Response of long focal length optical systems to thermal shock

Joseph M. Geary

Air Force Weapons Laboratory
Optical Systems Branch
Kirtland AFB, New Mexico 87117

Abstract. Aerial reconnaissance optical systems are often subjected to extremes in thermal environment. Designers have been able to engineer systems which maintain stable performance over a wide range of steady-state temperatures. But how long does it take a reconnaissance system to reach steady state after being subjected to a thermal shock (or step function)? This paper reports on experimental measurements made on several long focal length reconnaissance lenses exposed to thermal step functions. The most significant finding showed that the thermal recovery time is on the order of *hours* . . . . a period during which the reconnaissance mission may already have been completed.

Keywords: aerial reconnaissance, optical systems, thermal shock.

Optical Engineering 19:2:233-239 (March/April 1980).

I. INTRODUCTION

The purpose of this study was to determine *empirically* the response of long focal length optics to a large thermal step function. Concern over the thermal environment of such optical systems is not a recent phenomenon. Perhaps the earliest reported work of this genre was made by Woodford[1] back in 1945 with his investigation of Army Air Force reconnaissance lenses. With the advent of the space age and the use of probe satellites, the role of thermal radiation in the analysis of fast, catadioptric photographic objectives came into prominence.[2] Later on, attempts were made to model[3] the thermal response of long focal length objectives in order to predict image quality.

Studies concerned with the thermal environment of optical systems have relevance in many fields. But the inspiration and motivation for this particular work was supplied by aerial reconnaissance. The group of lenses selected generally reflects types used by the reconnaissance community in the decade of the seventies.

It was not uncommon some years ago for reconnaissance lenses to be subjected to large fluctuations in thermal environment over short periods of time. For example, on a hot summer day the camera bay of a recon aircraft parked on the apron could reach temperatures in excess of 150 F. Now suppose the pilot climbs aboard to start a mission. He powers up his ship (including *air conditioning* in the bay), taxis, takes off, and is over his target, perhaps all within an hour. However, his mission is less than successful because the returned target imagery is significantly below the quality expected. The reason for the poor system performance is thermal destabilization. The camera lens either did not have sufficient time to adjust to the temperature change and was still in a transient state when the target was reached, or if it had reached a steady state, it was not the same state enjoyed when the system was calibrated on the ground.

Because of this and similar problems, a modest experimental program was conducted to gain some laboratory estimates of the recovery times involved when state-of-the-art long focal length reconnaissance objectives were exposed to a thermal step function.

Original manuscript 1580 received May 2, 1979
Revised manuscript received July 30, 1979
Accepted for publication August 1, 1979

II. EXPERIMENTAL ARRANGEMENT

A schematic of the experiment is shown in Figure 1. The thermal box was constructed of styrofoam in two separable parts: base and cover. This allowed easy access to the interior for setting up and aligning the various lenses. The entrance and exit windows were incorporated into the cover. They consisted of 9.5 mm thick BK-7 plates (approximately two fringes in the visible across their widths). The air in the box was recirculated through a thermostatically controlled heater to bring the interior temperature up quickly to the desired value. Heated air did not blow directly onto the lens but was baffled sidewise. Laboratory thermometers were inserted at two locations through the top of the cover to provide independent air temperature checks.

Each lens tested was supported on the base by well-dried wood vee blocks. Thermocouples were attached at several points along the barrel to monitor lens temperature. (When heat was applied, air temperature in the box rose to the desired value within 20 minutes. The lenses, however, took several hours to reach the same temperature.)

The collimated input was provided by a 180″ f/5 parabolic mirror. The collimator and testing area all resided on a common vibration isolated concrete slab.

The aerial image was examined with a dual channel microscope: one channel for visual observation; the other for photographic recording. The microscope was mounted to a heavy micrometer base.

Figures 2 and 3 show front and rear view of the actual experimental arrangement. (The thermal box, while unsophisticated in appearance, worked quite well and was economically constructed.)

III. TEST PROCEDURE

Once a lens had been instrumented, aligned with the collimator, and covered, the microscope was focused on the aerial image formed in the space outside the box. In this way, the focal shift introduced by the window was nulled out. This aerial image (only slightly degraded by the spherical aberration and longitudinal color induced by the window) was recorded on 35 mm Pan-X film from which system resolution would be determined. (It should be noted that a strobe light source was used to make the exposures.) These

