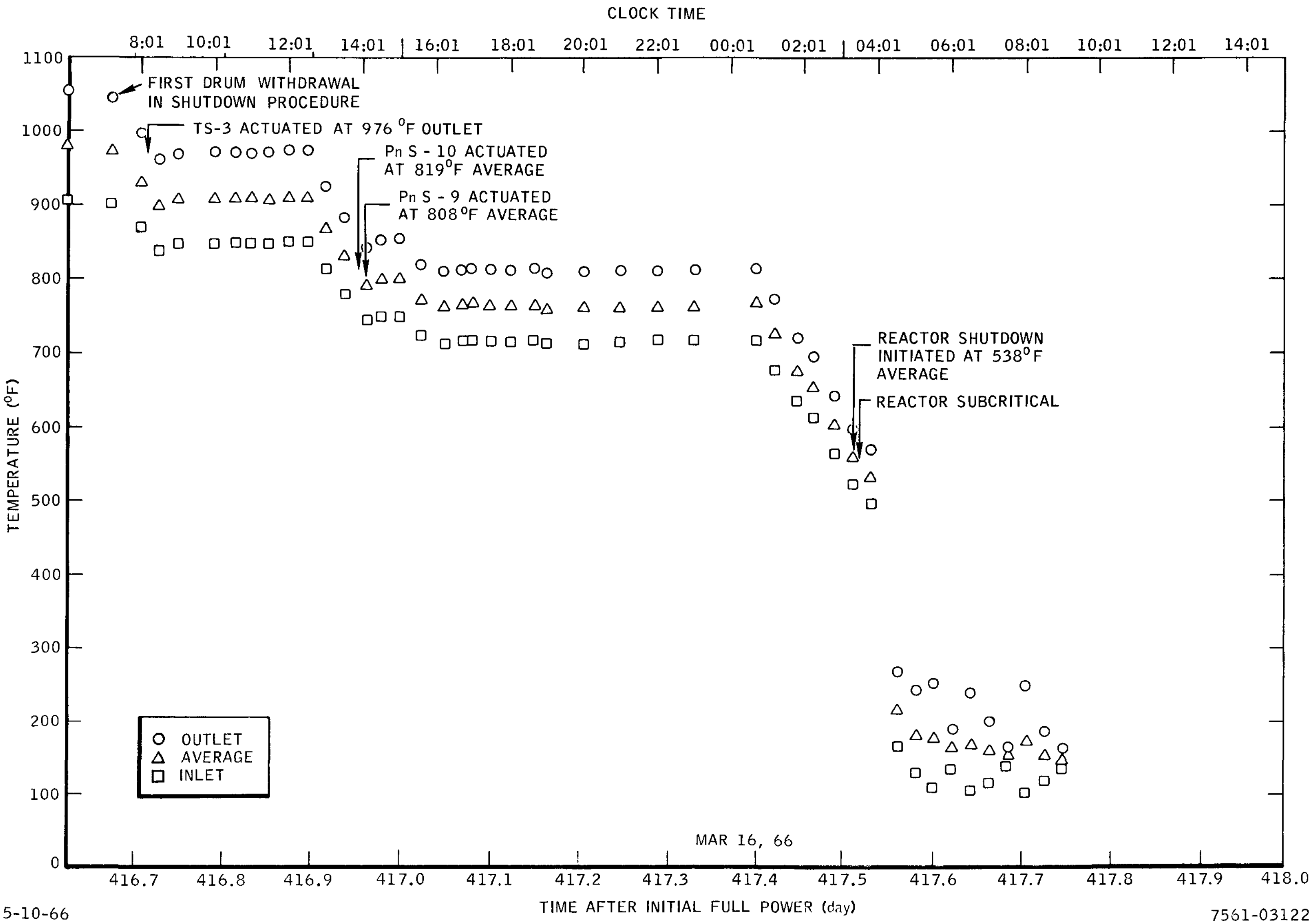

Figure 30. Reactor Temperatures During Shutdown

