Testing of Participant’s Power Electronics Component for Circuit Performance and Efficiency

Cooperative Research and Development Final Report

CRADA Number: CRD-19-16343

NREL Technical Contact: Andy Walker

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5C00-91459
September 2024

Testing of Participant's Power Electronics Component for Circuit Performance and Efficiency

Cooperative Research and Development Final Report

CRADA Number: CRD-19-16343

NREL Technical Contact: Andy Walker

Suggested Citation
Walker, Andy. 2024. *Testing of Participant's Power Electronics Component for Circuit Performance and Efficiency: Cooperative Research and Development Final Report, CRADA Number CRD-19-16343.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5C00-91459. https://www.nrel.gov/docs/fy24osti/91459.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5C00-91459
September 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This work was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, its contractors or subcontractors.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Cooperative Research and Development Final Report

Report Date: September 20, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: T4D Lab

CRADA Number: CRD-19-16343

CRADA Title:

Testing of Participant's Power Electronics Component for Circuit Performance and Efficiency

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

Andy Walker | andy.walker@nrel.gov

Name and Email Address of POC at Company:

R. David Gibbs | r.davidgibbs@gmail.com

Sponsoring DOE Program Office:

Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$ 50,000.00
TOTALS	$ 50,000.00

Executive Summary of CRADA Work:

The "Solar SEED Smart Controller is a charge control device to condition solar power to load voltage with or without Battery (also called a "DC Power Platform") invented by David Gibbs and T4D Labs Inc. T4D Inc. and the SEED Smart Controller invention were selected for American Made Challenges Solar Prize, which includes voucher for NREL to provide technical assistance.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope,
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results:

NREL assistance involved the following 4 tasks:

Task 1: Test Preparation and Monitoring: NREL prepared "design of experiment" and instrumentation for testing, but the partner did not deliver the prototype for testing so focus shifted to modeling performance and energy savings attributable to the SEED Controller

Task 2: Data Analysis: The partner did not deliver the prototype for testing so focus shifted to modeling performance and energy savings attributable to the SEED Controller. NREL prepared a model of PV Array I-V curve to estimate improvement in performance of voltage-adjusting SEED controller compared to constant-voltage "clamped" controller.

Task 3: Monthly Status Meetings: NREL staff and partner conducted monthly meetings regarding planning and status.

Task 4: Final CRADA Report: Final CRADA Report was prepared to summarize results and conclusions.

Conclusions from the modeling are that the Solar SEED Smart Controller can improve power delivery much more than initially expected. This is important information for manufacturers of direct drive (no battery) solar applications and also for consumers of such products. Modeling was conducted for conditions described in IEC standards 65813-1, which describes 5 test conditions of varying insolation and temperature. For each condition we simulate the position on the I-V curve of a PV array (in this example 180 W mono-crystalline silicon PV module) and the current and voltage to the load with and without the Solar SEED Smart Controller. The results are listed in Table 1 below.

Table 1. Power from PV module with and without Solar SEED Smart Controller compared to "clamped" voltage of 24V; for five different test conditions specified in IEC standard 65813.

Condition	I (Wm/2)	Tcell (C)	Power with SEED (W)	Power without SEED (W)	Percent Improvement with SEED
Standard Test Condition	1000	25	179.2	119.2	50%
Nominal Operating Cell Conditions	800	42.4	125.0	93.7	33%
Low Irradiance Conditions	200	25	38.5	23.8	61%
High Temperature Condition	1000	75	136.7	108.0	27%
Low Temperature Condition	500	15	96.3	59.9	61%

Conclusions are that the Solar SEED Smart Controller improves delivered power compared to the case of "clamped" voltage by at least 27% in the high temperature case and as high as 61% in the low irradiance and low temperature conditions. At low insolation and low temperature conditions the elevation of voltage above the load voltage is the greatest and thus the greatest potential for the Solar SEED Smart Controller to adjust this high voltage to the load voltage without a loss of total power (the controller increases current and decreases voltage to the load).

Recommendations for future work include:

- Complete a prototype for testing and product certifications.
- Expand model to other calculations of voltage (resistant, inductive) to represent the operating condition of different types of loads.

Expand model to an hourly simulation of performance with different load profiles in different climate locations.