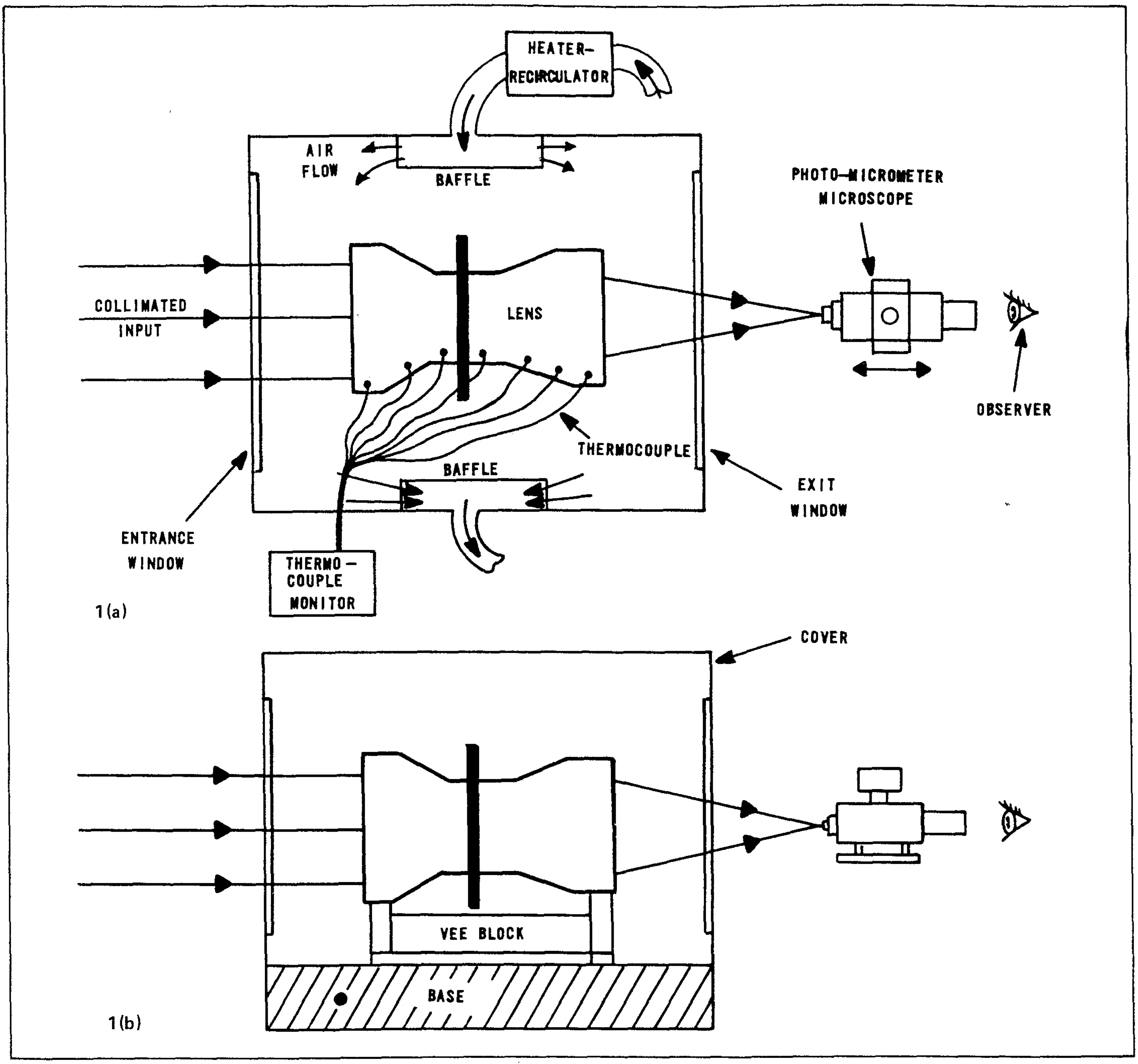

Figure 1. (a) Schematic of experimental arrangement top view; (b) side view of same.

focus and resolution values, then, comprised the starting point of the experiment, all of which measurements were made on-axis.

The air in the box was now heated. Photographs were taken initially at 10-minute intervals both at the starting focus position and at a refocus position. The amount of refocus for best image and barrel temperature was recorded. When these observations were made, the air circulator was momentarily cut out to avoid image degradation induced by vibration and air turbulence in the box. After two hours, data were collected at 20-minute intervals until termination of the experiment.

There was some concern that the change in air density in the heated box, in the region between the last lens surface and the exit window, would seriously impact focus shift values during the first 15 minutes of the experiment. However, an estimate utilizing the 36″ F.L. system showed that the shift induced because of the lower refractive index of the heated air (at 140 F) came to less than 20 microns. . . an insignificant amount compared to the magnitude of the shifts observed during the experiments.

