DEPARTMENT OF THE AIR FORCE
ARMSTRONG LABORATORY (AFMC)

10 May 1996

MEMORANDUM FOR OC-AL/TIESW (Capt Greg Sharp)
4750 Staff Drive
Tinker AFB OK 73145-3317

FROM: AL/OERS
8305 Hawks Road, Building 1182
Brooks AFB TX 78235-5324

SUBJECT: Consultative Letter, AL/OE-CL-1996-0159 , Report of a Radio Frequency (RF) Radiation Hazard Survey of Pacer Crag C/KC-135 E/R Weather Radar System, WXR-700X.

1.0 Introduction. This consultative letter was prepared to document the findings from a field survey conducted by Ms. Nancy L. Beauregard, Illgen Simulation Technologies, Inc., on-site manager, RF Radiation Consulting Function, Armstrong Laboratory. The survey was conducted at a Rockwell International facility located in Shreveport, LA. Captain Greg Sharp, the B-1/KC-135 Test and Evaluation Program Manager requested the support of Armstrong Lab in conducting this evaluation. The purpose of this survey was to establish the electromagnetic field strengths associated with the use, operation, and testing of the new WXR-700X Radar, and to establish safe operating distances for Air Force employees working near the new radar. Safe operating distances for refueling operations and for electroexplosive devices were determined by Jim Laycock, 738 EIS/EEEX, Keesler, MI. Safety distances for fuels and explosives are discussed in paragraph 4.0.

1.1 Current Permissible Exposure Limits (PELs). The Department of Defense Instruction, DODI 6055.11, establishes the maximum PELs for the protection of all DOD civilian and military personnel who may be exposed to radio frequency electromagnetic fields (RF EMF). The DODI establishes separate PELs for controlled and uncontrolled environments. This system will only be operated in flight, or within controlled environments, such as Air Force flightlines. The PELs established for the frequency range of this radar are listed below:

Controlled Environments	10.0 mW/cm^2 for an averaging time of 6 minutes
Uncontrolled Environments	6 mW/cm^2 for an averaging time of 1 minute

A complete list of PELs established at various frequencies for both controlled and uncontrolled environments is attached.

1.2 Personnel Contacted:

Capt Greg Sharp, B-1/KC-135, Test and Evaluation Program Manager
Dave Garza, Engineer, Rockwell International
Mark Burton, Test Manager, Rockwell International
Long Hoang, Radar Engineer, USAF
Capt Vince Orlando, QT&E Test Director, USAF

1.3. Terms Explained:

Far-Field Region. The region far enough from an antenna that the radiated power per unit area decreases with the square of the range. In the far-field, the field has a predominately plane-wave character, i.e., uniform distributions of electric (E) and magnetic (H) fields in planes transverse to the direction of propagation.

Hazard Distance. The distance from an antenna, or other radiating element where field power density levels are equal to the PEL.

Near-Field Region. A region, generally in close proximity to an antenna in which the electric and magnetic fields do not exhibit a plane-wave relationship, and the power does not decrease with the square of the distance from the source. For most antennas, the outer boundary of the near field is defined as a distance of one-half the wavelength from the surface of the antenna.

Permissible Exposure Limit (PEL). The PEL is established for the protection of personnel. There are no expectations that any adverse health effects will occur with exposures that are below the PEL, even under repeated or long-term exposure conditions. In controlled environments, where restrictions on access may be implied, the PEL is based on maintaining exposures below a specific absorption rate of 0.4 watts per kilogram (W/kg). That level incorporates a safety factor of 10 below a SAR of 4 W/kg that is considered as a threshold, above which, there is an increasing possibility for adverse biological effects, but below which, there is no established evidence of any harm to health. In uncontrolled environments, where access is not restricted, lower levels (equivalent to a SAR of 0.08 W/kg) have been adopted over the human resonance range as a consensus for maintaining lower exposure levels in public areas. Since SAR is not an easily measured quantity, PELs are given in terms of measurable field parameters E, H, or power density (S) as a means for demonstrating compliance with SAR.

Plane Wave. An electromagnetic wave characterized by mutually orthogonal electric (E) and magnetic (H) fields that are related by the impedance of free space (377 ohms). For plane waves, power density (S), E, and H exhibit the following relationship: $S=E^2/3770 = 37.7\ H^2$, where S is in units of mW/cm^2, E is in V/m, and H is in A/m.

