Large-area solar simulators – critical tools for module manufacturing

Harvey B. Serreze & **Roger G. Little**, Spire Corporation, Bedford, MA, USA

This article first appeared in *Photovoltaics International* Edition 1 in August 2008.

ABSTRACT

The importance of rapid and accurate measurement of the electrical power output and related characteristics of photovoltaic (PV) modules or panels concluding the manufacturing process cannot be overemphasized. Even though these modules will likely be deployed under a variety of outdoor solar illumination conditions, they must be tested under a set of standard conditions to assure consistency of results demanded by both the manufacturer and the customer. The ability to provide a measurement tool for this critical manufacturing step that possesses the proper specifications and qualities, ranging from spectral accuracy to ease-of-use, is imperative.

Introduction

Solar simulators used in the production testing of PV modules must exhibit several basic, but important properties:

- They must accommodate the most common modules being tested, be easy to use and maintain, and be sufficiently rugged and reliable for daily use in a manufacturing environment.
- They must fit conveniently into high volume production and factory automation.
- Their output spectrum must be sufficiently close to that produced by natural sunlight to give accurate performance results.
- Variations in optical output (irradiance), both spatially over the area of the test plane and temporally during a given test and from test-to-test, must be sufficiently small to not impact the test results.
- They should be traceable to known and accepted standards.

Most solar simulators used for large-area PV module testing possess two common characteristics. First, they generally employ one or more appropriately filtered xenon-filled gas discharge lamps as their light source. Second, they are usually operated in a pulsed optical mode (as opposed to continuous or cw mode) to minimize electrical power consumption, minimize module heating during test, and maximize the time between required lamp changes.

The two basic types of large-area simulators that Spire currently provides are (short) multi-pulse and single long pulse (SLP). The company also currently offers two different test plane sizes; the smaller model, Spi-Sun Simulator™ 3500, is 102cm x 162cm (40" x 64") and the larger model, Spi-Sun Simulator™ 4600, is 137cm x 200cm (54" x 79"). On the multi-pulse machines, a single data point of the I-V curve is obtained during each pulse, typically ~1 ms in duration. A full I-V curve typically requires 100 data points and, hence, 100 flashes. With the SLP machines that generate light pulses ~50-100ms long, the entire I-V curve is obtained in a single pulse. The industry trend is moving toward SLP rather than multipulse for several reasons, including faster test time, higher throughput, the use of very high efficiency Si solar cells, and reduced sensitivity to various solar cell physical phenomena that are most common in thin-film cells such as a-Si, CdTe, or CIGS.

Spectral performance standardization

The need to standardize the three most critical parameters related to the optical output (irradiance) of large-area solar simulators used to test PV modules has been long recognized by two leading standards organizations, ASTM International and the International Electrotechnical Commission (IEC). To address this important need, each agency has issued standards over the past several years that define the spectral output, the spatial uniformity, and the temporal (time) stability of solar simulators that are used to test terrestrial PV modules. Specifically, ASTM's version is defined in their E927-05 standard [1] and IEC's in their 60904-9 standard [2]. While there are some subtle differences between these two standards, they are essentially similar. Both standards specifically address what the spectrum of the light emitted from the simulator must be, how the intensity of this light can vary spatially over the test area, and how the intensity can vary with time during both an individual pulse and from pulse-to-pulse.

Of these three parameters, the one that has traditionally been the hardest to address, both in terms of ability to achieve and ability to measure, is the irradiance spectrum. Nearly all PV modules are designed to work best under solar illumination conditions that correspond to sunlight impinging at an angle above the horizon (the elevation) that results in the light rays effectively going through 1.5 atmospheres and having both direct and diffuse (scattered) components. This illumination is commonly referred to as AM1.5 Global (or AM1.5G) and is described in more detail in ASTM Standard G-173.

> "The industry trend is moving toward SLP rather than multipulse for several reasons, including faster test time, higher throughput, the use of very high efficiency Si solar cells, and reduced sensitivity to various solar cell physical phenomena."