After a system had thoroughly stabilized at 140 F, the cooldown part of the cycle would begin. The lens was immediately exposed to room temperature by simply removing the thermal box cover. A starting focus value was quickly obtained. The sequence of events thereafter was monitored much the same as during the heatup cycle

IV. TEST LENSES

Five reconnaissance lenses were tested. These are listed in Table 1.

Schematics of the optical layouts of the first four lenses are shown in Figure 4. Photographs are shown in Figure 5.

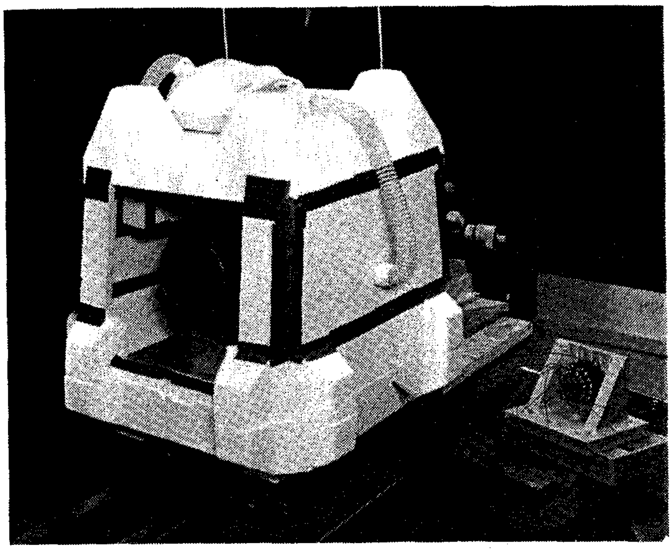

Figure 2. Front view of thermal box.

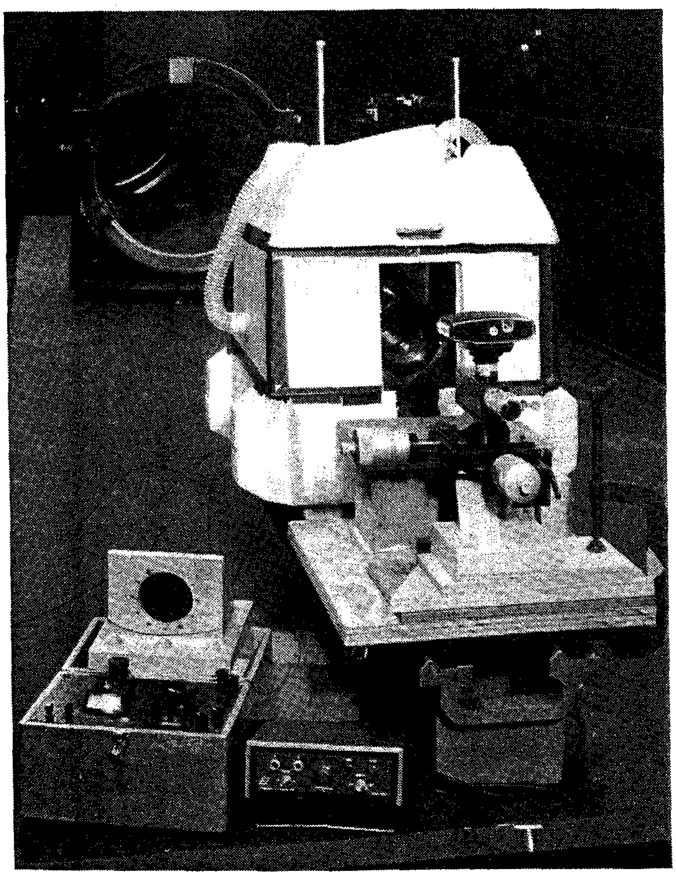

Figure 3. Rear view of thermal box.

