Space-Based Solar Power (SBSP) envisions the generation of electric power by capturing sunlight in space, converting it to radio frequency (RF) energy 'beaming' it to special rectifying antennas (rectennas) on the earth's surface then distributing the energy to terrestrial users via the pre-existing power grid. The beam would utilize a 2.45 or 5.8 GHz microwave signal to provide between 1 and 5 GW of power to the ground.

The legal operation and public acceptance of SBSP, especially the wireless power transmission (WPT) from space component will depend, in large part, on the human occupational exposure experience accumulated over the past sixty years and basic research on the effects of microwaves on human beings, plants and animals. Fortunately, there is a long history concerning the safety of microwave energy. Modern RF/microwave standards are based on the results of critical evaluations and interpretations of the relevant scientific literature.

The term “microwave” denotes a specific interval of the electromagnetic spectrum that is defined as “non-ionizing.” This interval is bounded on one end by AM-band radio waves and infrared as well as visible light on the other. Included in the microwave spectra are signals that carry FM radio and TV transmissions. Microwaves have become ubiquitous in the terrestrial environment during the last 60 years.

**Non-ionizing Radiation**

The term “non-ionizing” describes any type of electromagnetic radiation that does not carry enough energy to ionize atoms or molecules. In other words, it cannot remove an electron from an atom or molecule. Ionizing radiation, on the other hand, such as far ultraviolet, x-ray or gamma rays possess sufficient energy to strip away electrons; thereby creating charged ions (“free radicals”) that can damage DNA and other susceptible biomolecules.

The biological effects and health implications of microwave radiation have been an intense subject of study for many years. We know that non-ionizing radiation is not mutagenic. It does not increase the frequency of mutations in DNA, for example, above the natural background level. Instead of creating charged ions when passing through matter, non-ionizing electromagnetic radiation has energy sufficient only for ‘excitation.’ Rather than removing an electron, the energy can only move an electron to a higher energy state; this results in local heating which is, to date, the only demonstrated biological effect of microwave exposure. Cumulative data from multiple scientific and medical studies have allowed the establishment of detailed microwave exposure limits for humans under a wide variety of exposure conditions (see next section).
Standards for RF Exposure at Microwave Frequencies

Current RF/microwave standards are based on the scientific and medical literature. The specific absorption rate (SAR) threshold for the most sensitive effect (heat) is used as the basis of the standard. The SAR is only related to a heating problem, which is regarded as the ONLY MICROWAVE EFFECT on human health.

The International Council on Non-Ionizing Radiation Protection (ICNIRP) has a two-tiered set of RF exposure limit guidelines (the Japanese also use the ICNIRP limits). One is for Occupational Exposure and one if for General Exposure. The occupational exposure is for workers and the general exposure limits are for the general population who may or may not know they are being exposed to RF.

The guidelines for 2.45 and 5.8 GHz are the same and are as follows:

The Occupational limit is 5 mW/cm². The General limit is 1 mW/cm²

The corresponding IEEE maximal exposure limits are a little more complicated because they are time averaged. The IEEE standards are for "controlled" and "uncontrolled" situations rather than Occupational vs. General exposures but the concept is similar. Controlled exposures are averaged over six minutes. Uncontrolled exposures are averaged over 30 minutes.

At 2.45 GHz the exposure limits are 8.16 mW/cm² (averaged over six minutes) or 1.63 mW/cm² (averaged over 30 minutes). At 5.8 GHz the limits are 10 mW/cm² (averaged over six minutes) or 3.87 mW/cm² (averaged over 30 minutes).

To put these numbers in perspective, at 2.45 GHz, the power density projected at the perimeter of the rectenna is about 1-5 mW/cm²; the same amount of microwave radiation permitted (by standards) to leak up to 5 cm from any external surface of a regular kitchen microwave oven.

Characteristics of the Beam

In a typical SBSP system, the beam transmitting the energy from space would be approximately 2 to 4 kilometers wide. The strength of the beam is highest in the center and rapidly decreases to very low levels at the periphery of the beam. The peak power density at the center of the beam at it intersects the rectenna is on the order of 300 watts per square meter (W/m²) or 30 miliwatts per square centimeter (mW/cm²).