Realizing that precise simulation of an AM1.5G spectrum using artificial light could be extremely difficult, both ASTM and IEC set up three classifications for the spectral accuracy of large-area simulators. These classifications define what fraction of the total spectral irradiance should lie within six distinct wavelength ranges (Table 1). For a spectral Class A designation, the irradiance fraction must be within +/-25% of AM1.5G for each wavelength interval or bin; for Class B, it must be within +/-40%; and for Class C, within +100 to −60% (Figure 1 shows regions and classifications). For a simulator to be classified as Class A (spectrally), its measured output points must *all* fall within the green region. Similarly, Class B must fall within the yellow region and Class C must fall with the brown region. The worst data point defines the classification; e.g., if all the data points from a single measurement are green but one is brown, then the classification must be Class C.

Instrumentation development

For many years, the National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA has recognized the need for accurate measurement of the spectral irradiance from solar simulators. Over the years they have developed a sophisticated instrument, the PASS (Pulse Analysis Spectroradiometer System), which is able to give accurate and repeatable, NIST-traceable measurements of pulsed solar simulator output spectra [3,4]. Their system consists of an integrating sphere attached to a single stepping monochromator, appropriate optical detectors, switchable gratings and filters, and control and data analysis hardware and software. Traceable to NIST calibrations, the system measures the 400 to 1100nm spectrum in 5nm increments, with a single optical pulse required for the measurement of a single wavelength increment. This requires a minimum of 140 pulses; consequently, measurement of an SLP simulator having typical cycle times of 15 to 30 seconds can take up to an hour or more. Measurement of multiple points on a single simulator can thus be very impractical. Since it is also a relatively sophisticated instrument, it requires a highly-trained and knowledgeable individual to use it properly.

Despite the shortcomings of the NREL PASS, Spire realized the benefits that ownership of such an instrument would have. Contracting with NREL, Spire procured the only copy of their instrument with software that exists outside of NREL in February 2008. A photograph showing this instrument in use at Spire is shown in Figure 2. Despite the relative complexity of its operation, we utilize it to measure selected simulators and to periodically verify the calibration of a simpler, easier-to-use, Spire-developed dual-spectrometer spectral analyzer (described below).

Based on several of the key features of the NREL PASS, Spire undertook a task to develop an easier-to-use instrument to perform routine spectral measurements of our simulators at the conclusion of the manufacturing cycle. Figure 3 shows a block diagram of the dual-spectrometer instrument, while Figure 4 shows the instrument itself, which affords much faster spectral measurement than the PASS – an important consideration when performing multiple measurements on the same simulator. Using the same type of optical collector on the test plane as the PASS, fiber optics are used to distribute the optical signal to two separate grating spectrometers. Gratings and filters in each of the spectrometers are chosen to optimize the performance of each within its respective wavelength band. Both utilize TE-cooled Si detectors to assure optimum sensitivity over their entire wavelength ranges. Response of the two units overlaps in the 800 to

Wavelength Range (nm)	Irradiance Fraction						
	AM1.5G Standard	Class A		Class B		Class C	
		Min	Max	Min	Max	Min	Max
400-500	0.184	0.138	0.230	0.110	0.258	0.074	0.368
500-600	0.199	0.149	0.249	0.119	0.279	0.080	0.398
600-700	0.184	0.138	0.230	0.110	0.258	0.074	0.368
700-800	0.149	0.112	0.186	0.089	0.209	0.060	0.298
800-900	0.125	0.094	0.156	0.075	0.175	0.050	0.250
900-1100	0.159	0.119	0.199	0.095	0.223	0.064	0.318
Total	1.000	–	–	–	–	–	–

Table 1. ASTM and IEC definition of spectral classification by assigning specific irradiance fractions to the six most important wavelength ranges from 400 to 1100nm.