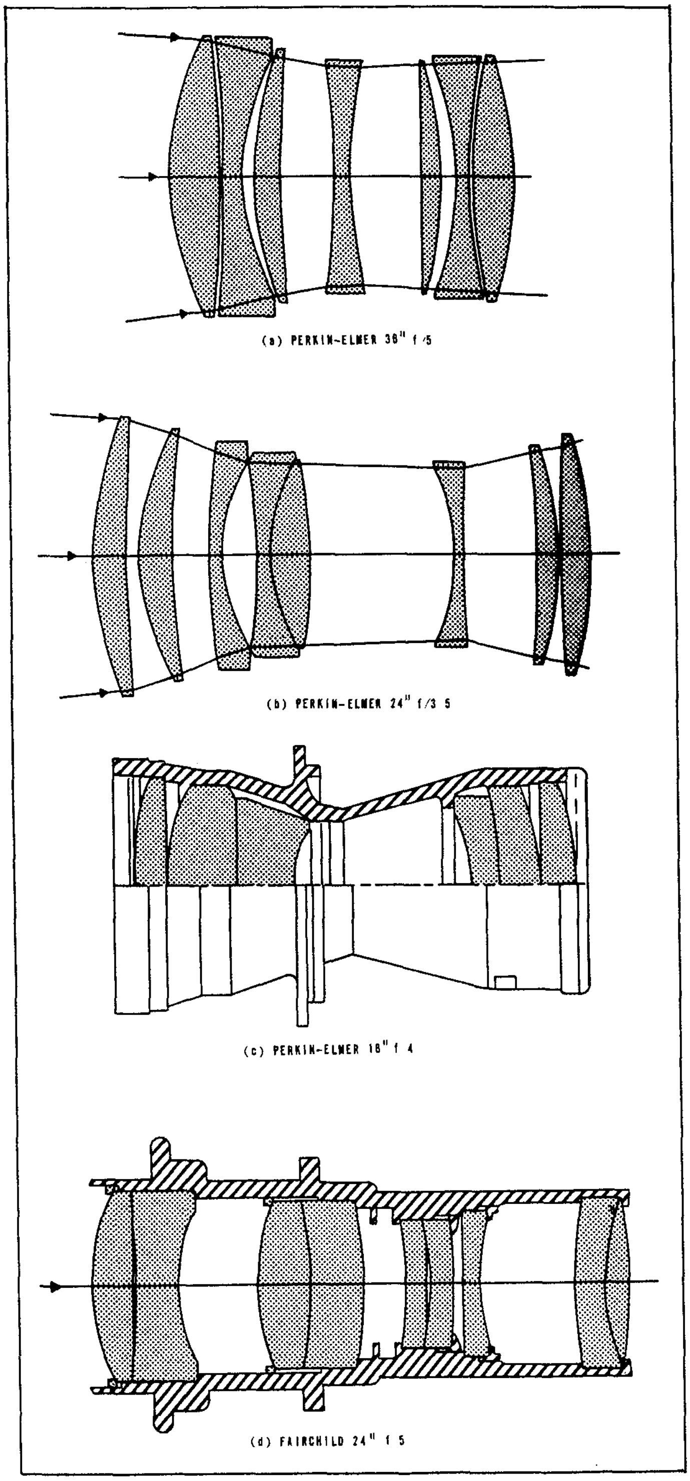

Figure 4. Optical layouts of lenses tested.

TABLE I. Lenses Used in the Thermal Experiments

Manufacturer	F L.	F/No	Type	Weight	Length	Diameter	Barrel	Element
Perkin-Elmer	36"	5 0	Refractive	40.10 lb	9 9"	10.5"	AL	7
Perkin-Elmer	24"	3.5	Refractive	31 25 lb	14.2"	9.4"	AL	8
Perkin-Elmer	18"	4.0	Refractive	18 60 lb	11.0"	6 1"	AL	6
Fairchild	24"	5 0	Refractive	49 60 lb	15 0"	5 5"	SS	9
Photronics	24"	3 8	Catadioptric		Information is not available			

Figure 5. Photographs of lenses tested.

V. RESULTS

Focal shifts as a function of time for a positive thermal shock (71 F → 140 F) are shown in Figure 6 for the three 24″ F.L. lenses. The Perkin-Elmer lens stabilized first after two hours, but with a permanent focus offset of +0.36 mm. The catadioptric settled down after three hours with a +0.49 mm offset. The Fairchild had reached a maximum focal deflection of 1.23 mm at 60 minutes. But, even after five hours, its transient response still had not flattened out. The trend, however, does seem to indicate that stabilization will finally occur at a focus not far from the initial value.

Figure 7 presents the data for the Perkin-Elmer 18″ and 36″ F.L. systems. The longer system has a maximum deflection of 1.91 mm at 100 minutes, and stabilizes at a +1.0 mm offset after 5 hours 20 minutes. Imagery was quite bad (even at best focus) during the first four hours. Thereafter, image quality began improving. The shorter system has a maximum deflection of +0.72 mm at 45 minutes, and stabilizes with a +0.03 mm offset after 3.5 hours.

Table II provides resolution data for three of the lenses (as read-off film exposed during the thermal test) both for the initial focal position and for best refocus as a function of time. An Air Force $\sqrt[6]{2}$ 3-bar target (Figure 8) was used at the focal plane of the collimator.

Figure 9 provides focal shift data on the Perkin-Elmer 36″ lens for thermal differences above room temperature of 5, 10, and 15 F.

