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Comparison of shipping, handling, and shock instrumentation results for two 3.5-m class primary mirrors

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ABSTRACT

Packing, shipping, and handling procedures employed during several transportation activities for two large telescope primary mirrors are presented along with detailed shock recording results. Operations monitored included craning, forklifting, and shipping by air, sea, and land during all phases of manufacture and installation. The mirrors monitored were the SOR 3.5-m Telescope spun cast borosilicate primary mirror and the AEOS 3.67-m Telescope Zerodur thin meniscus primary mirror. Shock recording instrumentation included 2-, 5-, and 10-g Omni-G® impact indicators, 10-g Impact-o-graph® 3-axis recording accelerometers, and high-resolution 3-axis accelerometers with Astromed Dash 8 eight-channel chart recorders and audio indicators. Shock results for some operations were monitored to the 0.01-g level. In-shipment temperature data are also presented and discussed. Effects of lifting operations, road conditions via truck, flight conditions via C-5B aircraft, and transportation via sea-going barge are discussed. Data are presented for three different crate designs and configurations and, in some cases, include mirror-in-cell shipping data. Shock results were observed from as low as a few hundredths-g to over 3-g's during various operations.

Keywords: large mirrors, shock monitoring, optics handling and transportation

1. INTRODUCTION

As telescopes have grown in aperture over the past few decades, the logistical problems, cost, replacement time, handling complexity, and risks associated with their large primary mirrors have become a major concern, both during fabrication and transportation to the end use site. Logicon RDA has been extensively involved in addressing these issues and risks for several large optics projects since the 1985 time period[1]. Specifically, issues of crate design, shock mitigation and monitoring, handling fixtures, lifting equipment and techniques, shipping procedures, modes of transportation, and other associated areas have been addressed. Many DoD and astronomical community end users never see or appreciate the extent of the planning, complexity, and sophistication of large optics handling. This work area is typically handled by the engineers and project personnel "in the trenches" and is rarely well-documented for the benefit of future operations.

One of the first large telescope efforts to receive intense technical scrutiny and even national level attention in this regard was the 200-inch Mt. Palomar Hale Reflector. In April 1936, moving of the giant 200-inch Pyrex disk from the Corning Glass Works in NY to the Pasadena, CA optical shop in March received national attention. Thousands of people lined up along the railroad tracks to catch a glimpse of the "giant eye" as it made its way cross-country. The 200-inch mirror blank survived this 1936 rail trip and more than 11 years later its ride via truck to the Mt. Palomar site, a journey that was front-page news across the country. Stories have been told of engineers placing a cup of water on the crate or truck as a measure of shock received for some primary mirror moves. A radio-crystal detector was attached to the 200-inch mirror crate and wired to an indicator in the tractor cab for the 200-inch primary mirror journey to Mt. Palomar in November 1947, a fairly sophisticated monitoring technique for that time period[2].

In this paper we present an overview of the crate designs, moving and handling activities, shock recording instrumentation, and results for the SOR 3.5-m Telescope and AEOS 3.67-m Telescope primary mirrors. This summary comparative assessment of the logistical operations on these two large mirrors between 1992 and 1997 contains numerous insights into the planning and monitoring of large mirror moves where the cargo, just as for the Palomar mirror move more than half a century ago, was so precious and delicate.

2. INSTRUMENTATION

Several types of shock measuring instrumentation were used to monitor the shock history during the moving and handling of the two mirrors. The first type used was impact indicators, extremely simple instruments that indicate only if a maximum pre-set "g" level has been exceeded. For the activities reported in this paper, Omni-G® 2-g and 5-g resettable indicators (Figure 1) and 5-g and 10-g non-resettable indicators (Figure 2) were used. The resettable units are available with ratings from 2-g through 300-g. The non-resettable units are available in the range of 5-g through 300-g. Also used was a commercially available, portable, battery-powered x, y, z axis recording Impact-o-graph® Model M as shown in Figure 3. The actual instrument used had an x, y, and z range of 10-g. The chart speed was selected so that a complete shock record of the shipping could be recorded within the time of shipment.

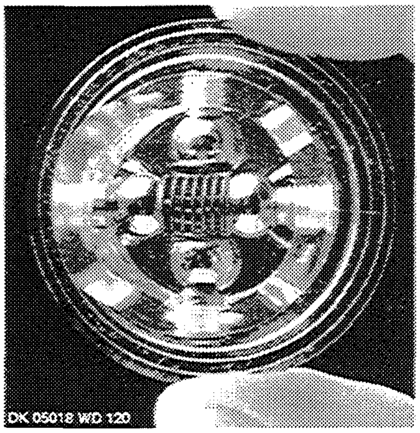

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Figure 1. Resettable Omni-G® impact indicator

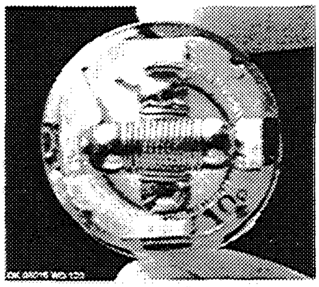

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Figure 2. Non-resettable Omni-G® impact indicator

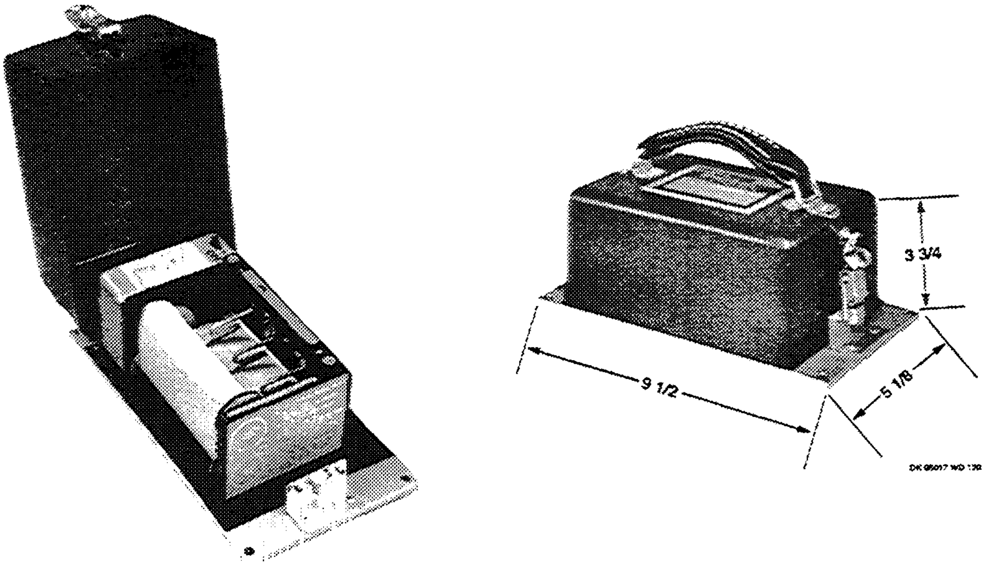

Figure 3. Portable x, y, z recording Impact-o-graph® Model M

An Astromed Dash 8 eight-channel chart recorder with audio indicator instrument provided by Contraves Brashear Systems was used for the moves in the Pittsburgh, PA area and is pictured in Figure 4. This multi-channel instrument recorded the signals from accelerometers and was attached to an alarm in the truck that indicated shocks in excess of 1-g.