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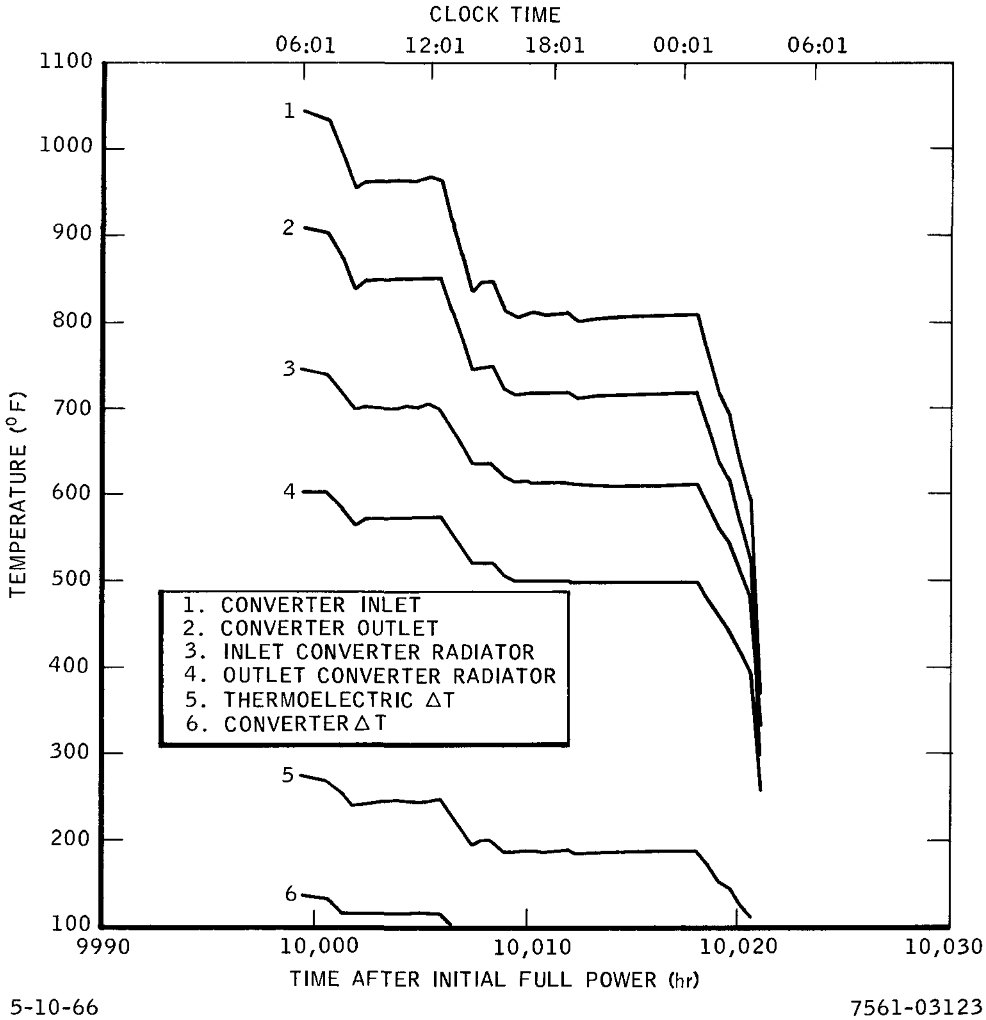