Focal shifts as a function of time for a *negative* thermal shock (140 F → 71 F) are shown in Figure 10 for the three 24″ F.L. lenses. Figure 11 provides results on the 18″ and 36″ F.L. lenses. In Figure 12, imagery obtained from the 24″ Fairchild lens is presented as a function of time and barrel temperature for the starting focus and refocused positions.

VI. CONCLUSIONS

Transient effects of thermal shock on the symmetrical optical system show up not only as changes in its linear dimensionality (resulting in focal shifts), but also by the introduction of slight asymmetries in surface figure (causing degraded imagery even at best refocus). Once the optical system has stabilized in its new thermal environment, there often remains a permanent focal offset from the original focus (determined at a different temperature). In many cases, image quality still suffers because the slightly new thicknesses (both glass and air spaces) are no longer optimal at the new temperature.

It is obvious, then, that a lens design cannot be separated from

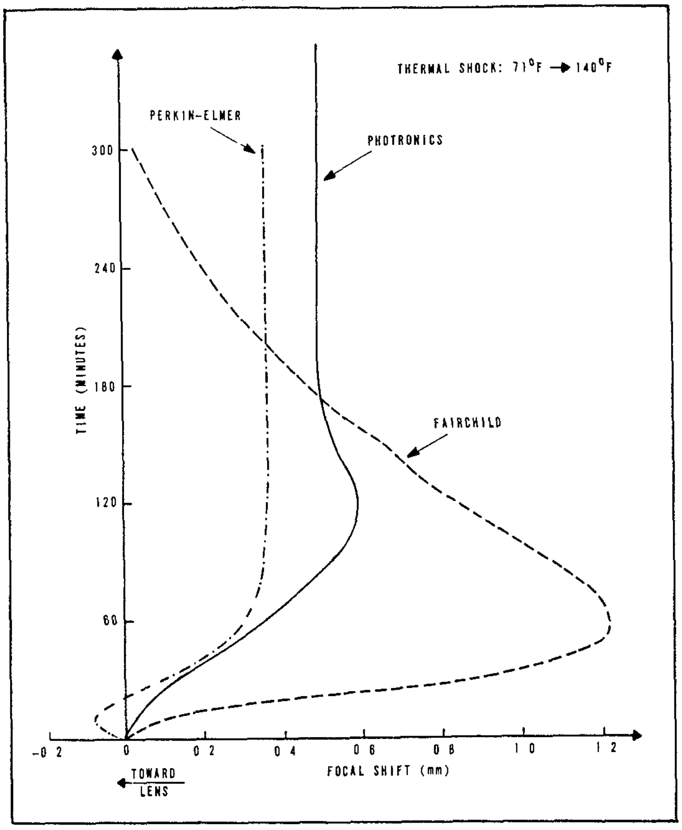

Figure 6. Response of the 24" F.L. lenses to a positive thermal shock.

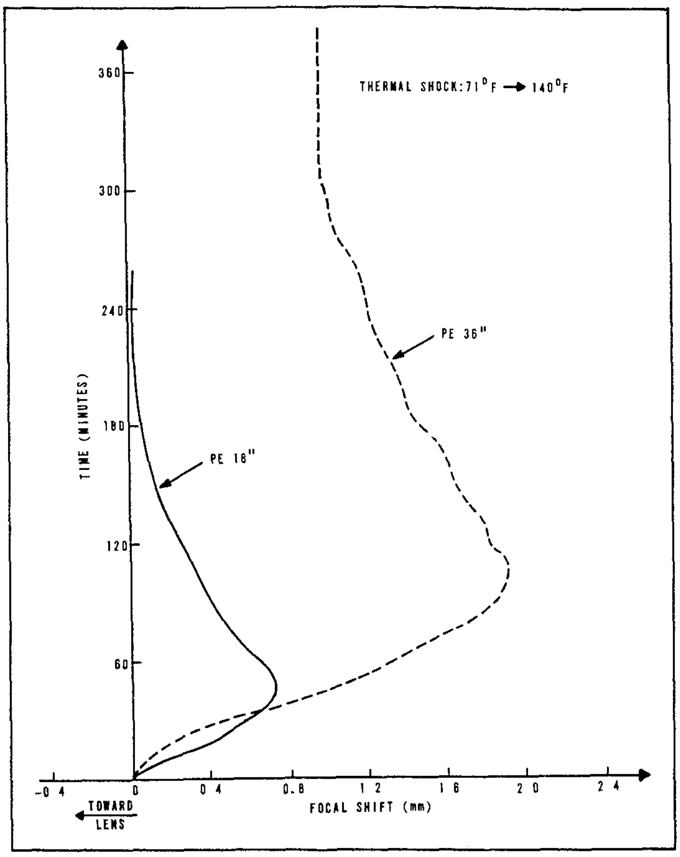

Figure 7. Response of the 18" and 36" F.L. lenses to a positive thermal shock.