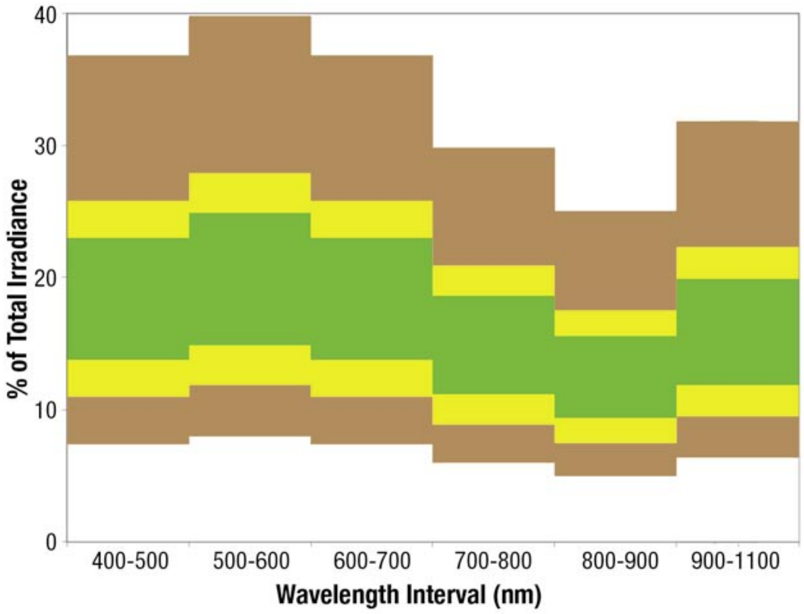

Figure 1. Graphical representation of the three ASTM and IEC spectral classification definitions. The wavelength region of interest, 400 to 1100nm, is divided into six wavelength intervals or bins of either 100 or 200nm width. For Class A, *all* irradiance values must fall in the green region; Class B corresponds to the yellow region, and Class C to the brown region. Outside of the brown region, the simulator is considered unclassified. A simulator's classification is based on its worst bin.

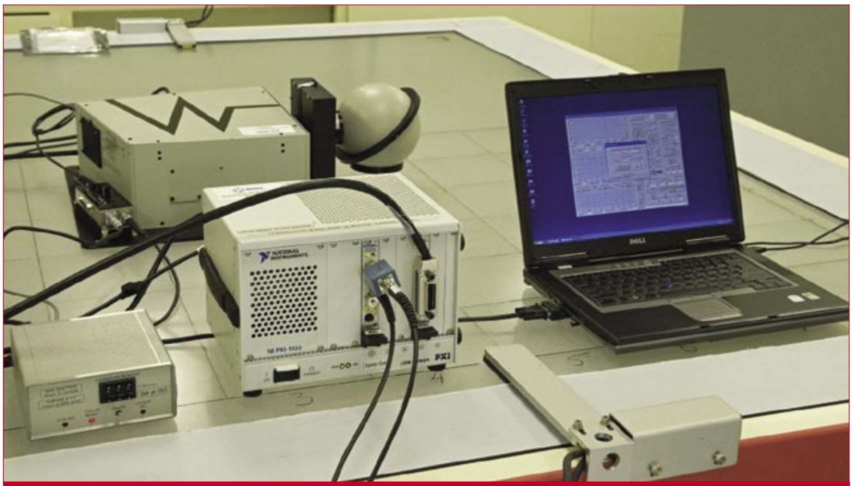

Figure 2. The NREL-designed and built Pulse Analysis Spectroradiometer System (PASS). This critical instrument exists only at Spire and NREL.