The device is unique for operation without battery. Applications for direct solar PV power use without a battery include:

- Water pumps such as stock wells
- Air compressors.
- Coolers or refrigerators
- Fans such as attic fans, crop dryers, and fans for composting toilets
- Entertainment or advertising such as audio and visual devices
- Other applications where the product can be stored (such as pumped water or compressed air) or are non-critical loads (entertainment) available only when the sun is shining

In such applications PV modules are currently connected directly to the load device without any power conditioning, although some solar water pump manufacturers do already provide voltage adjustment in their pump controller. The resulting condition depends on the type of load:

- Resistive loads: the resistance is the slope of a straight line on a V-I curve and the operating voltage and current (and power) are where this intersects with the I-V curve for the PV array.
- Inductive Loads: the torque of a motor is created by current, and the voltage depends on the resistance of the armature and a resistance imposed by the rotation of the motor. As current and voltage change, torque and speed also change and to provide stable operation most motors operate at a given voltage.
- Electronics: it is important to most electronics to operate at the specified voltage.

In this study we consider such a device connected directly to a load and resulting in a voltage called the "clamped" voltage, which is representative of a rated voltage of the device, in this case 24 VDC. The utility of the Solar SEED Smart Controller is to operate the PV array at a voltage and current which maximizes power output (which changes with temperature and sunlight) and converts that to the fixed 24 VDC voltage of the load device.

This scope-of-work originally expected to test a Solar SEED Smart Controller at NREL Energy Systems Integration Laboratory (ESIF). However, due to circumstances beyond control the partner was unable to deliver a prototype for testing. This report describes upshots from the plans for such testing but also presents the results of computer modeling that NREL did to inform the design of experiment and to advance the development of the product without physical testing.

Conclusions from the design-of-experiment and preparation for testing center around how to measure efficiency of a very efficient device where input power and output power are close to each other in magnitude, on the same order as the accuracy of the measuring equipment. The approach depends on:

- High accuracy hall-effect current transducers (<0.1%, compared to 2% for typical power meter)
- High bit Analog-to-digital converter (datalogger) for high resolution relative accuracy across a given range.
- Tight range on datalogger to "zoom in" on expected range of values and improve absolute accuracy for a given relative accuracy.

Task 1: Test setup preparation and monitoring

Task 1 will include the acquisition of the necessary material for the monitoring of current and voltage in the 3 spots shown in Figure 1, the resistors to be dedicated to load, the setup of the monitoring system and the acquisition of data. The participant will provide the charge controller device and battery with standard, available connector types to be specified in the design of experiment. NREL will provide PV Generator and Load.

NREL will check data on a regular basis for possible problems and to avoid data losses.

1.1 NREL will test the performance and efficiency of the charge controller according to the configurations shown in Figure 1 and Figure 2 (below).

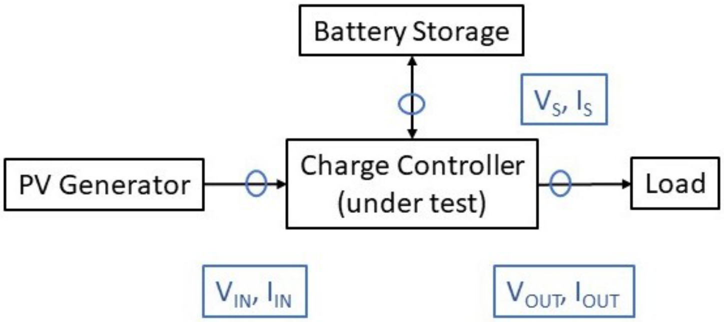


Figure 1. Test configuration indicating the monitoring points with battery

As shown in Figure 1, the charge controller will be operated with a connected battery configuration connected to a photovoltaic source capable of providing 125% of the rated current of the intended circuit. The battery terminals will be connected to a battery operating at the rated battery voltage. The output of the will be connected to a constant load, which will be adjusted to draw the maximum rated current of the charge controller. Once operational, the load will be tuned over two (2) ranges of operations, excluding short-circuit: it will work at full constant load and at 50% constant load. Voltage and current will be measured at the PV input point, load output point and at the interface with the battery storage, to have the possibility to evaluate the performance and efficiency of the charge controller device.

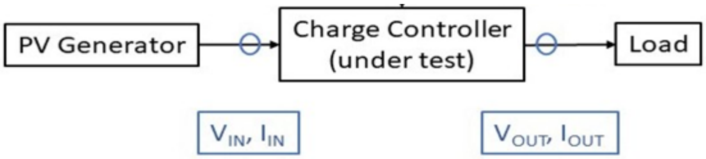


Figure 2. Test configuration indicating monitoring points without battery

As shown in Figure 2, the charge controller will be operated without a connected battery configuration. It will be connected to a photovoltaic source capable of providing 125 % of the rated current of the intended circuit. The output of the charge controller will be connected to a constant load, which will be adjusted to draw the maximum rated current of the charge controller. Once operational, the load will be tuned over two ranges of operations, excluding short-circuit: it will work at full constant load and at 50% constant load.