TABLE II. Resolution Values in ℓ/mm as a Function of Temporal Thermal Changes

	P-E 18" f/4				P-E 24" f/3.5				Photronics 24" f/3.8			
	Start Focus		Refocus		Start Focus		Refocus		Start Focus		Refocus	
TIME	HOR	VER	HOR	VER	HOR	VER	HOR	VER	HOR	VER	HOR	VER
0	170	170			213	213			107	107		
10	32	56	160	101	107	95	190	190	95	95	120	107
20	14	56	90	50	213	190	240	190	85	76	120	95
30	9	9	50	90	120	53	190	190	85	75	85	38
40	9	9	45	56	60	95	213	169	38	24	107	76
50	9	9	101	90	19	21	190	169	21	19	95	34
60	9	9	101	113	21	42	190	169	85	34		
70	9	9	25	71	19	17	190	151			107	34
80	9	9	71	90	15	17	190	190	21	19	95	30
90					30	21	151	151	21	17	76	34
100	9	9	80	71	17	17	190	190	11	9	76	34
110					21	17	151	190	9	8	48	30
120	16	18	20	50	19	17	190	190				
140	25	28	25	50	21	17	190	190	9	9	67	30
160	25	37	28	101	19	17	151	151	9	9	48	24
180	25	25	90	56	21	17	213	213	8	11	67	30
200	50	101	25	45	21	17	213	213	8	11	60	27
220	32	63	113	113					9	11		
240	113	80	80	101							60	30
260	113	127							9	11	60	27

the kind of thermal environment in which it will be operated. Even a lens designed to maintain a specific back focal length over a wide temperature range still needs *a lot of time to return* to that position once thermal shock has forced it into the transient state.

It is important to emphasize that the results of these shock tests on reconnaissance lenses were decoupled from the camera system. The focal shifts we have seen for the objectives may be compensated for to some extent by the shift in the film plane caused by

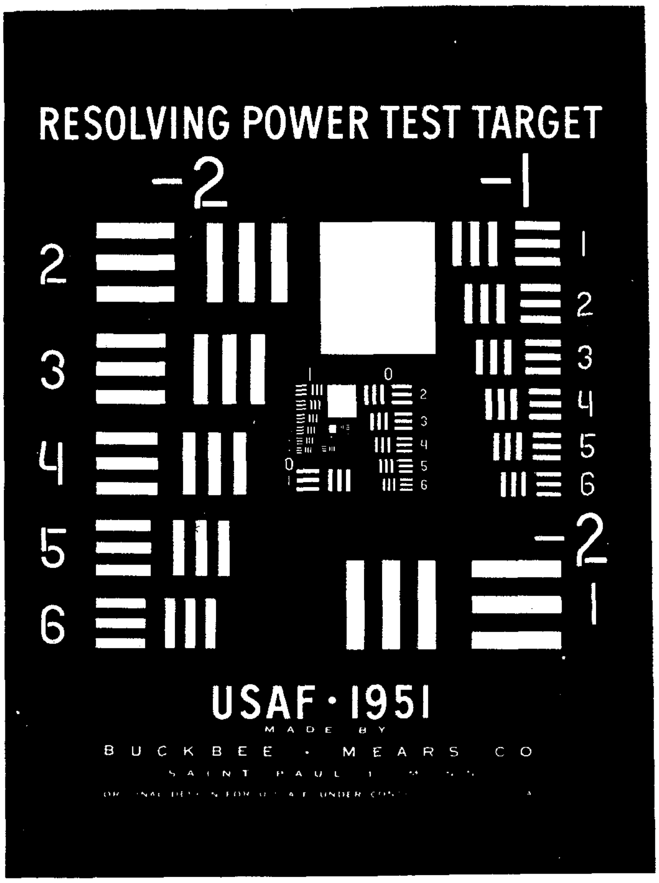

Figure 8. Resolution target used for the experiment.