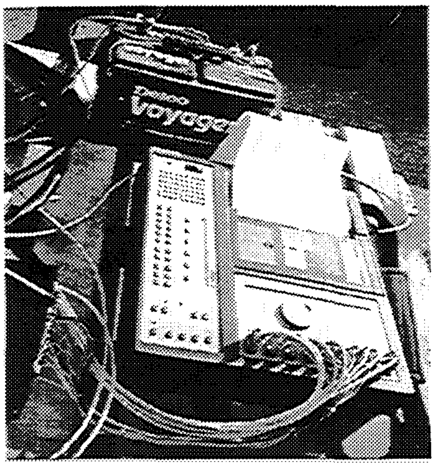

Figure 4. Eight-channel shock recording instrumentation for monitoring impact loads during AEOS 3.67-m mirror moves

3. MIRROR AND CRATE DESIGNS

3.1 Mirror designs

The design and optical material for the SOR 3.5-m primary mirror and the AEOS 3.67-m primary mirror were significantly different. The SOR 3.5-m primary mirror was made of Ohara E6 borosilicate glass. It was spun cast to near net shape with a honeycomb-cored structure at Steward Observatory Mirror Lab (SOML). The design of this mirror is shown in Figure 5. The AEOS 3.67-m primary mirror was a solid Zerodur thin meniscus mirror as shown in Figure 6. The differences in the mirror material and design dictated differences in the crate design used to transport the mirrors. Both mirrors had a focal ratio of f/1.5.

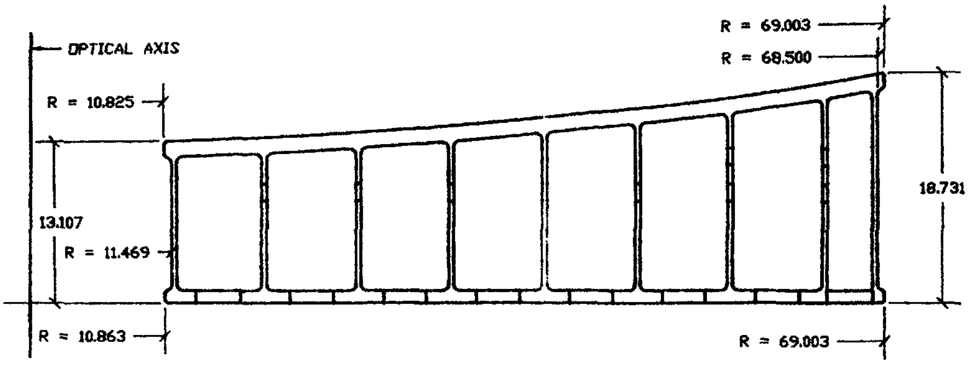

Figure 5. SOR 3.5-m primary mirror design

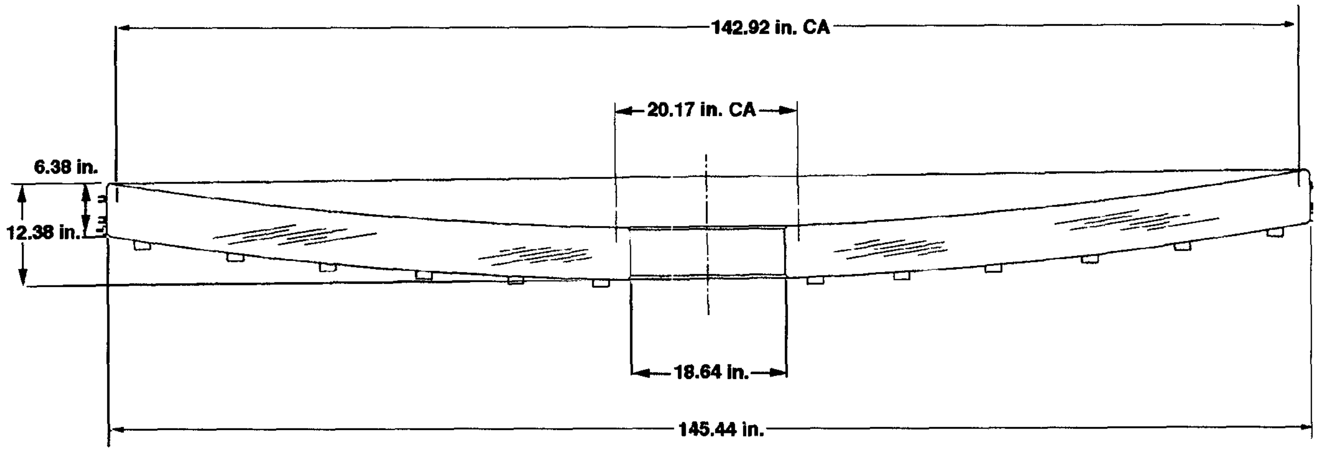

Figure 6. AEOS 3.67-m primary mirror design

3.2 Crate designs

Three different crates were used to ship the two mirrors. The crate design shown in Figure 7 was used for the SOR 3.5-m primary mirror since it was always shipped outside of the mirror cell. Two levels of shock isolation are provided. The first level has sixteen load spreaders attached to the one-inch thick plywood floor with the load on each spreader resting on three Barry isolators Model WB6-30. The second level of isolation is provided between the lifting frame and mirror box by three Barry inflatable isolators Model SLM 48A located on the steel beam lifting support. The steel bellyband around the 3.5-m SOR primary mirror was used for lifting and holds the mirror in a mild compressive state for shipping in the crate. The bellyband consists of 90-degree steel segments weighing about 100 pounds each. The band is about 20 inches wide and is held together by two turnbuckles at each joint. The inside of the band is covered by rubber to provide padding and friction for lifting the mirror using lifting lugs attached to the band and a load spreader. The bellyband concept worked extremely well.