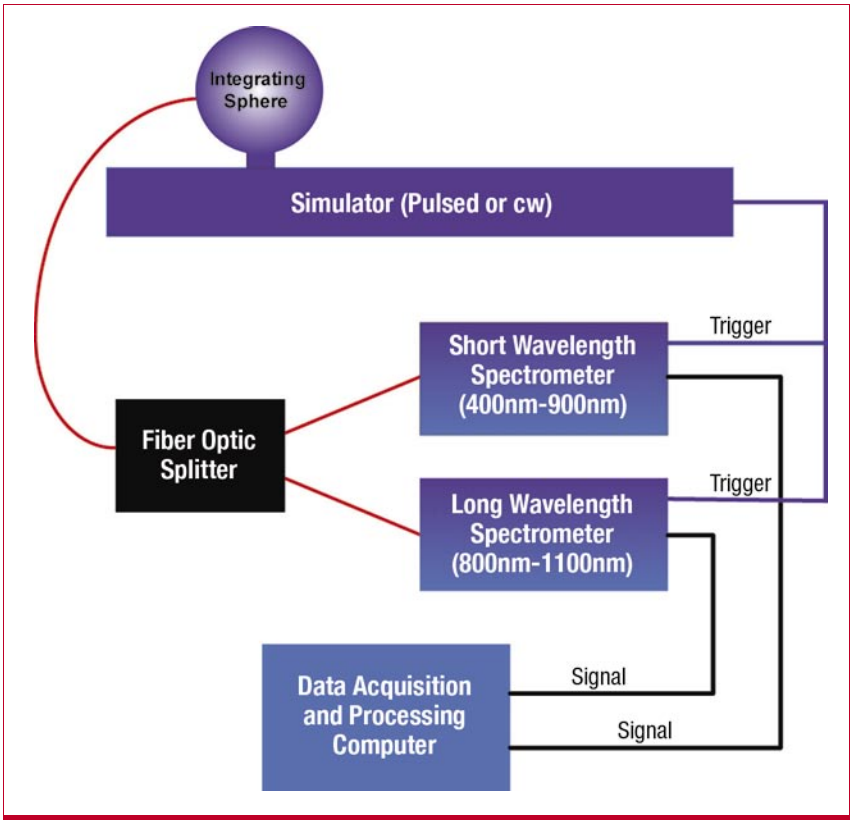

Figure 3. Block diagram of the dual-spectrometer, pulsed solar simulator spectral analyzer. The intensity calibration lamp used to check the system prior to each use is not shown.

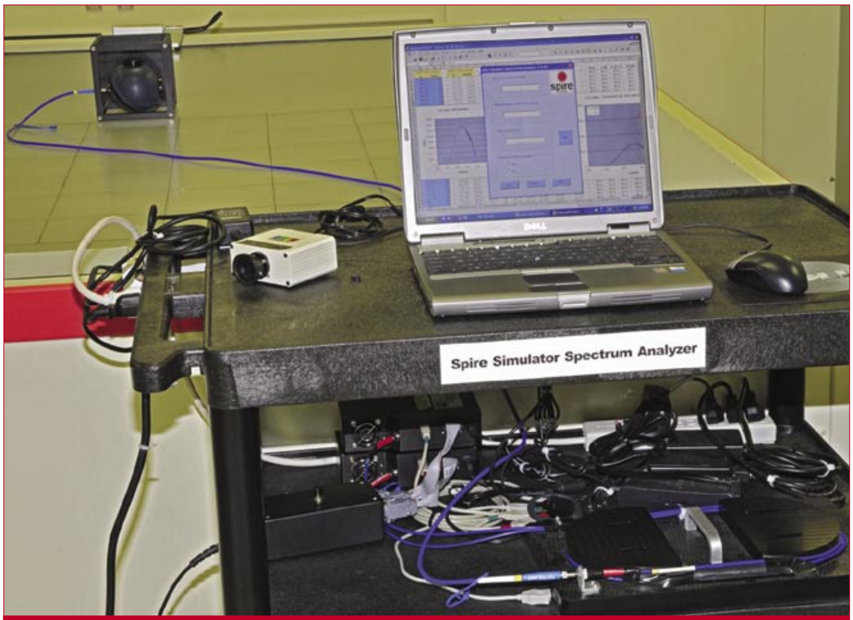

Figure 4. Spire-designed dual-spectrometer spectral analyzer measuring a Spi-Sun Simulator 4600. The sphere sits on the simulator test plane and is connected by a fiber optic cable. The principal spectrometer components are on the shelf below the laptop computer.

900nm interval; since the outputs of the two must obviously agree in this region, this feature is used as a double-check of proper operation and calibration during each use (Figure 5 illustrates the level of agreement between measurements taken with this dual spectrometer system and the two PASS units).

Data acquisition triggering is provided by a trigger signal from the simulator to the two spectrometers. Unlike the PASS, the entire spectrum can be obtained from a single optical pulse (although multiple pulses – typically ~30-50 – are preferred when measuring a multipulse simulator to give better statistics). Finally, calibration of the unit is checked daily using a cw calibration lamp that is periodically checked against a NIST-traceable lamp.

Measurement of simulator spectra

Using the dual-wavelength spectral analyzer, we have studied the irradiance spectra of numerous simulators, both multi-pulse and long pulse. As discussed earlier, a major benefit of our dual-wavelength analyzer is the rapid measurement time that allows relatively easy mapping of spectra with spatial position. Figure 6 shows results of one such study, in which a total of eleven points distributed over the full test plane of a Spi-Sun Simulator 3500SLP were examined. It is apparent that all eleven points are Class A. This performance actually exceeds that required by both the ASTM and IEC standards; these two standards require that the spectrum meet the given classification only at a single point in the test plane.