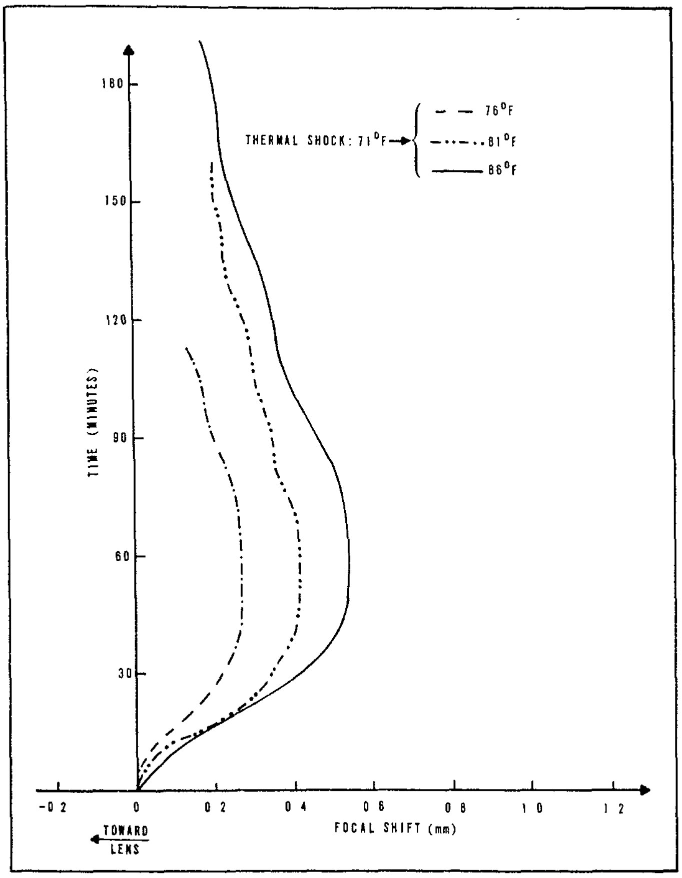

Figure 9. Response of the 36" F.L. lenses to three levels of positive thermal shock.

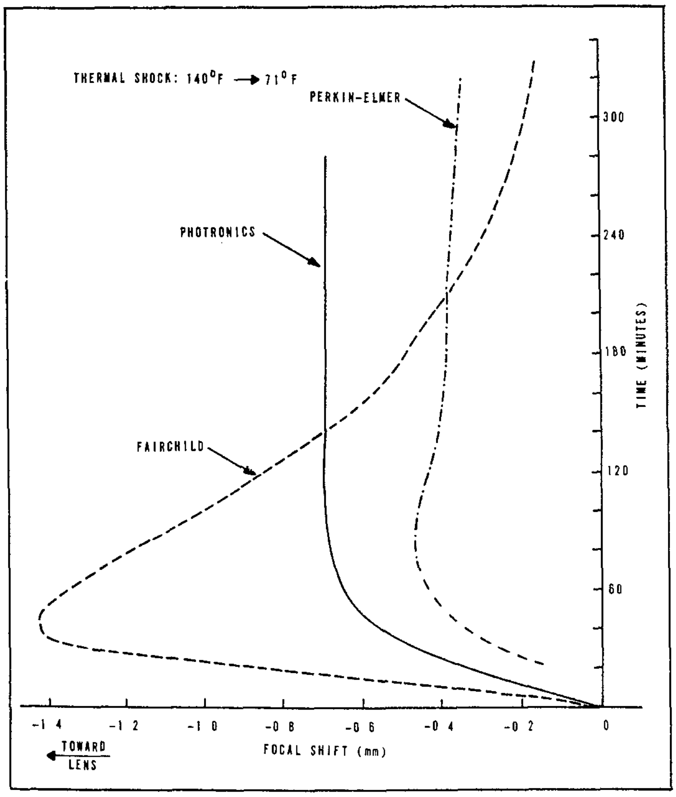

Figure 10. Response of the 24" F.L. lenses to a negative thermal shock.

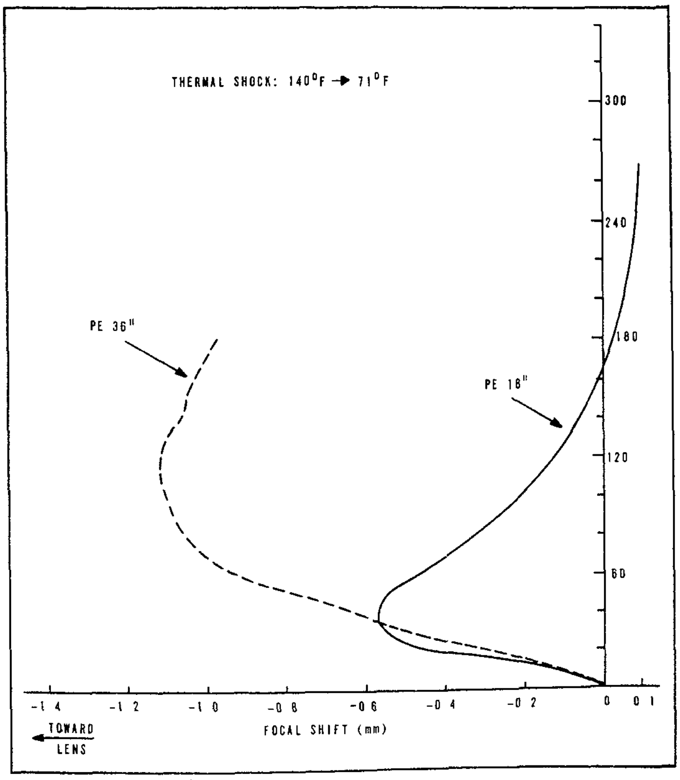

Figure 11. Response of the 18" and 36" F.L. lenses to a negative thermal shock.