To put 30 mW/cm² in perspective, the energy generated inside a typical kitchen microwave oven is approximately 1000 mW/cm². This means the power density at the center of an SBSP beam is only 3% as strong as a typical countertop microwave oven.
Such peak power densities envisioned for SBSP could never even come close to ‘cooking’ birds in flight. Studies have shown that at 25 mW/cm², some birds exhibit behaviors suggesting they might be able to detect microwave radiation. If true, some migratory birds, flying above the rectenna, might suffer disruption of their flying paths. At higher ambient temperatures, larger birds, having greater body mass and thus absorbing a relatively greater amount of microwave radiation, could tend to experience more heat stress than smaller ones. No doubt birds would learn to avoid areas of the sky associated with transient local heating. No evidence has been found that continuous power densities from 1 to 50 mW/cm² (at 2.45 GHz) have any biological effects on honeybees.

During normal operations microwave intensity in the area above the rectenna (and perhaps even around the rectenna in some circumstances) exceeds the human exposure standards documented in the previous section. Except for maintenance personnel, human exposure would normally not be permitted in these areas. However, in the case of occupationally required presence, the only protective measures required to reduce exposures to permissible levels are simple personal protective equipment such as glasses, gloves and reflective garments.

The energy transmitted by SBPS from space to Earth is five orders of magnitude less than the total solar radiation reaching the Earth (i.e. the power density of the beam is weaker than the power density of sunlight). Therefore, SBPS will not worsen global warming problems. Since rectenna efficiencies are very high (see below), very little of the total energy is lost as heat. SBSP does not generate CO₂, change atmospheric chemistry or contribute to climate change.

The SBPS microwave downlink will need to be monitored continuously to ensure tightly tuned phased-array techniques and beam control are functioning properly (perhaps by utilizing a ‘pilot signal’ from Earth). Should a loss of beam focusing control occur, beam-defocusing techniques would be required to automatically disperse the power from the beam; resulting in a widely dispersed beam of very low intensity.

As the beam passes through the atmosphere from geostationary orbit, a loss of no more than 2% of total beam power is predicted. In abnormal circumstances, such as scintillations in the ionosphere or rain cells in the troposphere, the power loss may temporarily be greater.

The effects of powerful microwaves on the stratosphere have been studied, mostly to study the effects of ozone-destroying pollutants in the troposphere or to create an artificial ozone layer by interaction with high-energy electromagnetic waves. The
field strength necessary to do this is much higher than power densities that would be used by SBSP systems. SBSP is therefore not expected to impact the atmosphere.

The anticipated power densities at the center of the beam does exceed US Federal Aviation Administration (FAA) RF exposure standards for aircraft even though the passengers would not be affected. This area should therefore be placed ‘off limits’ to air traffic control.

The collection efficiency of the rectenna in capturing the energy of the beam approaches an impressive 87%. Because so much energy of the beam energy is filtered out by the rectenna, it is highly likely the area underneath the rectenna, especially in the out segments, will be usable for other applications perhaps even including agriculture (remember microwave signals are non-ionizing).

Summary

Is SPS safe?
Based on our present knowledge, the answer is yes, provided current exposure standards are satisfied.

Bio
Dr. Logan is an eighteen-year veteran of NASA. He has avidly studied Space Based Solar Power for almost two decades and is a subject matter expert in the medical/biological aspects of wireless power transmission. His area of expertise is human space operations, space physiology and space medicine. His previous positions held at NASA include: Chief of Flight Medicine, Chief of Medical Operations, Chief of Human Test Support, and Chief of Medical Informatics and Health Care Systems. Mission Control certified, Dr. Logan was Crew Surgeon, Deputy Crew Surgeon and Mission Control Surgeon for 25 space shuttle missions. He served on the original Space Station Skunk Works at Johnson Space Center, as well as the first Space Station Operations Task Force at NASA Headquarters.