In simulator utilization, the stability and lifetime of the xenon flash lamps and other optical components that affect or contribute to the irradiance spectrum and total intensity are also important. With use, there is the possibility of lamp failure, change in output spectrum as the lamp ages, and change in optical characteristics of all the internal reflecting and transmitting surfaces. With this in mind, we undertook a study of simulator output as a function of cumulative flashes, the results of which are shown in Figure 7. During the course of the study, which lasted over 100,000 flashes – the expected lamp lifetime under long-pulse conditions – we monitored the short-circuit current of a 75W PV module and two portions of the irradiance spectrum. The shortest wavelength region was from 400 to 500nm, and the longest from 900 to 1100nm. During this study, no changes or adjustments were made to any of the simulator settings. Figure 7 demonstrates the long-term stability of the lamp and of all other components in terms of both total output, as exemplified by the flat I_{sc} curve for the module, and of the spectrum, as indicated by the lack of changes in either the long or short wavelength portions of the spectrum.

Summary and conclusions

As solar simulators find increasing use in the PV module manufacturing industry, the need for spectral accuracy has become more apparent. Realizing this, Spire undertook a major effort to develop its own spectral measurement capability rather than to constantly rely on outside services. Using this capability, we now routinely measure every simulator that we manufacture. Through careful design and manufacturing control, our simulators have been demonstrated to routinely produce Class A spectra both at system installation and after 100,000 pulses of use. We plan to continue using this unique capability in the design and manufacture of future, even larger-area and more versatile solar simulators.

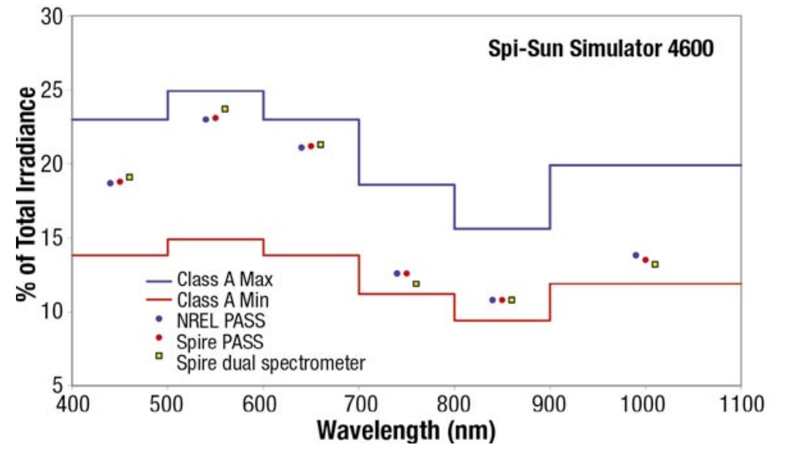

Figure 5. Spectral measurement results taken at the same single point on a Spi-Sun Simulator 4600 using NREL's PASS, Spire's PASS, and Spire's dual-spectrometer analyzer (each data point set is intentionally spread out horizontally to facilitate viewing). In contrast with Figure 1, the upper and lower boundaries only for the Class A region are shown. The agreement between the three instruments is apparent.

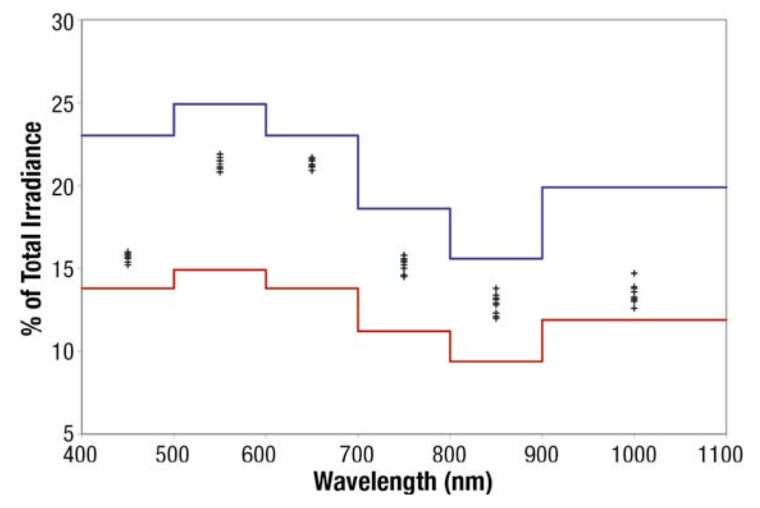

Figure 6. Spectral measurement results taken with Spire's dual-spectrometer analyzer at eleven different test points distributed over the entire test plane of a Spi-Sun Simulator 3500SLP. The spatial uniformity of the Class A spectrum is apparent.