Figure 31. Converter Temperatures During Shutdown

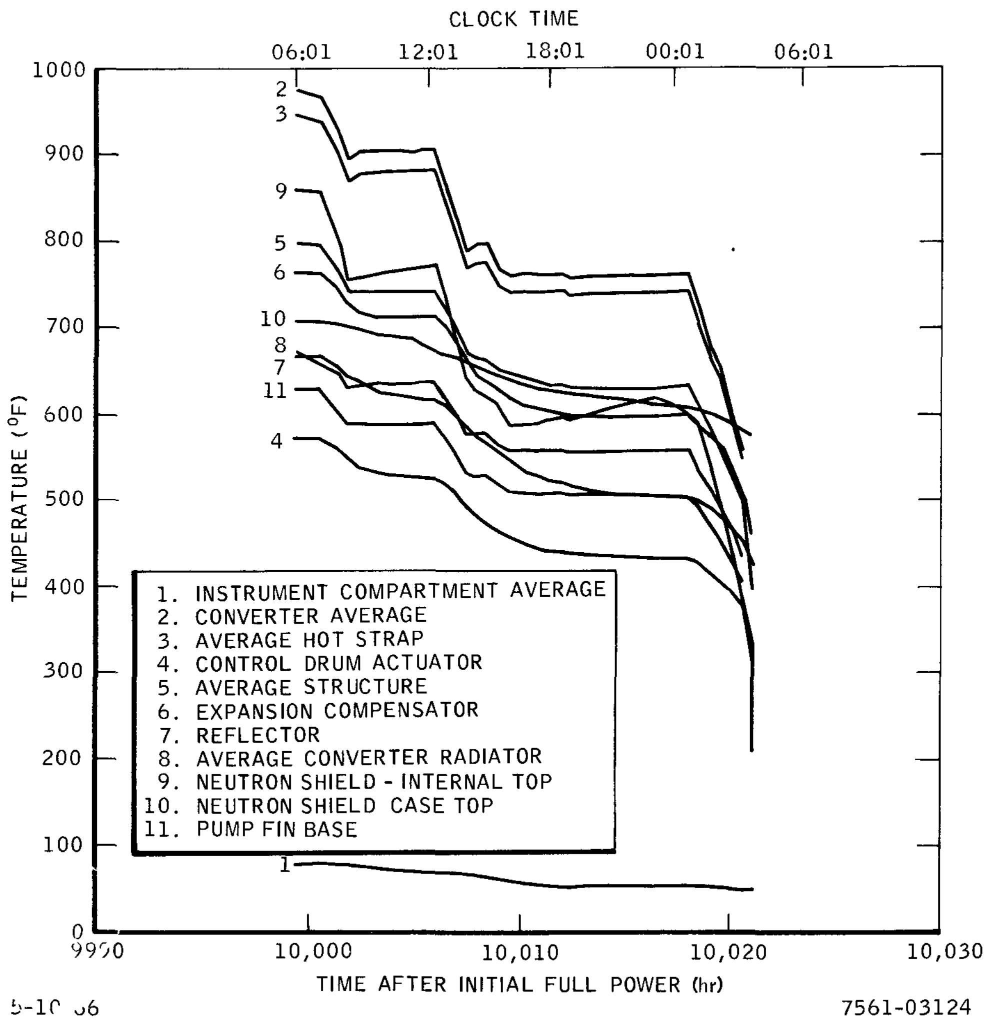

Figure 32. Component Temperatures During Shutdown

Figure 33 is a comparison of maximum structure temperature during thermal acceptance tests to that during shutdown. The higher structure temperatures during acceptance tests resulted from the use of electrical heaters mounted on the NaK return lines as the source of heat. Detailed system heat balances at each of the temperature plateaus are given in Tables 9 and 10. A comparison of Tables 4 and 9 show no significant differences in any of the heat balance terms between the end of one year of operation and system shutdown. Due to instrumentation difficulties during FS-3 thermal acceptance test, no comparison is available for Table 10.