Power Density (S). Radiated power per unit area, expressed in units of watts per square meter or milliwatts per square centimeter (mW/cm^2).

Specific Absorption Rate. The rate at which RF energy is imparted to an element of biological body mass. Average SAR in a body is the rate of the total energy absorbed divided by the total mass of the body. SAR is expressed in units of watts per kilogram (W/kg), can only be measured in a laboratory under strict scientific guidelines, and is used as the basis for determining acceptable power density levels for exposure to humans.

2.0 Survey Data:

2.1 Functional Description of the System and Operating Conditions. The WXR-700X is the prototype weather radar system developed to replace the existing APN-59. Eventually, this system will be installed on board all KC-135 aircraft in the Air Force Inventory. The antenna for the new replacement radar is a 2.3 x 2.8 foot, flat plate, slot array antenna as pictured below:

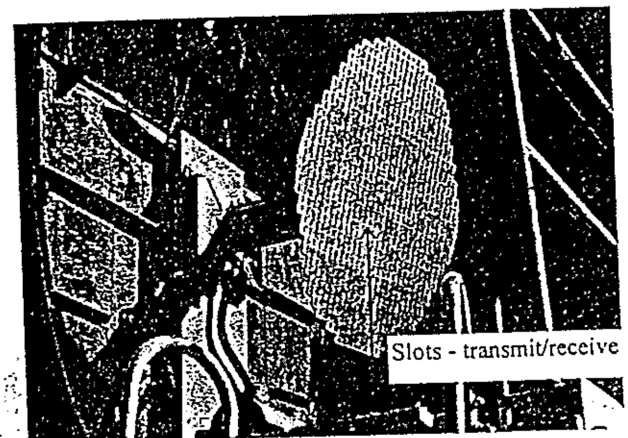

Photo 2 Face of WXR-700X Antenna

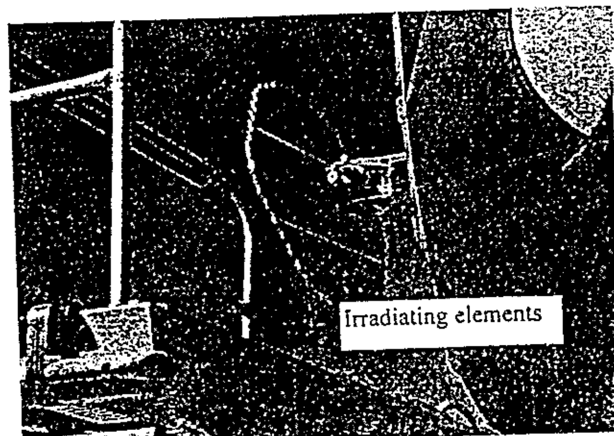

Photo 1 Back of the WXR-700X Antenna

The maximum peak power of the transmitter is 180 Watts. The individual slots in the array are tuned to either transmit or to receive signals. The beam is steered by the mechanical motion of the flat plate antenna. Under normal conditions the antenna mechanically scans a 180 degree horizontal sector, and can be vertically tilted to cover a 90 degree vertical sector in front of the aircraft. In order to stop the horizontal scanning motion, the antenna must be mechanically disabled.

The pulse parameters used during operations are software selected and driven such that the duty cycle is always 1 percent. The system is designed to be capable of generating pulsed signals ranging from 1-20 usecs and 180-16000 pulses per second, but it requires a software modification to select different pulse widths and pulse repetition frequencies. The worst case combination of pulse characteristics would produce a duty cycle of 32 percent. This could not be accomplished during the testing procedures, so only the typical operating conditions were examined and evaluated during this survey.

2.2 Pre-Survey Theoretical Hazard Evaluations: Theoretical hazard evaluations were accomplished to predict the distance where the field power density may exceed the PEL of 10 mW/cm^2. These values were then corrected to account for near field and horizontal scan conditions. Table 1 contains an evaluation which estimates the distances for selected power densities under the normal operational conditions using a duty factor of 1 percent. Table 2 is a theoretical estimate for the "worst case" pulse configuration, which would result in a much longer duty cycle of 32 percent. The latter conditions are not normally expected for this system, but must be evaluated to ensure the most conservative approach has been taken in assessing potential risks to personnel working near the antenna.