Two different crates were used to ship the AEOS 3.67-m primary mirror. The first, manufactured by Zeiss and used to ship the blank alone, is shown in Figure 8. This crate was fabricated from 3/8-inch steel and used three different types of internal damping materials and heavy plywood supports. A second crate manufactured by Contraves was used to ship the mirror in the mirror cell. This crate design is shown in Figure 9. This crate had a massive steel frame and plywood sides. Shipping of mirrors in their cells is not recommended unless the mirror cell is specifically designed to withstand shipping and handling loads and can provide proper support and protection for the primary mirror.

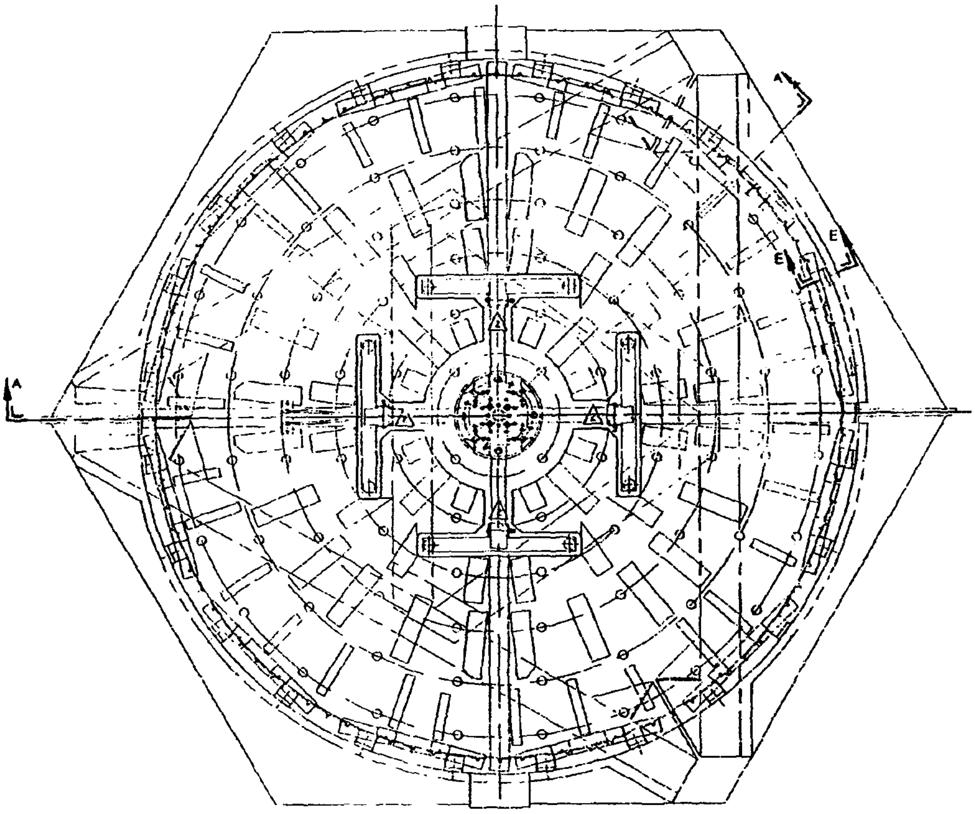

Figure 8. Zeiss design for the AEOS 3.67-m primary mirror crate

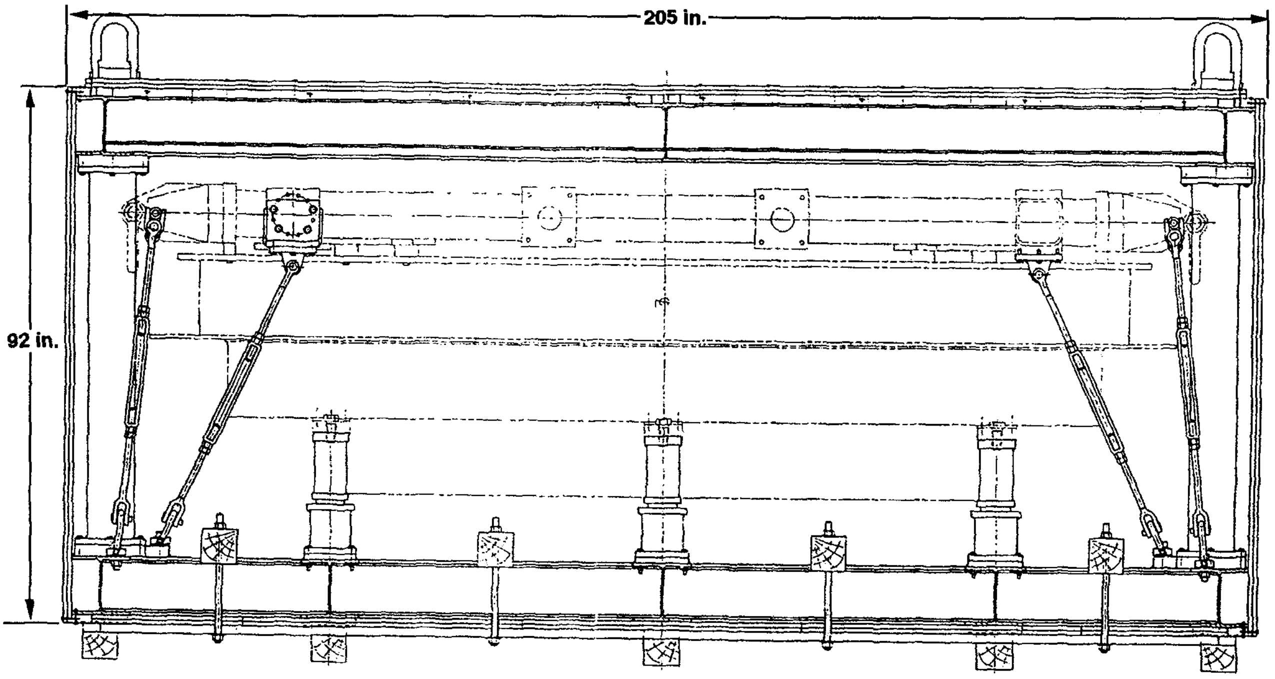

Figure 9. Contraves design for the AEOS 3.67-m primary mirror cell crate

4. SHIPPING OF SOR 3.5-M PRIMARY MIRROR

4.1 SOR 3.5-m primary mirror crate performance

The overall performance of the 3.5-m primary mirror crate was excellent. The 48 rubber isolators provide excellent load spreading and shock isolation of the mirror from the crate. The inflatable bladders that support the wooden crate on the steel beam base provided even more shock isolation. This isolation, along with that provided by the air-ride truck and the rubber pads which support the mirror inside the box, constitute one of the best shock isolation systems we have seen to date. A summary of the mirror transportation is provided in Table 1.