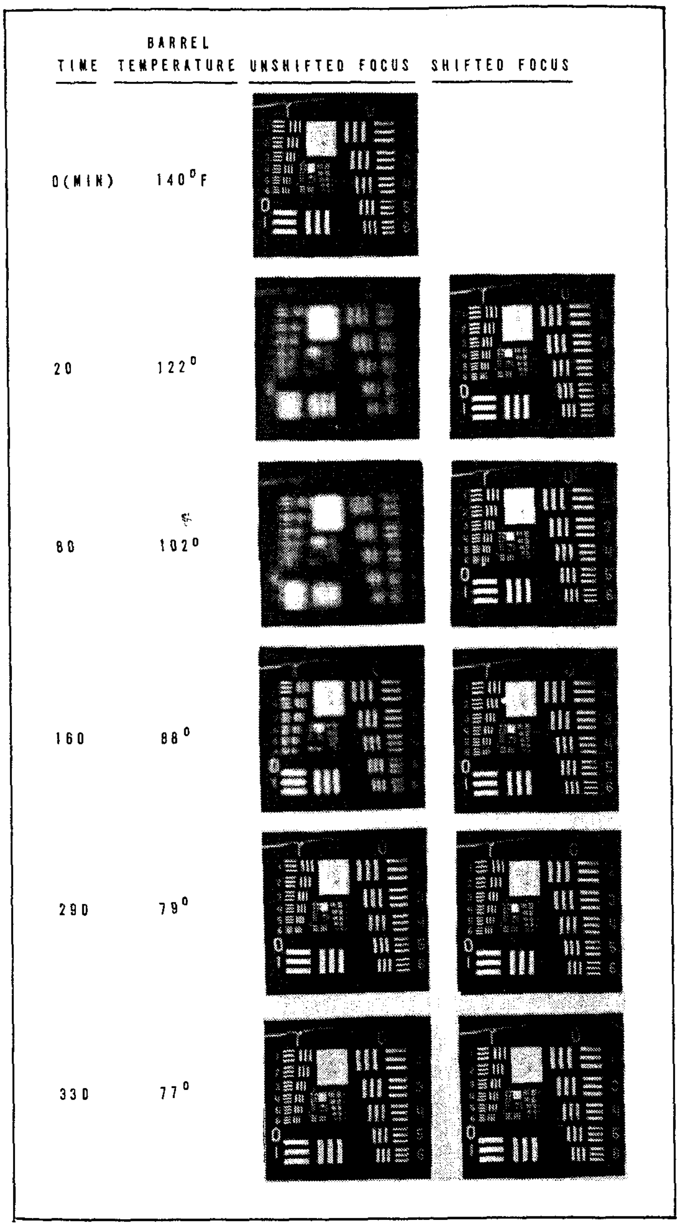

Figure 12. Imagery obtained from 24" F.L. Fairchild lens for a negative thermal shock.

thermal expansion in the lens cone. However, the image degradation (at best focus) due to altered element spacing, curvatures, and surface asymmetrics during transient response cannot be gotten around so easily. This clearly indicates why camera bays (or pods) must themselves provide a long term stable thermal environment for objectives regardless of outside ambient temperatures and their rates of change. The thermal environment of the bay should be maintained at the temperature for which the camera system was calibrated. Returning, then, to our mission scenario, the 150 F camera bay should be brought to the system operational temperature several hours before the pilot climbs aboard so that the lens has had plenty of time to recover from the transient state.

ACKNOWLEDGMENT

The author wishes to thank R. Oakley, A. Passamante, E. Haley, and J. Price for their assistance in conducting these long and tedious tests. He also wishes to thank D. Hoyt and G. Ferguson for their helpful comments and suggestions during the course of these experiments. All of the gentlemen are with the Naval Air Development Center in Pennsylvania.

REFERENCES

1. E. B. Woodford; R. N. Nierenberg, JOSA/35:10 (1945).
2. W. P. Barnes, Jr., Appl. Opt. 5:5 (1966).
3 W W Goodridge; L. K. Norton, paper presented at the October 1971 meeting of the Optical Society of America