2.2.1 Analysis of Data from Table 1, Normal Operating Conditions. In the far field region, the "hazard distance" is estimated to be 7 feet in front of a fixed beam or stationary antenna. This

Theoretical Main Beam Power Density Analysis 3-19-96
For The WXR-700X Weather Radar - Normal Operational Configuration

Transmitter Data:

Peak Output Power (KW):	0.18	Average Output Power (KW):	0.002
Pulse Rep Freq (Hz):	180.00	Pulse Width (microsec):	60.000
Duty Cycle:	0.01080		
Frequency (MHz):	9000.0000	Wavelength (cm):	3.333

Antenna Data:

Aperture Type:	Rectangular		
Gain (dB):	35.00		
Horizontal Dimension:	2.30 ft	Vertical Dimension:	2.80 ft
Horizontal Beamwidth:	2.50 deg	Vertical Beamwidth:	2.10 deg
Horizontal Illumination:	Uniform		
Vertical Illumination:	Uniform (Cosecant Squared Vertical Pattern)		
Aperture Efficiency:	0.467		
Scanning Plane:	Horizontal		
Scanning Beamwidth (deg):	2.5		
Scanned Sector (deg):	180		

Field Parameters

Peak ERP (MW):	0.5692	Transition Region Begins (ft):	35.8
Average ERP (MW):	0.0061	Far Field Begins (ft):	143.4

Average Power Density (mW/cm2)	Peak E Field Intensity (kV/M)	MAIN BEAM DISTANCES (ft) FAR FIELD Uncorrected Fixed	Scanning	NEAR FIELD Corrected Fixed	Scanning
5.00	1.32	10	2	0	0
6.00	1.45	9	2	0	0 (uncontrolled environment)
7.00	1.56	9	1	0	0
8.00	1.67	8	1	0	0
9.00	1.77	8	1	0	0
10.00	1.87	7	1	0	0 (controlled environment)

Table 1, Theoretical Hazard Eval for Normal Operations far field distance assumes that the waveforms, which consist of both E and H field components, are fully formed, and completely in phase. Since the waveforms do not begin to "take shape" or come into phase until a distance of about 35 feet, and are not actually in phase until 143 feet from the emitter, then corrections must be applied to determine the values for near field (out-of-phase) conditions. In near field conditions, the power density levels become negligible so a hazard distance of zero feet results, meaning there is no need to restrict access to any region directly in front of the radiating antenna. Also, under normal conditions, the antenna is scanning horizontally. For this evaluation, we used a horizontal scan sector of 180 degrees and corrected the main beam power density values for a fixed field to predict safe operating distances. As the values indicate, as long as the antenna is scanning absolutely no restrictions are required. This conclusion was later supported by field power density measurements taken under these operating conditions (see paragraph 2.4, Field Power Density Measurements).

2.2.2 Analysis of Data from Table 2, Worst Case Operating Conditions. The worst case configuration was theoretically evaluated assuming that it could one day be possible to use a 32 percent duty cycle with a stationary beam. Using these parameters, and correcting for near field conditions, it appears very possible to obtain levels at the PEL at approximately 32 feet from the antenna. Again, with the antenna scanning, either horizontally or vertically, the power density levels are negligible. Therefore, access to the area in front of the antenna does not have to be controlled or restricted while the antenna is scanning, even under worst case conditions.

Theoretical Main Beam Power Density Analysis 3-19-96
For The WXR-700X Weather Radar - Normal Operational Configuration

Transmitter (same as previously listed in Table 1, except for the following):

Average Output Power (KW):	0.058	Pulse Rep Freq (Hz):	16000.00
Duty Cycle:	0.32000	Pulse Width (microsec):	20.000

Antenna Data: (same as previously listed in Table 1):

Field Parameters:

Peak ERP (MW):	0.5692
Average ERP (MW):	0.1821
Transition Region Begins (ft):	35.8
Far Field Begins (ft):	143.4

Average Power Density (mW/cm2)	Peak E Field Intensity (kV/M)	MAIN BEAM DISTANCE (ft) FAR FIELD Uncorrected Fixed	Scanning	NEAR FIELD Corrected Fixed	Scanning
5.00	0.24	56	9	52	0
6.00	0.27	51	9	46	0
7.00	0.29	47	8	42	0
8.00	0.31	44	7	38	0
9.00	0.33	42	7	35	0
10.00	0.34	39	7	32	0

Table 2, Theoretical Hazard Eval for Worst Case Conditions

2.3 Survey Equipment. Field strength measurements were conducted with a broadband, radioisotropic probe, model number 8721, and survey meter, model number 8718. Both instruments are manufactured by Loral Microwave-NARDA.