Table 1. Summary of shipping of SOR 3.5-m primary mirror

From	To	Mode	Instrumentation
SOML, Tucson, AZ	Kitt Peak, AZ	Air ride truck	Impact indicators, 3-axis recording accelerometer
Kitt Peak, AZ	SOML, Tucson, AZ	Air ride truck	Impact indicators, 3-axis recording accelerometer
SOML, Tucson, AZ	SOR, KAFB, NM	Air ride truck	Impact indicators, 3-axis recording accelerometer, temperature recorder

4.2 Accelerometer and impact indicator results for SOR 3.5-m primary mirror

A recording accelerometer and shock impact indicators were attached to the 4500-pound primary mirror and the mirror crate during moving of the mirror between Kitt Peak and SOML and for the move from SOML to the SOR. Neither the accelerometer nor the impact indicators recorded significant shock impact on the mirror or crate during any of the moves and handling operations. The Impact-o-graph® recording accelerometer was attached to the top of the mirror box and oriented with the z-axis vertical, the y-axis in the direction of travel of the truck, and the x-axis in the cross-travel direction. Recording sensitivity was about 2.5-g's per 1/8-inch of stylus deflection on the chart. With care, deflections indicating shocks down to a few hundredths-g's can be read. The unit does not have high temporal resolution capability, but shocks separated by a few minutes in time can be resolved by carefully examining the recording tape.

The recording tape showed no significant vibration, impacts, shocks, or acceleration during any of the 3.5-m mirror operations. An indication on the order of 0.13-g maximum was observed during the engagement of the fifth wheel to the truck flatbed at Kitt Peak. No significant shock indications were observed on the accelerometer during the over-the-road transportation to and from Kitt Peak and to the SOR, the maximum shock noted being in the range of a quarter g. Typical levels were only a few hundredths of a g. More detailed results of the 3-axis shock monitoring for all operations conducted between 8 March and 8 April 1993 are summarized in Table 2.

Table 2. Results of 3-axis shock monitoring during transportation of SOR 3.5-m primary mirror

Date	Time	Event	Indicated "g" Loads
8 March 1993	1035 MST	Impact-o-graph® on mirror crate at SOML. Crate on truck.	None
8 March 1993	1200 MST	Truck departs SOML for Kitt Peak	None
8 March 1993	1215 to 1445 MST	Truck on road, minor shock indications	x = 0.03 to 0.06 g y = 0.26 g max z = < 0.03 g
8 March 1993	1500 MST	Truck at Kitt Peak	None
8 March 1993	1605 MST	Truck in 4-m coating chamber facility, cab removed	x = 0.03 g y = < 0.03 g z = 0.14 g
9-16 March 1993		Crate lid removed, mirror prepared for coating operation, coating deposition accomplished	None
17 March 1993	0930 MST	Mirror in crate; Impact-o-graph® on for trip from KPNO to SOML	None
17 March 1993	0945 MST	Fifth-wheel engaged at KPNO	x = 0.12 g y = 0.13 g z = 0.07 g
17 March 1993	1000 MST	Depart KPNO for SOML	None
17 March-5 April 1993		Truck arrives at SOML; Impact-o-graph® read and turned off, post-coating optical testing conducted	None
5 April 1993	1500 MST	Impact-o-graph® installed for trip from SOML to SOR	None
6 April 1993	0600 MST	Depart SOML for Las Cruces, NM	None

Date	Time	Event	Indicated "g" Loads
6 April 1993	0800 MST	Truck on road – minor shock indications in Tucson, AZ area	x = 0.03 g y < 0.03 g z < 0.03 g
6 April 1993	1000 to 1300 MST	Minor shock indications on road	x = 0.02 to 0.09 g y = 0.05 g z = 0.02 g
6 April 1993	1400 MST	At Las Cruces, NM; remain overnight	Very small indications
7 April 1993	0830 MST	On road from Las Cruces to SOR	Very small indications
7 April 1993	0830 to 1200 MST	On road from Las Cruces to SOR	x = 0.06 g y = 0.05 g z = 0.04 g
7 April 1993	1400 MDT	At KAFB, NM Hanger 760, lid removed and Impact-o-graph® read	None
7 April 1993	1500 MDT	Mirror crate lid replaced	None
8 April 1993	0625 MDT	Depart Hanger 760 for SOR RADLAC storage building	None
8 April 1993	0735 MDT	At SOR, small shock indications	x = 0.06 g y = < 0.03 g z = 0.05 g
8 April 1993	0950 MDT	Mirror crate lid removed by crane inside RADLAC bldg. and set on floor. (Note: The 1.7-g is the Impact-o-graph® indication of the lid set-down shock only. Since lid was separate from mirror at time, it did not affect mirror.)	x = 0.15 g y = 0.13 g z = 1.7 g (See note under Event)

x = transverse direction, y = direction of travel, z = vertical direction

Five impact indicators with trip levels of 2-g and 5-g were attached to the mirror bellyband and to the inside bottom of the mirror crate. These indicators were not tripped and were still intact at the end of the mirror moves to and from Kitt Peak, AZ and to KAFB, NM. Thus, the maximum impact seen at any time by the mirror in the crate during any operation was less than 2-g, consistent with the results of the recording accelerometer. In general, the recording accelerometer profiles for the SOR 3.5-m mirror during transportation were lower than those for the AEOS 3.7-m mirror blank during its move from Germany to the United States. The AEOS mirror shock profiles were low, thus the SOR primary mirror and SOML crate shock readings are quite impressive.

4.3 Temperature recording during shipping of SOR 3.5-m primary mirror

Temperature changes in excess of 10 Kelvin are possible during shipping and while in storage. Since the bellyband is made from cold steel and the mirror from E6 glass, the effect of temperature changes on the mirror in a tightened bellyband can be significant. When the mirror and band cool, the steel band shrinks faster than the borosilicate mirror. This can result in considerable tightening of the band on the mirror. The rubber pad on the inside of the bellyband should limit shrinking stresses transmitted to the mirror surface and back plate (Figure 5) where contact between the mirror and the bellyband is maintained. Rubber can, however, become brittle and harden with age or exposure. The precise stress induced in the mirror for various temperature changes is difficult to quantify. Additional uncertainty of the stress induced in the mirror occurs because the 4-piece band is not a perfect circle and does not make perfectly uniform contact with the mirror around its circumference, so stresses are not uniform.