Voltage and current will be measures at the PV input point, and load output point to have the possibility to evaluate the performance and efficiency of the charge controller device.

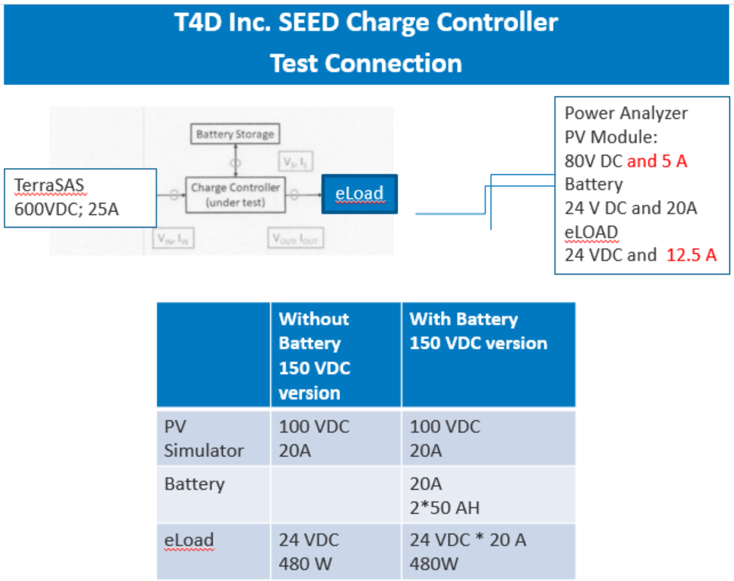
Commercial calibrated sensors for current and voltage measurement will be used. The sensors will be connected to data acquisition systems that will allow to collect data on a local computer.

This scope-of-work originally expected to test a Solar SEED Smart Controller at NREL Energy Systems Integration Laboratory (ESIF). NREL staff designed the experiment in terms of both hardware and testing protocol. NREL staff also provided project management and engineering to prepare and satisfy NREL planning requirements such as review by Safety Officer. However, due to circumstances beyond control the partner was unable to deliver a prototype for testing. This report describes upshots from the plans for such testing but also presents the results of computer modeling that NREL did to inform the design of experiment and to advance the development of the product without physical testing.

Resources provided by NREL for the testing include:

- PV Simulator; TerraSAS 600VDC 25 A rating; operating 80 VDC and 5A
- e-Load: electronic load simulator; 24 VDC, 12.5A
- Power Analyzer: Yokogawa 1800

Test was designed both with and without battery.

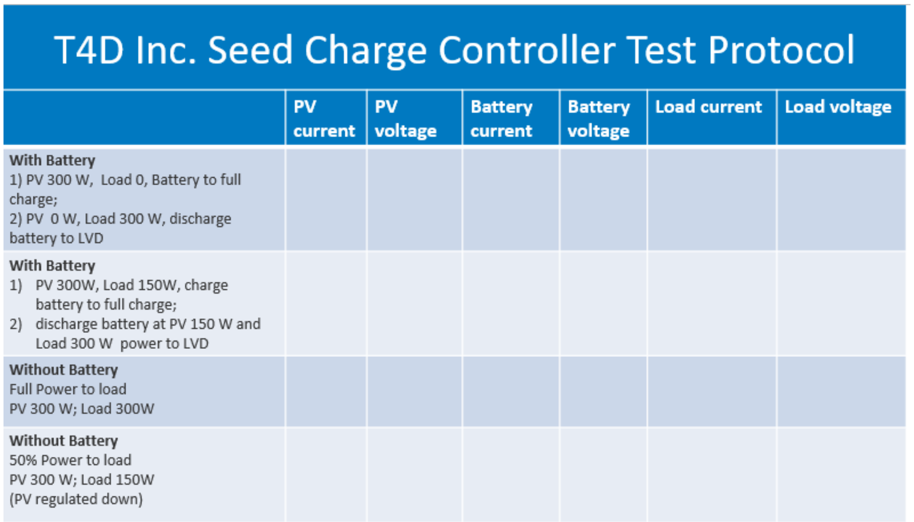


T4D Inc. SEED Charge Controller
Test Connection

Power Analyzer
PV Module:
80V DC and 5 A
Battery
24 V DC and 20A
eLOAD
24 VDC and 12.5 A