2.4 Field Power Density Measurements.

2.4.1 Methodology. Survey measurements were conducted at the Rockwell Test Facility in Shreveport LA on March 21, 1996. To facilitate measurements, the mechanical scan function had to be physically disabled to make the antenna stationary, and the antenna was tilted to zero degrees elevation to ensure that measurements were taken along the main beam axis. Power density measurements were stored directly into the programmable survey meter and assigned a sequential number to identify the location of each measurement point. Using an RS-232 cable interface, the measurements were downloaded directly from the meter into a pentium laptop computer for inclusion in this survey report.

2.4.2 Measurement Results and Findings. A list of the power density measurements taken along the main beam axis directly in front of the transmitting antenna between 0 and 150 feet from the source is shown in Table 3 below:

File - 2103602.SVY Power Density Measurements in Front of WXR-700X Radar Antenna				
Meter Model 8718	S/N: 1030	Cal Date: 10\27\95	Due: 10\27\96	
Probe 8721	S/N: 15001	Cal Date: 10\27\95	Due: 10\27\96	
Freq: 9.33 GHz	Cor. Factor: 0.92	Logging Rate:		
Ave Mode: None	Ave Time:	Display Update:		
Antenna Tilted to Zero Degrees Elevation:				
Ref#	Date	Time	mW/cm^2	Distance
01	03/21/96	14:48	0.10	@ 100 feet
02	03/21/96	14:48	0.08	@ 130 feet
03	03/21/96	14:49	0.06	@ 150 feet
04	03/21/96	14:49	0.06	@ 150 feet
05	03/21/96	14:49	0.13	< 1 foot
06	03/21/96	14:50	0.12	< 1 foot
07	03/21/96	14:52	0.07	2 feet
08	03/21/96	14:54	0.07	2 feet
09	03/21/96	14:58	0.02	3 feet
Antenna Tilted to < Zero Degrees Elevation				
10	03/21/96	15:00	0.10	

Table 3, Field Power Density Levels

It should be noted that before the survey measurements were taken, it became evident that the equipment was experiencing interference from multiple sources located in the general vicinity. The control tower for the airport and an air surveillance radar could be seen from the measurement location. Since the Rockwell test facility is located at Shreveport International Airport, it was not possible to have the airport systems shut down for the purpose of this survey. The levels measured from the WXR-700X radar were barely distinguishable from the background noise in the general area.

3.0 Conclusions and Recommendations.

3.1 Normal Operating Conditions. Based on analysis of the equipment parameters, theoretical hazard evaluations, and the field power density measurements, the WXR-700X radar, equipped with a flat plate, slot array antenna, does not produce power density levels that could reasonably be expected to exceed the PEL under normal operating conditions. Therefore, it is not necessary to establish restricted access zones in front of the antenna under these conditions. Normal operating conditions are defined as:

a) antenna is operated only in a scanning mode during transmission, or

b) only pulse width and pulse repetition frequency combinations which do not exceed a 1 percent duty cycle are selected and utilized.

The system may be operated at 1 percent duty cycle with the scanning motion disabled without restricted access zones, as long as the duty cycle does not exceed 1 percent.

3.1 Special Operating Conditions. If the scan function is disabled and duty factors greater than 1 percent are required for testing, then a minimum distance of 35 feet along the main beam axis should be established, and controlled with cones or other markers. If a pulse width or pulse repetition frequency combination that produces a maximum 32 percent duty cycle is selected, and the antenna scanning function is disabled, then a minimum hazard distance of 35 feet must be established.

3.2 Scanning Conditions. As long as the antenna is allowed to scan freely, no restricted access zones are required regardless of the selected duty cycle.

4.0 Safe Distances for Refueling and Electro Explosive Devices (EEDs). This survey report and the radar parameters were submitted to Mr. Jim Laycock, 738th Engineering Installation Services, Keesler AFB, MI, for his review and evaluation of fuel and explosive ordinance safety concerns. Mr. Laycock determined these safe distances based upon the worst case parameters of the radar, not the normal operating conditions, see paragraphs 4.1 and 4.2.