A two-probe digital max/min, indoor/outdoor thermometer was installed on the shipping box for temperature monitoring during the trip from SOML to the SOR. The unit was installed on the crate at SOML and the temperatures of the mirror and outside air were recorded. One probe was attached to the mirror side band, and the other recorded outside air temperature. The results of these measurements are shown in Table 3. The maximum/minimum temperature is the range of temperature observed since the last reading. The bellyband tightness was adjusted and checked before the lid was closed at SOML and upon arrival at KAFB, NM and the SOR storage area. Band tightness was judged acceptable and no temperature-related problems were noted.

Table 3. SOR 3.5-m mirror shipping temperature summary

Date	Time	Location	Air Temp (°C)	Mirror Temp (°C)	Air Max/Min (°C)	Mirror Max/Min (°C)	Comments
5 Apr 93	1500	SOML, AZ	23.3	22.8	---	---	Crate on truck, closed
7 Apr 93	1400	Hanger 760, NM	25.6	15.8	28.9/2.2	23.8/15.0	Crate on truck, closed
7 Apr 93	1445	Hanger 760, NM	15.2	15.8	28.9/2.2	23.8/15.0	Crate on truck, opened (bellyband top/bottom turnbuckles check, adjusted)
8 Apr 93	0600	Hanger 760, NM	15.0	15	28.9/2.2	23.3/15.0	Crate on truck, closed
8 Apr 93	0745	RADLAC/SOR, NM (outside bldg)	3.9	15.4	28.8/1.7	23.4/15.1	Crate on truck, closed
8 Apr 93	0930	RADLAC/SOR, NM (inside bldg)	9.0	14.6	28.8/1.7	23.4/14.6	Crate off truck, opened, bellyband removed

5. SHIPPING OF AEOS 3.67-M PRIMARY MIRROR

5.1 AEOS 3.67-m primary mirror crate performance

The performance of the Zeiss 3.67-m mirror crate and the Contraves 3.67-m mirror/cell crate were judged to be excellent. The Zeiss crate had a somewhat firmer mirror support system and, therefore, experienced more road shock effect than the SOML 3.5-m crate. On the other hand, its massive steel construction and custom-fitted cover provided better impact and weather protection. The Contraves 3.67-m mirror/cell crate performed well but as previously stated, we do not recommend shipping large mirrors in their operational telescope cells unless they are designed for shipping and then only when necessary.

The AEOS 3.67-m primary mirror had significantly more handling and shipping than the SOR 3.5-m primary mirror. The shipping and handling operations for the AEOS 3.67-m primary mirror are listed in Table 4. Instrumentation for shipment from Schott, Mainz, GE to Contraves, Keystone Commons, PA included two Impact-o-Graph® Model M 3-axis recording accelerometers, 2-g and 5-g resettable Omni-G® impact indicators and 5-g and 10-g non-resettable impact indicators. All these devices were manufactured by the Impact-o-Graph® Division, Chatsworth Data Corporation, Chatsworth, CA. These devices and their recording ranges were selected based on previous Logicon RDA experience in large optics handling and on calculations of safe drop and impact parameters for the 10,000-pound, 3.67-m thin meniscus mirror in the Zeiss steel crate. The mirror and crate weighed 31,000 pounds.

Table 4. Summary of shipping of AEOS 3.67-m primary mirror

Date(s)	From	To	Mode	Crate	Instrumentation
26 Mar 92	Mainz, GE	Rhein Main AFB, GE	Air ride truck	Zeiss crate	Impact indicators, 3-axis recording accelerometer
31 Mar 92	Rhein Main AFB, GE	Stewart AFB, NY	C5-B aircraft	Zeiss crate	Impact indicators, 3-axis recording accelerometer
1 Apr 92	Stewart AFB, NY	Pittsburgh Airport, PA	C5-B aircraft	Zeiss crate	Impact indicators, 3-axis recording accelerometer
2 Apr 92	Pittsburgh Airport, PA	Keystone Commons, PA	Air ride truck	Zeiss crate	Impact indicators
—	Keystone Commons, PA	Wampum, PA	Air ride truck	Zeiss crate	Impact indicators, 3-axis recording accelerometer
—	Wampum, PA	Contraves Bldg 3, PA	Air ride truck	Zeiss crate	Contraves recording and indicating accelerometer
—	Contraves Bldg 3, PA	Wampum, PA	Air ride truck	Cell crate	Contraves recording and indicating accelerometer
23 May 96	Wampum, PA	Keystone Commons, PA	Air ride truck	Cell crate	Cab alarm, 3-axis recording accelerometer, impact indicators
14 Jan - 20 Jan 97	Keystone Commons, PA	Kitt Peak, AZ	Air ride truck	Zeiss crate	Cab alarm, 3-axis recording accelerometer, impact indicators

Date(s)	From	To	Mode	Crate	Instrumentation
20 Jan - 31 Jan 97	Davis-Monthan AFB, AZ	Kitt Peak, AZ	Air ride truck	Zeiss crate	Cab alarm, 3-axis recording accelerometer, impact indicators
7 Feb - 15 Feb 97	Kitt Peak, AZ	Vancouver, WA	Air ride truck	Zeiss crate	Cab alarm, 3-axis recording accelerometer, impact indicators
3 May - 21 Mar 97	Vancouver, WA	Kahului, Maui, HI	Seagoing barge	Zeiss crate	3-axis recording accelerometer, impact indicators
31 Mar 97	Kahului, Maui, HI	Puunene, Maui, HI	Air ride truck	Zeiss crate	3-axis recording accelerometer, impact indicators
15 Apr 97	Puunene, Maui, HI	Haleakala, Maui, HI	Air ride truck	Cell crate	3-axis recording accelerometer, impact indicators

5.2 Accelerometer and impact indicator results for the AEOS 3.67-m primary mirror

5.2.1 Transportation of AEOS 3.67-m mirror from Schott, Mainz/Rhein Main, GE to Pittsburgh, PA

An M-series Impact-o-Graph® recording up to 10-g shocks in x, y, and z with a chart speed of ½ inch per hour was used for the trip from Mainz to Pittsburgh. It was attached to the wooden top panel of the steel Zeiss crate. The Impact-o-Graph® recorded three types of g loads: a g load as might be seen during vehicle acceleration or deceleration, vibration loads similar to those noted later during takeoff at Rhein Main Frankfort Airport, and shock loads which might occur due to dropping or bumping the crate. Within nominal limits, the first two types of g loading are not normally as damaging as the third type of impact loading. A summary of the shock monitoring results is shown in Table 5.