	Without Battery 150 VDC version	With Battery 150 VDC version
PV Simulator	100 VDC 20A	100 VDC 20A
Battery		20A 2*50 AH
eLoad	24 VDC 480 W	24 VDC * 20 A 480W

Figure 3. Test set up with NREL PV simulator, electronic load bank, and power analyzer. Partner to provide Solar SEED Smart Controller and Battery (24V)



T4D Inc. Seed Charge Controller Test Protocol

	PV current	PV voltage	Battery current	Battery voltage	Load current	Load voltage
With Battery 1) PV 300 W, Load 0, Battery to full charge; 2) PV 0 W, Load 300 W, discharge battery to LVD						
With Battery 1) PV 300W, Load 150W, charge battery to full charge; 2) discharge battery at PV 150 W and Load 300 W power to LVD						
Without Battery Full Power to load PV 300 W; Load 300W						
Without Battery 50% Power to load PV 300 W; Load 150W (PV regulated down)						

Figure 4. Test protocol to measure unit capacity and efficiency with and without battery.

Conclusions from the design-of-experiment and preparation for testing center around how to measure efficiency of a very efficient device where input power and output power are close to each other in magnitude, on the same order as the accuracy of the measuring equipment. The biggest problem in efficiency calculation is that losses cannot be measured directly with a high enough accuracy. Revenue meters may offer a basic accuracy of 0.1 % [ANSI C12.20 Class 1]. The problem is that the losses cannot be measured directly but only by the difference in input and output power. The errors of both input and output measurements add and in the worst case could be opposite. A device like this may have an efficiency on the order of 95 % to 99 %. Optimizing device parameters and control settings require detection of small changes in efficiency. This project identified an approach to address this problem that involves:

- High accuracy “flux-gate” current transducers with galvanic isolation for measurement of DC current (<0.0001%, compared to 0.1% for typical power meter)
- High bit Analog-to-digital converter (datalogger) for high resolution relative accuracy across a given range. Specify 16-bit AD converter type instead of 12-bit AD converter type.
- Tight range on datalogger to “zoom in” on expected range of values and improve absolute accuracy for a given relative accuracy.

Task 2: Data analysis (possibly overlapping with Task 1 – early 2020 to mid-2020)

Task 2 will involve the analysis of the acquired data to evaluate performance and efficiency of the charge controller.

2.1 NREL will use the test setup to collect data.

2.2 NREL will analyze the data along the data collection period.

2.3 NREL will onboard Participant staff to participate in testing set-up and data collection.

This Task 2 could not be completed because a hardware prototype was not delivered for testing. Rather, a simulation of PV module current-voltage characteristics (I-V curve) was written and was used to compare voltage and current and power to load with and without Solar SEED Smart Controller. The simulation program is general and can be used with any combination of PV module specifications and load voltage. But the results are very specific to the PV module specifications (the inputs to the simulation). As an example, we consider a PV module with the following specifications:

Table 2. Improvement in performance due to Solar SEED Smart Controller depends on the PV and load characteristics. In the example given, we use the parameters listed in this table for PV current/voltage equation

Parameters from PV Module Data Sheet		
I ref	1000	W/m2
T ref	25	C
Isc ref	5.25	A
Voc ref	45	V
I mpp ref	4.87	A
V mpp ref	36.8	V
I temp coef	0.06	Amps/C
V temp coef	-0.37	Volts/C
I ref NOCT	800	W/m2
T ref NOCT	20	C
NOCT	48	C

The I-V curve simulation is based on the equations presented in [Energies 2016 A Complete and Simplified Datasheet-Based Model of PV Cells in Variable Environmental Conditions for Circuit Simulation Silvano Vergura]. The parameters beta and gamma used in the simulation are described in that reference. Modeling was conducted for conditions described in IEC standards 65813-1, which describes 5 test conditions of varying insolation and temperature. For each condition we simulate the position on the I-V curve of a PV array (in this example 180 W mono-crystalline silicon PV module) and the current and voltage to the load with and without the Solar SEED Smart Controller. The results are listed in Table below.

Table 3. The parameters of the I-V curve (Rseries, Rshunt, beta and gamma) are calculated based on the PV module characteristics.

