CALCULATION OF ARGON-41 CONCENTRATIONS FOR THE UNIVERSITY OF FLORIDA TRAINING REACTOR USING ATMOSPHERIC DISPERSION MODELING CODES: STAC2.1 AND CALPUFF

By

VICTORIA SPRING CORNELISON

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2008

To my mom, dad, stepfather, family and friends who have nurtured my intellectual curiosity and academic pursuits throughout all trials and triumphs

ACKNOWLEDGMENTS

I thank the chair and members of my supervisory committee for their mentoring, and the staff and faculty of the UF NRE Department for their help, knowledge, and support. I thank my family and friends for their loving encouragement, which motivated me to complete my studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Ar-40	Isotope of Argon with a mass of 40; atomic number is 18.
Ar-41	Isotope of Argon with a mass of 41; atomic number is 18.
ASME	American Society for Mechanical Engineers
CALMET	Atmosphere and terrain modeling program in CALGROUP.
CALPOST	Post processing program in CALGROUP.
CALPUFF	Puff or slug based concentration calculation modeling program in CALGROUP.
CFR	Code of Federal Regulations
EPA	Environmental Protection Agency
IWAQM	Interagency Workgroup on Air Quality Modeling
MM5	Pennsylvania State University / National Center for Atmospheric Research mesoscale model
NRC	Nuclear Regulatory Commission
STAC2.1	Gaussian computer model: STAC2 Version 2.1 Build 1.5b
UF	University of Florida
UFTR	University of Florida Training Reactor
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WRF	Weather Research and Forecasting model

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science

CALCULATION OF ARGON-41 CONCENTRATIONS FOR THE UNIVERSITY OF FLORIDA TRAINING REACTOR USING ATMOSPHERIC DISPERSION MODELING CODES: STAC2.1 AND CALPUFF

By

Victoria Spring Cornelison

August 2008

Chair: Glenn Sjoden
Major: Nuclear Engineering Sciences

Atmospheric plume dispersion modeling and meteorological data were applied to estimate downwind concentrations of Ar-41 exhausted during routine University of Florida Training Reactor (UFTR) operations. Two Gaussian-based concentration prediction codes were employed: STAC2.1 and CALPUFF. Gaussian plume atmospheric models are based on methods initially developed by Pasquill, Briggs, and Turner; these methodologies were adopted by the EPA, Federal Coordinator of Meteorology, and ASME.

Yearly maximum average predicted concentrations, dose rates, operational limits, dilution factors, and a stack height study were performed for routine UFTR operational parameters, with impact assessments assuming dedicated winds near campus buildings at full reactor power (100kW). Calculations were accomplished using STAC2.1, developed at UF, and for independent correlation, results were compared to those derived from CALPUFF, an established, detailed air pollution transport code. Results from both independent codes were quite consistent. Moreover, all work in this area was integral to the UFTR NRC re-licensing process.

CHAPTER 1
INTRODUCTION

This work focuses on atmospheric plume dispersion modeling, integrating fluid dynamics, statistical, and meteorological data to achieve an estimate of the downwind concentration of Ar-41 effluent emitted from the University of Florida Training Reactor (UFTR) exhaust stack during routine operations. The atmospheric modeling system utilized is based on the methods constructed by Pasquill, and further expounded upon by Briggs and Turner [1 – 4], with related methodologies applied in US Atomic Energy Commission studies [5]. These methods have been adopted and used as a basis for many computer algorithms and methodologies used by the EPA, Federal Coordinator of Meteorology, and the ASME [1, 4, 6 - 8].

Atmospheric Effects in Program Methodology

As effluents are dispersed, wind direction and atmospheric conditions such as temperature, quantity of solar radiation, and wind speed distinctly affect the transport pathway of any effluent traveling from the stack [1 – 4, 9]. Time of day or night conditions play an important role in the concentration due to the change in heating from the sun and cloud cover, affecting the lapse rate. These varying conditions, incorporated into our mathematical models, allow the concentration of Ar-41 to be conservatively estimated via a one-wind, Gaussian computer model: STAC2 Version 2.1 Build 1.5b (STAC2.1) [1 – 4, 8]. In addition, these parameters are employed in the CALPUFF atmospheric transport code package, used in this work to validate results from STAC2.1; CALPUFF is an EPA approved atmospheric dispersion concentration prediction modeling program.