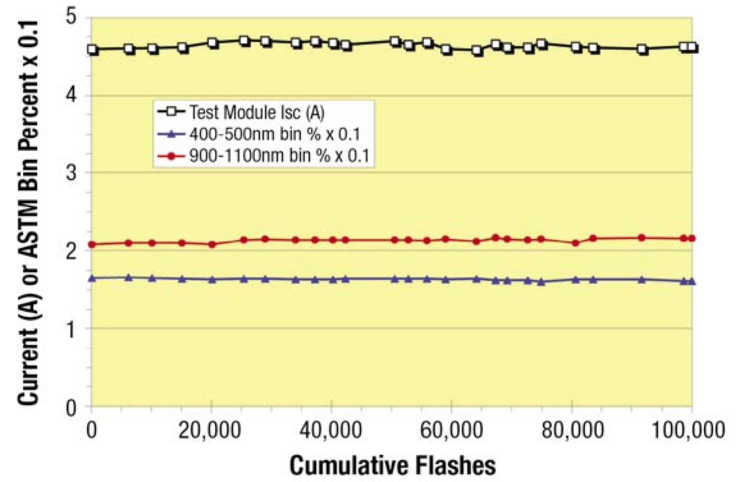

Figure 7. Long-term stability of a long-pulse Spi-Sun Simulator 3500SLP. Each lamp pulse was approximately 100ms in duration and pulse repetition rate was approximately 2/min. Shown is the short-circuit current for a 75W test module placed on the simulator and the fractional amounts of irradiance in the 400-500 and 900-1100nm wavelength intervals (bins). No significant changes in any of the parameters occurred during the rated 100,000 flash lifetime of the xenon lamp.

Acknowledgements

The authors are indebted to numerous individuals who contributed to this work. In particular, ***W. Neal*** and ***H. Sobhie*** supplied major technical guidance and input, ***S. Sutherland*** and ***S. Moore*** set a lot of the early groundwork, ***S. Hogan*** provided much-needed encouragement and support, and ***A. Andreas*** of NREL gave significant technical assistance.

References

[1] ASTM International 2005, 'Standard Specification for Solar Simulation for Photovoltaic Testing', ASTM Designation E 927-05 (April 1, 2005), West Conshohocken, PA.

[2] International Electrotechnical Commission (IEC) 2007-10, 'International Standard – Photovoltaic Devices – Part 9. Solar simulator performance requirements', IEC 60904-9, Edition 2.0, 2007-10, Geneva, Switzerland.

[3] Cannon, T.W. 1998, 'Spectral Measurements of Pulse Solar Simulators', presented at National Center for Photovoltaics Program Review Meeting, Denver, CO (September 1998).

[4] Myers, D., Andreas, A. et al 2005, 'Fiscal Year 2005 Solar Radiometry and Metrology Task Accomplishments', presented at 2005 DoE Solar Energy Technologies Program Review Meeting, Denver, CO (November 2005).

About the Authors

Dr. Harvey B. Serreze received his Ph.D. in electrical engineering from Tufts University in 1974. Dr. Serreze was responsible for fabricating the first EFG silicon solar cells at Mobil-Tyco Solar Energy Corporation and for designing and building their first solar simulator test system. He joined Spire in 1993. Dr. Serreze is now an Advanced Technology Engineer and Product Manager for Spire's line of Spi-Sun Simulators.

Roger G. Little received his B.A. in physics from Colgate University in 1962 and his M.Sc. in physics from the Massachusetts Institute of Technology in 1964. Mr. Little founded Spire Corporation in 1969. Since then, he has guided the commercialization of Spire's technology and directed Spire's growth to a diversified solar energy company with 250+ employees, and now holds the roles of Chairman of the Board of Directors, Chief Executive Officer and President of the Company.

Enquiries

Dr. Harvey B. Serreze
Advanced Technology Engineer & Product Manager
Tel: +1 781 275 6000

Roger G. Little
Chairman and CEO
Tel: +1 781 275 6000