The smallest discernable shock that can be read on the recording graph paper on the Impact-o-Graph® is between 0.02-g and 0.05-g. The smallest discernable time resolved distance on the chart at the speed employed was about 0.01 inches and, thus, the shortest time resolution for repetitive shocks was approximately one minute. The accelerometer units will record shocks of much shorter duration but cannot separate them timewise on the recording chart. In a series of tests with the units prior to installation they responded well to a wide range of impacts and were relatively easy to read and operate. The manufacturer advertises that the units have a working accuracy of 10 percent. The Impact-o-Graph® on the top of the Zeiss crate was under the rubberized cover used to protect the crate and mirror blank from rain and dust. This cover was partially removed to secure extra tiedowns for the crate after it was loaded onto the C-5B aircraft at Rhein Main AFB. This was the only time the unit was checked until the cover was removed and the blank inspected at the airport in Pittsburgh on 1 April 1992. During this inspection of the blank by Contraves and Logicon RDA personnel, it was noted that none of the 2-g or 5-g units mounted on the blank itself had been tripped.

Realizing that there were no instruments readily accessible for in-process monitoring of the crate during shipment, another 2-g resettable impact indicator was attached to one of the four tiedown lugs on the crate after it was loaded on the C-5B at Rhein Main AFB. When this unit was read after landing at Stewart AFB, one spring-loaded axis of the two axis indicators had tripped, indicating that a shock or equivalent vibration load very close to 2-g had been sustained. It was assumed that this had occurred upon takeoff at Frankfort where the taxiway and runway were rough. A very pronounced vibration was noted in the C-5B passenger area during taxi that increased to a peak during takeoff. It is possible that this vibration may have occurred near the natural frequency of the crate or the 16-hertz natural frequency of the Impact-o-Graph® recording stylus. This could have amplified the acceleration registered on the chart during takeoff. When the crate recording accelerometer was read after arrival in Pittsburgh on 1 April 1992, it showed a maximum displacement of about 5-g's on takeoff from Frankfurt. This was not due to impact shock, but to vibration and may have been intensified by natural resonances as has been previously noted.

The C-5B landing at Stewart AFB, NY was extremely smooth (almost imperceptible) and produced no deviation whatsoever on any axis (x, y, or z) of the accelerometer unit. Since 0.1-g is clearly discernable on the recording chart paper, the landing shock was < 0.05-g in any direction as a reference. Contrast this with the unusually hard L1011 landing in Albuquerque, NM monitored by one of the authors on 2 April 1992 that registered 0.96-g's (z), 0.47-g's (y), and 0.84-g's (x) in the passenger area as recorded on an Impact-o-Graph®. The C-5B landing in Pittsburgh on 1 April 1992 was discernable but much less jarring than the referenced L1011 landing. The Pittsburgh landing measured a single spike of 0.48-g's (z), < 0.10-g's (y), and 0.12-g's (x) on the crate

Impact-o-Graph®. A summary of all shocks, impacts, and vibration results on the crate is given in Table 5. The duration values in the table are intended to give the approximate time period over which the disturbance occurred. In some instances, there would be small peaks over a period indicating a few discrete events, while in other cases there would be almost constant jitter of the needle indicating prolonged, frequent low-level disturbances. When a single sharp spike occurred it is so noted.

Table 5. Synopsis of AEOS 3.67-m mirror crate shock monitoring from Mainz, GE to Pittsburgh, PA

Local Time, Date, Place	Shock Recording (g's)/Duration (min)			Comments
	X	Y	Z	
1015, 25 Mar, Mainz, GE	—	—	—	Impact-o-Graph® installed on crate at Schott, Mainz, GE
Note: No discernable shocks or impacts noted on Impact-o-Graph® for any operations on crate from 1015, 25 Mar until ~1630, 26 Mar 1992				
~1630-1745, 26 Mar, Mainz to Rhein Main AFB, GE	< 0.10/20	0.12/26	0.10/20	Move crate from Schott, Mainz, to Rhein Main AFB, GE (Note: The 20-26 minutes is on autobahn at 60-65 kph.)
~1800-2200, 26 Mar, Rhein Main AFB, GE in Germany	≤ 0.10 typ, all axes			Various operations including unloading crate from truck by crane, placing on pallets on K-loader, moving to warehouse, shoring crate, transferring from K-loader to warehouse and storage.
~1430-1530, 30 Mar, Rhein Main AFB, GE	≤ 0.10 typ, all axes			Move mirror crate from warehouse onto K-loader, transport to ramp and load on C-5B.
1620-1640, 30 Mar, Rhein Main AFB, GE	0.24/12	0.36/12	0.10/9	Some shocks recorded shortly after Impact-o-Graph® read. Probably associated with crate tie-down operation in C-5B.
1245, 31 Mar, Rhein Main AFB, GE	0.36/6	0.21/4	0.86-1.92 (typ)/4 5.1/spike	Takeoff from Rhein Main/Frankfort Airport on rough runway (strong bumping/vibration; 5-g spike probably a resonant phenomena).
Note: Now on EST; this time and all times below are 7 hrs earlier than Germany				
1345, 31 Mar, Stewart AFB, NY	< 0.05	< 0.05	< 0.05	Landing at Stewart AFB extremely smooth, nearly imperceptible.
0945, 1 Apr, Stewart AFB, NY	< 0.10	< 0.10	~ 0.10	Takeoff from Stewart AFB.
1100, 1 Apr, Pittsburgh, PA	0.12/12	< 0.10	0.48/spike	Land at Pittsburgh in light snow, touchdown bump discernible but still smooth landing.
~1200-1300, 1 Apr, Pittsburgh, PA	< 0.10	< 0.10	0.45/spike	Move crate from C-5B onto truck for shipment to Contraves. (Note: crate slid backward once during unloading and "bumped" aircraft floor bumper stops giving 0.45-g spike.)
0930-1130, 2 Apr, Pittsburgh, PA	0.12	0.16/115	< 0.10	Crate trucked from Pittsburgh Airport to Contraves East Pittsburgh facility (Keystone Commons).