Figures 34 through 37 show the converter power output, open- and closed-circuit voltages, current, and internal resistance as a function of average converter NaK temperature during shutdown. Figure 34 also compares converter power output during shutdown to power output during thermal acceptance tests; the vertical displacement between curves is due to the net result of two effects: (1) the higher structure temperatures during acceptance tests, which tends to reduce the displacement, and (2) converter degradation during the 10,000 hr of power operation, which causes the reduced power during shutdown. Figure 37

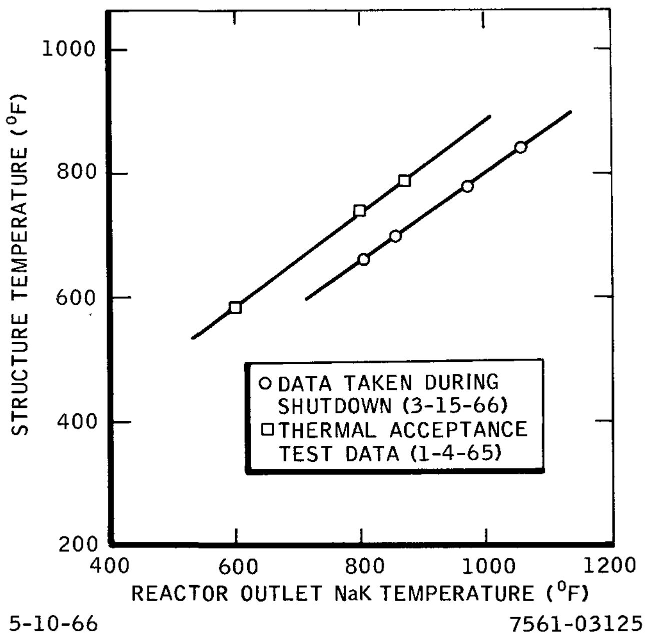

Figure 33. Maximum Structure Temperatures During Shutdown

TABLE 9

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
SYSTEM SHUTDOWN (T_{avg} = 911°F)

Calculated Reactor Thermal Power		36.35
Gains — Reflector Internal Heating	0.43	
Losses — Reflector	0.46	
Reactor top	0.27	
Reactor bottom	0.16	
Total	0.46	
Calculated Heat Gain by NaK in Core		35.89
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(35.82)
Gains — Neutron Shield Internal Heating	0.15	
Losses — Pump	0.96	
Supply lines	0.13	
Reactor support legs	0.48	
Neutron shield	(0.90)	
Upper torque box	0.72	
Total	2.14	
Calculated Heat to Converter		33.75
Measured Heat to Converter (Flow Temperature Drop)		(33.23)
Losses — Structure to Neutron Shield	0.38	
Structure to vacuum vessel	1.30	
NaK legs to vacuum vessel	0.28	
Return lines to structure	(0.09)	
Lower torque box	0.71	
Instrument compartment	0.50	
Low-pressure convection	0.14	
Electrical power produced	0.38	
Shunt losses to radiators	(2.61)	
Total	3.69	
Calculated Heat Rejected by Converter Radiator		30.06
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(33.06)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

TABLE 10

SNAP 10A FS-3 DETAILED SYSTEM HEAT BALANCE (kw)
SYSTEM SHUTDOWN (T_{avg} = 760°F)

Calculated Reactor Thermal Power		25.12
Gains — Reflector Internal Heating	0.29	
Losses — Reflector	0.30	
Reactor top	0.17	
Reactor bottom	0.06	
Total	0.24	
Calculated Heat Gain by NaK in Core		24.88
Measured Heat Gain by NaK in Core (Flow Temperature Rise)		(25.82)
Gains — Neutron Shield Internal Heating	0.31	
Losses — Pump	0.69	
Supply lines	0.08	
Reactor support legs	0.28	
Neutron shield	(0.76)	
Upper torque box	0.39	
Total	1.13	
Calculated Heat to Converter		23.75
Measured Heat to Converter (Flow Temperature Drop)		(23.95)
Losses — Structure to Neutron Shield	0.36	
Structure to vacuum vessel	0.86	
NaK legs to vacuum vessel	0.17	
Return lines to structure	(0.05)	
Lower torque box	0.46	
Instrument compartment	0.50	
Low pressure convection	0.12	
Electrical power produced	0.21	
Shunt losses to radiators	(1.46)	
Total	2.68	
Calculated Heat Rejected by Converter Radiator		21.07
Calculated Heat Rejected by Converter Radiator (Based on Radiator Temperature, °F)		(23.95)

NOTE: Terms in parenthesis are shown for information only and are not included in the heat balance.