4.1 Fuel Handling Operations. The maximum safe power density for fuel handling operations is given in Ref. 1 as 5 watts/cm^2 (5000 mW/cm^2) peak power density. The theoretical maximum distance at which this power density could occur can be calculated using the following far field power density equation:

$$D = 1.037 * \sqrt{\frac{P_{T(PEAK)} \; G_T}{4 \pi PD}}$$

Where:

D = Distance from the WXR-700X radar antenna in feet

$P_{T(PEAK)}$ = Peak outout power of the WXR-700X radar in watts, $P_{T(PEAK)}$ = 180 watts

G_T = Numeric gain of the WXR-700X radar antenna, G_T = 3162.3 (35 dBi)

PD = Maximum safe power density for fuel handling operations in mW/cm^2,

PD = 5000 mW/cm^2 peak power density

Using the worst case parameters for the WXR-700X radar, the radiation hazard to fuel handling operations does not extend beyond 3.2 feet from the radar antenna.

4.2 Electroexplosive Devices (EEDs). The recommended EED (all EED configurations) safe separation distance from the emitters operating at 9 GHz is given in Ref. 2 by the following formula:

$$D = 0.093 * \sqrt{P_T \; G_T}$$

Where:

D = Recommended EED safe separation distance from the WXR-700X radar antenna in feet

P_T = For pulsed systems with all pulse widths less than one millisecond,

P_T is equal to the larger of the following:

(1) Average Power in watts or,

(2) Peak Power in watts * (largest pulse width expresessed in milliseconds / one millisecond)

For the WXR-700X, P_T = 58 watts (0.058 kW)

G_T = Numeric gain of the WXR-700X radar antenna, G_T = 3162.3 (35 dBi)

For the WXR-700X radar, the recommended EED safe separation distance is 40 feet.

5.0. Conclusion. We are delighted to have been involved in the testing and evaluation phase of this system development. It is not often that we have the privilege of getting involved at such an early stage. Unfortunately, most of our surveys are conducted on systems after they have been deployed to the field and we find, all too often, that established controls for personnel protection are either inadequate for the protection of workers, or controls are so restrictive they interfere with the accomplishment of the maintenance mission. If you have any questions concerning this report or need additional assistance in the future, please feel free to contact Ms. Beauregard at DSN 240-1182, or Dr. Leonowich at DSN 240-2037.

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2 Attachments:

1. Permissible Exposure Limit Tables
2. References

PELS FOR CONTROLLED ENVIRONMENTS

Frequency Range (f) (MHz)	Electric Field (E) (V/m)	Magnetic Field (H) (A/m)	Power Density (S) (mW/cm²)	Averaging Time (T_{avg}) (E, S) (H)
0.003 - 0.1	614	163	$(10^2, 10^6)$	6
0.1 - 3.0	614	16.3/f	$(10^2, 10^4/f^2)$	6
3 - 30	1842/f	16.3/f	$(900/f^2, 10^4/f^2)$	6
30 - 100	61.4	16.3/f	$(1.0, 10^4/f^2)$	6
100 - 300	61.4	0.163	1.0	6
300 - 3000			f/300	6
3000 - 15000			10	6
15000 - 300000			10	$616000/f^{1.2}$

PELS FOR UNCONTROLLED ENVIRONMENTS

Frequency Range (f) (MHz)	Electric Field (E) (V/m)	Magnetic Field (H) (A/m)	Power Density (S) (mW/cm²)	Averaging Time (T_{avg}) (E, S)	(H)
0.003 - 0.1	614	163	$(10^2, 10^6)$	6	6
0.1 - 1.34	614	16.3/f	$(10^2, 10^4/f^2)$	6	6
1.34 - 3.0	823.8/f	16.3/f	$(180/f^2, 10^4/f^2)$	$f^2/.3$	6
3.0 - 30	823.8/f	16.3/f	$(180/f^2, 10^4/f^2)$	30	6
30 - 100	27.5	$158.3/f^{1.668}$	$(0.2, 9.4x10^5/f^{3.336})$	30	$.0636f^{1.337}$
100 - 300	27.5	0.0729	0.2	30	30
300 - 3000			f/1500	30	
3000 - 15000			f/1500	90000/f	
15000 - 300000			10	$616000/f^{1.2}$	

Attachment 1

References.

Ref. 1: IEEE/ANSI Standard C95.1-1991, Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300 GHz, April 27 1992.

Ref. 2: TO 31Z-10-4, Electromagnetic Radiation Hazards, 15 October 1981, change 5, 19 January 1989.

Ref. 3: AFM 91-201, Explosives Safety Standards, 7 October 1994.

Attachment 2