5.2.2 Move of AEOS 3.67-m mirror from Wampum, PA to Keystone Commons, PA in cell crate

Contraves polished the 3.67-m mirror in the Wampum Mine facility about 40 miles from their main Pittsburgh plant. Move of the mirror from the Keystone Commons facility to Wampum for polishing, back to the Contraves main plant for horizontal testing, and back to the mine for final vertical testing in the operational cell was monitored by Contraves and is not reported here. The shocks observed during these operations were all below 1-g. The move from Wampum to Keystone Commons for final assembled telescope factory testing was the first move of the finished mirror in the operational cell and was very closely monitored by Logicon RDA and Contraves.

Prior to the truck and its escorts departing the mine parking area, an escort vehicle returned from a brief route check with news that a nearby bridge was under construction and would not pass the wide crate load. The move was halted until a safe detour around the bridge was found. The minor route deviation from that planned was accomplished without incident. This is an indication of the requirement to continuously monitor the road conditions during shipment. During the move the 8-channel accelerometer outputs were monitored in real time. The alarm was set to trigger at 1-g. The alarm did sound to signal the 1-g shocks encountered during the move. Some sections of the road were quite potholed and even with the full air-ride tractor and trailer and going as slowly as 20-25 mph, the shocks were quite noticeable. Maximum speed attained during long, smooth, straight, or downhill sections was about 50 mph. Typical driving speed was about 35-45 mph. The average speed for the two-hour and 20 minute 60-mile trip was approximately 25 mph. The sequence of events during the move from Wampum to Keystone Commons is summarized in Table 6. The maximum shock recorded during this move was about 1.2-g.

Table 6. Chronology of 3.67-m primary mirror and cell move on 23 May 1996

Time	Event	Comments
0610	Hook up Contraves recording accelerometer.	At Wampum Mine, mirror in cell crate.
0615	Accelerometer hookup complete, move initiated.	Tugger speed, about 2.0 ft/sec (i.e., about 1.4 mph).
0625	Crate at mine portal, enters tunnel.	Small bump at entry, some side scraping, very tight clearance.
0630	Move halted to access clearance.	Double-check to assure that nothing from mirror cell is protruding beyond crate boundary.
0635	Move resumed at very slow speed.	Some light scraping continues in tunnel.
0645	Crate clears tunnel and pulls out of portal.	Personnel check crate/cell. Wood shavings noted but no other problems found.
0745	Crane arrives, begins setup.	Some congestion at mine entrance area as boat owners arrive to retrieve boats for the Memorial Day weekend.
0815	Begin positioning crate, tugger, and crane in preparation for pickup.	Mr. Mayo and others note overhead power line that must be cleared by crane. Large truck parked in area partially restricts access.
0835	Tugger moves crate to crane.	Accelerometer records about 0.25-g shock as tugger backs up over an unremoved wheel chock.
0840	Crane picks up crate off tugger trailer, trailer moved, truck backs into position under crate.	Pickup is very smooth, load hangs level and steady. Crew adjusts crate center over trailer.
0845	Crate is lowered onto trailer.	Set down is extremely smooth, barely 0.05-g noted on shock instrumentation.
0855	Crane unhooked from load, tie-down begins.	Crane prepared for departure, leaves site, crate tie-down proceeds.
0945	Tie-down completed, escort truck goes to check transportation route.	Tiedowns inspected and double-checked.
1030	Escort vehicle returns from route check, finds bridge clearance problem early along route.	Bridge on Route 351 is under construction. New Jersey barriers restrict width to 12 ft. 4 inches (crate is 14 ft. 4 inches wide). If safe bypass cannot be found, move will have to be cancelled and the state re-petitioned for a new route and move date. Escort leaves to find bridge bypass.
1115	Escort vehicle returns.	Escort has located bridge detour route, briefs team on route variation.
1118	Truck/escorts depart Wampum for Keystone Commons.	Instrumentation is monitored.
1140	Bridge detour complete.	Back on main route, maximum shocks noted thus far about 0.4-g.
1155	On route.	Route is very rough in this region. Recommend maximum speed of 35-40 mph. Shocks in the 0.3 to 0.6-g range encountered, some truck roll noted from uneven roadway.
1200	Over Monaca Bridge.	0.5 to 0.9-g shocks experienced, slightly higher than expected.
1212	High shock event on rough road.	1.2-g shock recorded, maximum during move, alarm sounds, speed reduced.
1214	High shock event on rough road.	1.1-g shock recorded, alarm sounds, speed reduced.
1220	On improved road, near greater Pittsburgh Airport.	Shocks back to lower levels, typically 0.1 to 0.3-g.
1235	In construction zone between airport and Pittsburgh.	Load takes both lanes and holds traffic back. Maximum shock of about 0.6-g recorded in this region.
1312	In town of Homestead.	After bypass of Ft. Pitt Tunnel and Squirrel Hill Tunnel, and crossing Ft. Pitt Bridge and Homestead Bridge, increased traffic and congestion.
1320	On Rankin Bridge.	Shocks continue to run generally less than 0.5-g maximum, congestion and traffic continue
1325	In town of Braddock.	Congested area, narrow road, tight turns.
1335	On Braddock Avenue, ramp.	Shocks increase to 0.6 to 0.8-g in this area approaching Keystone Commons.
1338	Enter Keystone Commons gate.	Commons guard requests convoy wait outside because of vehicles in the building.
1345	Inside building.	Convoy proceeds inside through congestion, notes large potted plants (trees) restricting entry into Contraves telescope assembly area.
1355	Truck, mirror, and crate inside telescope assembly area.	Truck maneuvered into high bay assembly area around potted plants and parked cars.

Time	Event	Comments
1400	Removal of crate side initiated by Contraves.	Because of the slightly high shock recordings noted during move, mirror inspection requested by Logicon RDA, requiring removal of crate side.
1430	Crate side off, Mr. Mayo begins mirror/cell inspection.	Inspection of mirror, cell, actuators, tie-downs, plastic wrap, opticoated surface, wiring, etc., begins.
1450	Mirror/cell inspection completed, Contraves prepares to lift crate from flatbed.	Loose screw and washer found inside crate on plastic under mirror and removed. Some sections of the opticoat/paper protective mirror coating have pulled free from the mirror surface. This needs careful attention when the opticoat is removed from the mirror surface as it may increase opticoat residue on mirror.
1455	Mirror/crate lifted by 75-ton bridge crane, truck removed from area, 6x6 shoring placed for lowering of crate onto floor.	Very smooth lift, no g's noted on chart at pickup.
1505	Crate lowered onto 6x6 shoring timbers on floor.	Very smooth setdown, very low shock noted. This completes the moving operation.