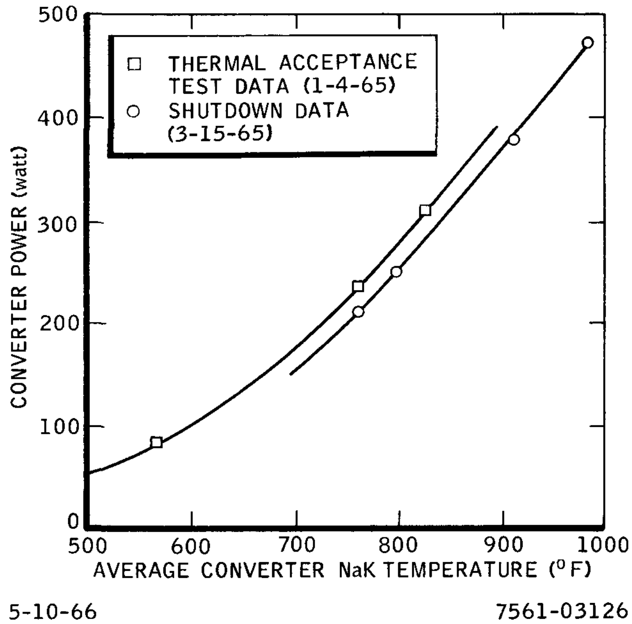

Figure 34. Converter Power During System Shutdown

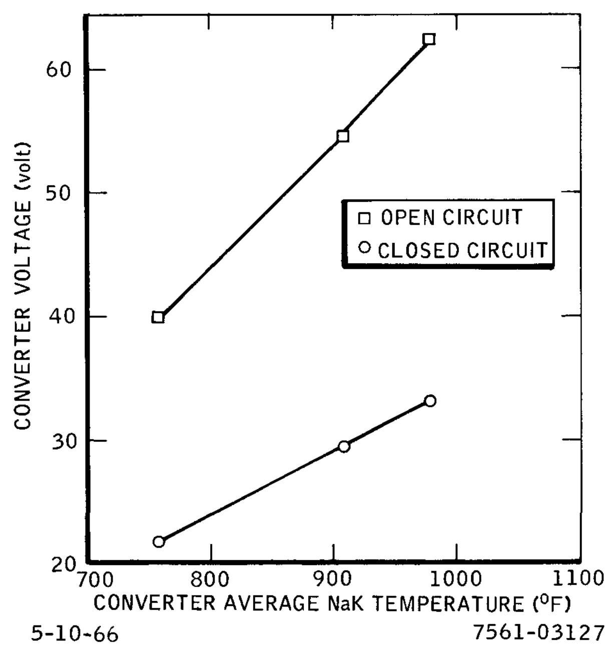

Figure 35. Converter Voltage During System Shutdown

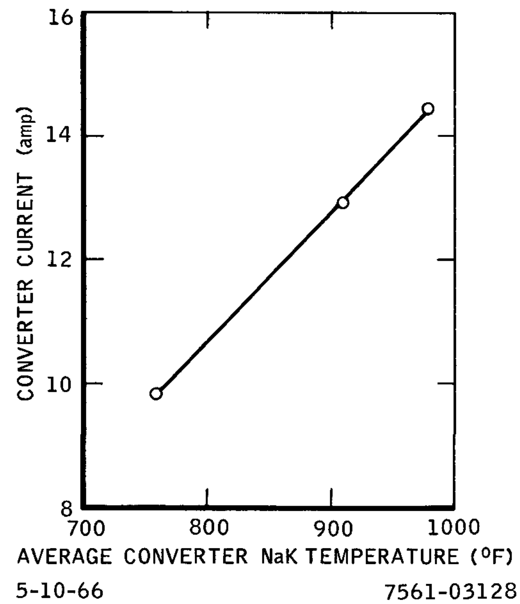

Figure 36. Converter Current During System Shutdown

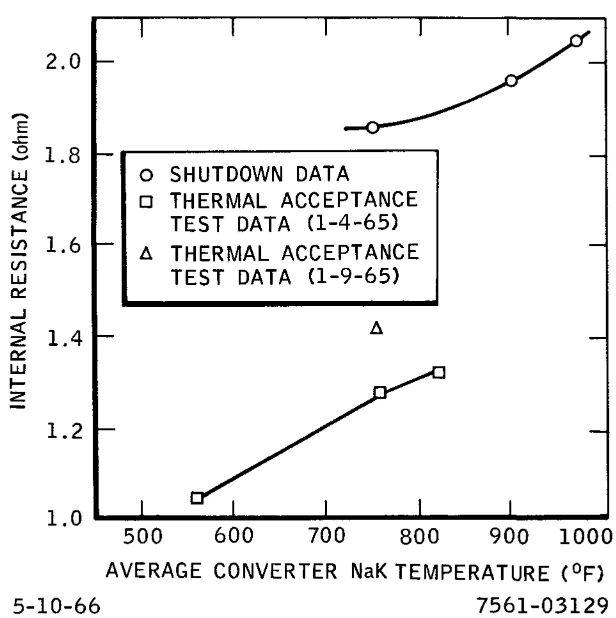

Figure 37. Converter Internal Resistance During System Shutdown

presents a comparison of converter internal resistance during shutdown to that observed during acceptance tests. The resistance data taken during the first thermal acceptance test was low due to capacitive loading by test equipment of the converter. The difference between resistances during shutdown and during thermal acceptance tests is a result of converter degradation. Converter resistance to ground during shutdown is shown in Figure 38.

Pump performance during system shutdown is shown in Figure 39 as a function of reactor outlet temperature. For comparison, flow data taken during thermal acceptance tests have been included in Figure 39. The most important conclusion to be drawn from Figure 39 is that after long-term operation the pump becomes insensitive to temperature changes above 900°F and that below 800°F there is no apparent change in flow from that observed during thermal acceptance test. Pump fin temperatures during shutdown are plotted in Figure 32.

The ECU position during shutdown is given in Figure 40. The performance of the units was as expected except that a sudden decrease in position was indicated at about 0.5 in. displacement (~800°F average temperature). The indicated position subsequently returned to normal. The cause of this sudden shift in position indicator output has not been determined. The setpoints of the ECU limit switches Pn S-9 and Pn S-10 are approximately 0.5 in., hence the possibility of mechanical interaction between the switches and position indicators exists. Similar indications were observed during FS-5 thermal acceptance tests at approximately the same average temperature and were attributed to the temperature sensitivity of the position indicators.

The ECU's reached their inner limits of travel at an average NaK temperature of 455°F, as expected, due to the loss of approximately 50 $in.^3$ of NaK to one secondary containment can during a primary bellows leak of April 14, 1965.

The diagnostic instrumentation performed satisfactorily during system shutdown except for the anomalous ECU position indicator behavior (discussed in the preceding paragraph) and a sudden drop in temperature indicated by TC-14 (Converter outlet — Tube 417). At 11:01 on March 15 the output of TC-14 dropped from 855°F to 113°F and remained at about 113°F until 17:17 at which time the output returned to normal. Since all other converter temperatures remained at