Condition	I (Wm/2)	T ambient (C)	Tcell (C)	Rshunt (Ohms)	Rseries (Ohms)	beta	gamma
Standard Test Condition	1000	25	25	193.6842	0.420945	5.25	0.13907
Nominal Operating Cell Conditions	800	20	42.4	226.5185	0.257427	4.243848	0.13962
Low Irradiance Conditions	200	25	25	968.4211	2.104723	1.05	0.13907
High Temperature Condition	1000	25	75	157.8526	0.105236	5.4075	0.140636
Low Temperature Condition	500	25	15	401.7011	2.104723	2.60925	0.138751

Table 4. The position on the I-V curve that the PV array operates at with and without the Solar SEED Smart Controller is compared for 5 different conditions specified in IEC standard 65813-1

Condition	I (Wm/2)	Tcell (C)	Voltage with SEED (V)	Current with SEED (A)	Power with SEED (W)	Load Voltage (V)	Current without SEED (A)	Power without SEED (W)	Percent Improvement with SEED
Standard Test Condition	1000	25	36.80	4.87	179.2	24	4.97	119.2	50%
Nominal Operating Cell Conditions	800	42.4	31.74	3.94	125.0	24	3.90	93.7	33%
Low Irradiance Conditions	200	25	39.52	0.97	38.5	24	0.99	23.8	61%
High Temperature Condition	1000	75	27.25	5.02	136.7	24	4.50	108.0	27%
Low Temperature Condition	500	15	39.77	2.42	96.3	24	2.50	59.9	61%

Task 3

3.1 NREL will update the Participant about the project status on a monthly basis via email messages and scheduled conference calls.

NREL arranged conference calls that included the partner principal David Gibbs. The NREL team participating in calls included:

- Principal Investigator: Andy Walker
- Research Operations Manager: Eric Kuhn
- Area Work Supervisor: John Baker
- Lead Operations Engineer: Kurtis Buck
- Facility Quality Manager: Emily Gogel
- ESH Point of Contact: Mike Day

Task 4

4.1 The Principal Investigator agrees to provide the following to DOE Office of Scientific and Technical Information (OSTI): (1) an initial abstract suitable for public release at the time the CRADA is executed; (2) a final report, within thirty (30) days upon completion or termination of this CRADA, to include a list of Subject Inventions; and (3) other scientific and technical information in any format or medium that is produced as a result of this CRADA.

This report serves as the deliverable for Task 4.

The Participant's tasks:

Task 1: Participant will consult with NREL on design of experiment and specification of instruments.

Participant consulted with NREL on design of experiment through periodic conference calls.

Task 2: The Participant will provide the hardware to be tested with enclosure and electrical connectors.

Participant was unable to deliver the hardware to be tested.

Task 3: The Participant will assist NREL in monitoring setup.

The monitoring was not conducted because the hardware was not delivered to NREL.

Task 4: The Participant will assist NREL int supervising the test of the control charger

The monitoring was not conducted because the hardware was not delivered to NREL.

Task 5: The Participant will discuss results.

The participant received and reviewed the results of the modeling.

Conclusions

Conclusions from the design-of-experiment and preparation for testing center around how to measure efficiency of a very efficient device where input power and output power are close to each other in magnitude, on the same order as the accuracy of the measuring equipment. The approach depends on:

- High accuracy flux gate current transducers (<0.0001% instead of 0.1% for typical power meter)
- High bit Analog-to-digital converter (datalogger) for high resolution relative accuracy across a given range (16 bit instead of 12 bit A/D converter).
- Tight range on datalogger to "zoom in" on expected range of values and improve absolute accuracy for a given relative accuracy.

Conclusions from the modeling are that the Solar SEED Smart Controller can improve power delivery much more than expected. This is important information for manufacturers of direct drive (no battery) solar applications and also for consumers of such products. Modeling was conducted for conditions described in IEC standards 65813-1, which describes 5 test conditions of varying insolation and temperature. For each condition we simulate the position on the I-V curve of an example PV array (180 W mono-crystalline silicon PV module) and the current and voltage to the load with and without the Solar SEED Smart Controller.

Conclusions are that the Solar SEED Smart Controller improves delivered power compared to the case of "clamped" voltage by at least 27% in the high temperature case and as high as 61% in the low irradiance and low temperature conditions. Under nominal operating conditions the Solar SEED Smart Controller could improve PV Array power by 33%. At low insolation and low temperature conditions the elevation of voltage above the load voltage is the greatest and thus the greatest potential for the Solar SEED Smart Controller to adjust this high voltage to the load voltage without a loss of total power (the controller increases current and decreases voltage to the load).

Recommendations for future work include:

- Complete a prototype for testing and product certifications.
- Expand model to other calculations of voltage (resistant, inductive) to represent the operating condition of different types of loads.
- Expand model to an hourly simulation of performance with different load profiles in different climate locations.

Subject Inventions Listing:

None.

ROI #:

None.