5.2.3 Move of AEOS 3.67-m primary mirror from Keystone Commons, PA to Kitt Peak, AZ in Zeiss crate

The move from Keystone Commons to Kitt Peak in the Zeiss crate was instrumented with the Impact-o-Graph® recording accelerometer, the Contraves indicating accelerometer with an alarm set at 1-g, and several Omni-G® indicating accelerometers. When the mirror reached Tucson, AZ, the strip chart on the recording Impact-o-graph® on the wooden portion of the steel crate was read. Only one short section of chart tape showed any notable shocks which had occurred a few days before arrival in Tucson. Based on a 0.25-inch-per-hour chart speed the shocks lasted a period of a few hours, never exceeded about 1-g maximum, and probably occurred on some rough road sections in Arkansas.

Due to the length of the 18-wheel rig and associated difficulty anticipated in getting it inside the coating facility, it was decided to transfer the 3.67-m primary mirror shipping container (weight approximately 31,000-pounds) and the eight-legged stand/fixtures crate (weight approximately 7,300 pounds) from the visitor's parking area at Kitt Peak to the 4-m chamber facility on 3 February 1997 using a separate flatbed truck (International 4900 DT 466E six-wheeler). Before the mirror was moved to the smaller truck, the Impact-o-Graph® mounted to the mirror shipping container was activated. The Impact-o-Graph® chart on the mirror shipping container was read when the mirror arrived at the 4-m coating chamber. No unusual shocks were noted. After the mirror was removed from the crate, the 2-g, 5-g, and 10-g Omni-G® trip indicators attached to the mirror Invar lateral support mounting pads were read and found untripped. This provided additional verification that the mirror had seen no shocks greater than 2-g's since these Omni-G® units were installed in Pittsburgh.

5.2.4 Shipment of AEOS 3.67-m mirror from Kitt Peak, AZ to Maui, HI in Zeiss crate

After coating, the mirror was reinstalled in the Zeiss crate, the 2-, 5-, and 10-g Omni-G® trip indicators were reattached, the two Impact-o-Graphs® were reinstalled and the Contraves indicating accelerometers were reattached for the trip from Kitt Peak, AZ to Vancouver, WA. At Vancouver the Contraves accelerometer was removed but the rest of the instrumentation remained intact. The crate was loaded onto an ocean-going barge along with other parts of the telescope and the heavy crane for the trip to Kahului, Maui, HI. After the equipment arrived at Maui it was visually inspected and stored in the dock area. None of the items showed any impact damage but all crates showed signs of exposure to moisture.

The mirror and mirror cell crates were loaded onto a single lowboy for transportation from the port area at Kahului to the warehouse at Puunene, a distance of about five miles. The mirror and mirror cell were moved to the C&H sugar warehouse in Puunene without incident. After the mirror crate was unloaded inside the warehouse, the 2-, 5-, and 10-g Omni-G® indicators inside the box were inspected. None of them had been tripped, indicating that the maximum shock occurring between Kitt Peak and Maui was less than 2-g. Unpacking of the mirror from the Zeiss crate, assembly into the mirror cell, and crating into the Contraves mirror/cell crate took place in the warehouse. Following mirror/cell integration, the mirror/cell assembly was secured in the cell crate and taken by air ride truck from the Puunene warehouse to the telescope facility atop Halaleaka. This move was monitored with Omni-Gs® and the recording Impact-o-Graph®. The Omni-Gs® were checked at a truck cool-down stop about five miles from the 10,000-foot summit and were untripped. After arrival on top and tight maneuvering of the truck at the AEOS facility involving some slight bumping off-pavement, the Omni-Gs® were rechecked. A 2-axis unit showed a small displacement of the spring-loaded ball in one axis but had not tripped. This and the Impact-o-Graph® indicated that loads of about 1.5-g had been encountered. The mirror and cell lift into the dome with the Campbell Demag TC1200 crane on 16 April 1997 was also monitored and showed a dead flat chart line. The 2-g Omni-G® also did not trip in this operation or during installation of the mirror cell assembly into the telescope. These operations in April 1997 concluded the six-year program of shock monitoring for the SOR 3.5-m and AEOS 3.67-m Telescope primary mirrors.

6. CONCLUSIONS

All three crates discussed in this report performed well. The SOML SOR 3.5-m primary mirror crate provided adequate impact and environmental protection and had an isolation system that gave an extremely smooth, low-g shock ride. The primary mirror bellyband internal tie-down approach did dictate temperature monitoring and might pose problems if shipping through rapidly changing temperature environments. The crate is well-insulated but is not fully sealed against moisture penetration. It should not be stored outside. Fortunately, no rain was encountered during the move from Tucson to Albuquerque. The SOML crate should be tarped for any moves where rain or moisture might be encountered. Steel plates could be added to the exterior of this wooden crate if added ballistic or penetration protection were needed. This option was actually discussed during crate design but was not implemented.

The Zeiss AEOS 3.67-m primary mirror massive steel crate was extremely rugged and had a multiple internal isolation system of heavy plywood and three different types of shock-absorbing and isolation materials. Its protection against negative-g shocks was not as high as positive-g but such shocks are less common. The steel crate itself had an area of heavy plywood sections on top and some areas where openings of about a centimeter were present. With its tight-fitting rubberized cover in place, it is fairly water-resistant. A small amount of condensation was noted inside the Zeiss crate upon arrival and inspection at Maui. Tears occurring in the cover during trucking from Pittsburgh to Tucson were repaired, but a small lifting lug cover on top of the crate blew off between Tucson and Vancouver, allowing some moisture to enter. This could be a problem for coated optics and a protective spray coating is recommended for most shipping operations with coated mirrors. Any direct contact with the coated mirror surface should be avoided or carefully considered since the jostling during transportation can abrade the coating.

The Contraves AEOS 3.67-m primary mirror cell crate performed well but did allow some moisture inside the crate and onto the bagged cell during the trip from Pittsburgh, PA to Kahului, Maui. Rusted areas noted on the primary mirror cell in Maui were scraped and repainted. The trip of the primary mirror to the summit of Haleakala in this crate after cell/mirror integration on-island went well and no moisture or excessive shocks were noted. We do not recommend moving large mirrors in their operational cells unless the cells are designed to handle the moving loads and shocks and to protect the mirror from damage. Even then we recommend this mode of primary mirror transportation only if absolutely necessary.

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In a special note of appreciation, we thank Mr. Dick Young of SOML, principal designer of the SOML 3.5-m crate, who passed away before he could see his creation put into service. We are sure he would have been pleased with its sterling performance and the almost imperceptibly low level of shock that the primary mirror saw during transportation in this crate.

8. REFERENCES

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