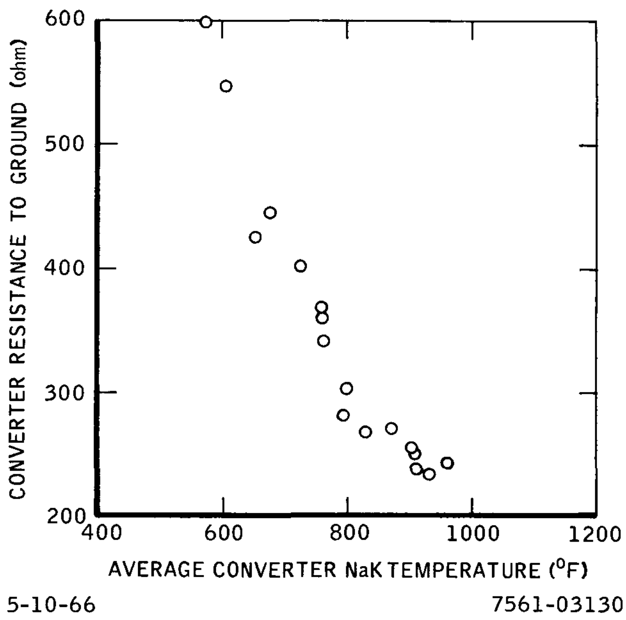

Figure 38. Converter Resistance to Ground During System Shutdown

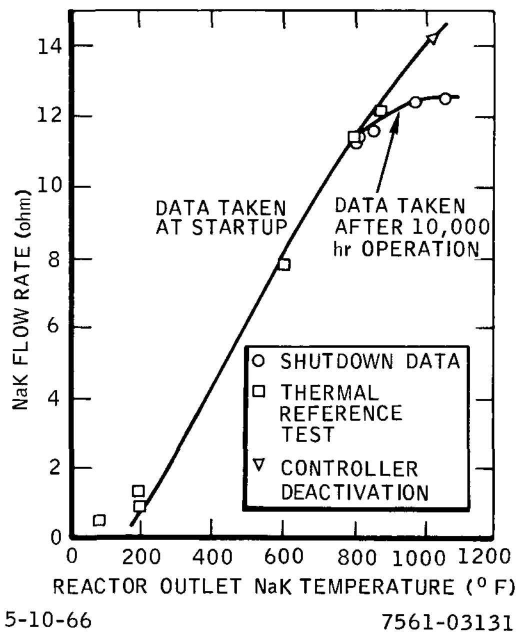

Figure 39. Pump Performance During System Shutdown

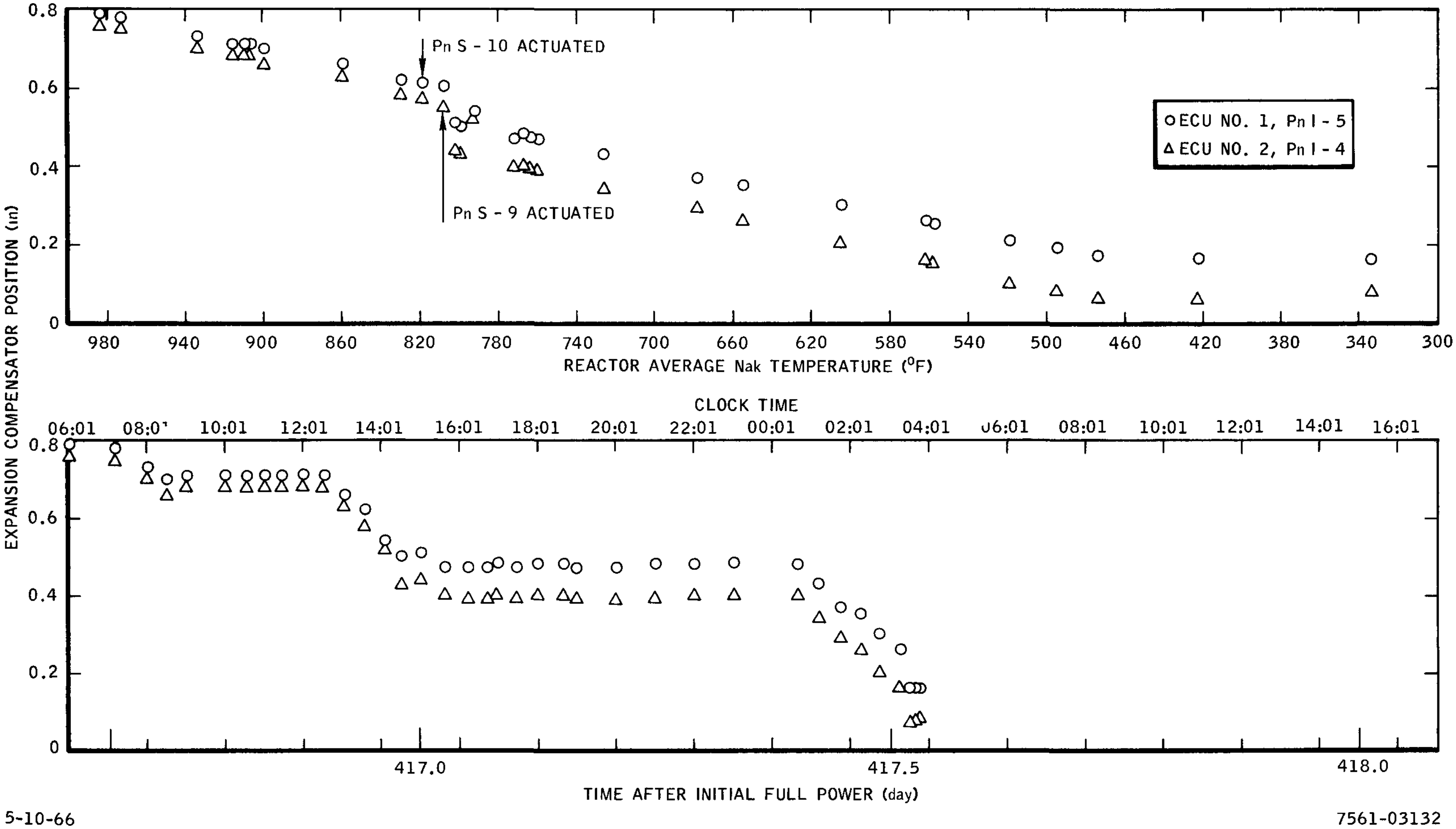

Figure 40. Expansion Compensator Position During System Shutdown

the normal level during this period, it is concluded that the low indicated temperature was caused by a temporary failure of TC-14. The cause of failure was not determined. Instrumentation status just before shutdown is summarized in Table 5.

Two approach-to-critical experiments were made with the FS-3 system about 70 hr after shutdown. In order to correct excess reactivity measurements, an estimate of the average core temperature was made based on measured reflector temperatures. Temperatures could not be accurately measured because of the partially void core and lack of flow. A core average NaK temperature of 235 ± 20°F was calculated. The average fuel temperature exceeds the NaK temperature by less than 1°F.

Analysis of the approach-to-critical experiments indicated an apparent loss of reactivity of 49 ± 6¢ since the initial critical experiments in 1965. Corrections for differences in core temperature and partially voided upper NaK plenum indicate a net reactivity loss of 19 ± 7¢ during the 10,000-hr run. Results of the approach to critical tests are listed as follows:

Reactivity Effects	Reactivity Values ($)	
Prestartup excess reactivity (80°F)		2.95 ± 0.05
Post-shutdown excess reactivity (uncorrected)	2.46 ± 0.03	
Correction for hot coolant (235 ± 20°F)	0.275 ± 0.038	
Correction for partially void upper NaK plenum	0.03 ± 0.02	
Corrected post-shutdown excess reactivity		2.76 ± 0.05
10,000-hr reactivity loss indicated by approach-to-critical tests		0.19 ± 0.07
10,000-hr reactivity loss indicated by temperature perturbation test		0.20 ± 0.01