Ar-41 Reaction and Location in the UFTR

Argon, as a natural constituent in air, was discovered by Lord Raleigh and Sir William Ramsey in 1894, but was initially suspected to exist by Cavendish in 1785 [10]. Ar-40 is ~99.6%

of this natural argon, which is ~1.3 weight percent, or about ~0.94 volume percent of air [10, 12, 13]. Ar-41, in reference to the reactor, originates from leakage neutrons undergoing capture by Ar-40 [12]. Ar-40 is present throughout the air spaces surrounding the UFTR fuel. Eq. 1-1 shows the activation of Ar-40. Note that the half-life of Ar-41 is 1.83 hours.

$$^{40}_{18}Ar + ^{1}_{0}n \rightarrow ^{41}_{18}Ar + \gamma \qquad (1\text{-}1)$$

The UFTR was built in 1959, and is one of the oldest of less than thirty university reactors in the United States. In 2005 – 2006, the fuel was converted from high enriched uranium (HEU) to LEU (19.75% U-235); the general structure of the UFTR has remained the same; fuel is surrounded by graphite and concrete, with cadmium control blades to control the reactor and regulate power [14]. Regarding basic features of the UFTR, in reference to the air locations, Fig. 1-1 illustrates these locations inside the UFTR, shown with the concrete shielding removed [15]. Air in the concrete, as well as that outside of the concrete in the reactor room is also a factor.

The concentration of Ar-41 is a limiting parameter for the operations cycle of the UFTR. Monthly concentration averages for Ar-41, as determined by the Nuclear Regulatory Commission (NRC) licensing regulations, must not exceed 1×10^{-8} Ci/m^3 (note: 1 Ci/m^3 = 1μCi/mL), at 100% reactor power (100kW), This is also per Florida state and federal guidelines (10CFR20), to preserve and maintain the health and environmental safety of the public [16, 17].

In order to estimate potential concentrations of Ar-41 and surrounding terrain relative to the UFTR, two maps are shown in Fig. 1-2 and 1-3 [11]. Fig. 1-2 contains the UF Campus main campus, and the relative position, indicated in the small black box, to the campus. Fig. 1-3 focuses on the more specific campus location of the UFTR, from the black box of Fig. 1-2.

The UFTR is in close proximity to many campus buildings: Ben Hill Griffin football stadium, other engineering departments, parking garages and students' residence halls. The closest student residence hall, East Hall, is a location with high routine occupancy [17]. This hall is approximately 190m west-southwest of the UFTR and in the path of a wind direction from east-northeast.

Purpose of this Research

The purpose of this work was to determine an estimate, using independent methods, of the Ar-41 concentrations and dose rates predicted at various down-wind ranges. Results from this study were used in reporting the Ar-41 burden in regions surrounding the University for purposes of relicensing for the Nuclear Regulatory Commission (NRC). This work is presented as follows: a discussion of the theory and methodology supporting the application of the Gaussian dispersion model used in the STAC2.1 dispersion code is presented in Chapter 2, validation methods for the code, and calculations made for determining the emission of Ar-41 from the UFTR are presented in Chapter 3. Note that validation methods for STAC2.1 employed include a fundamental manual approach using basic Pasquill and Briggs formulations [1-4], as well as a comparison of results from a robust CALPUFF model [8] as an independent corroboration of STAC2.1 predicted concentrations. Also presented, in Chapter 4, are the maximum Ar-41 concentrations for various atmospheric conditions, corresponding distances, attributed dose rates, correlations to UFTR operation hours, and other relevant information. This is followed by a discussion of the data, conclusions, and future work.

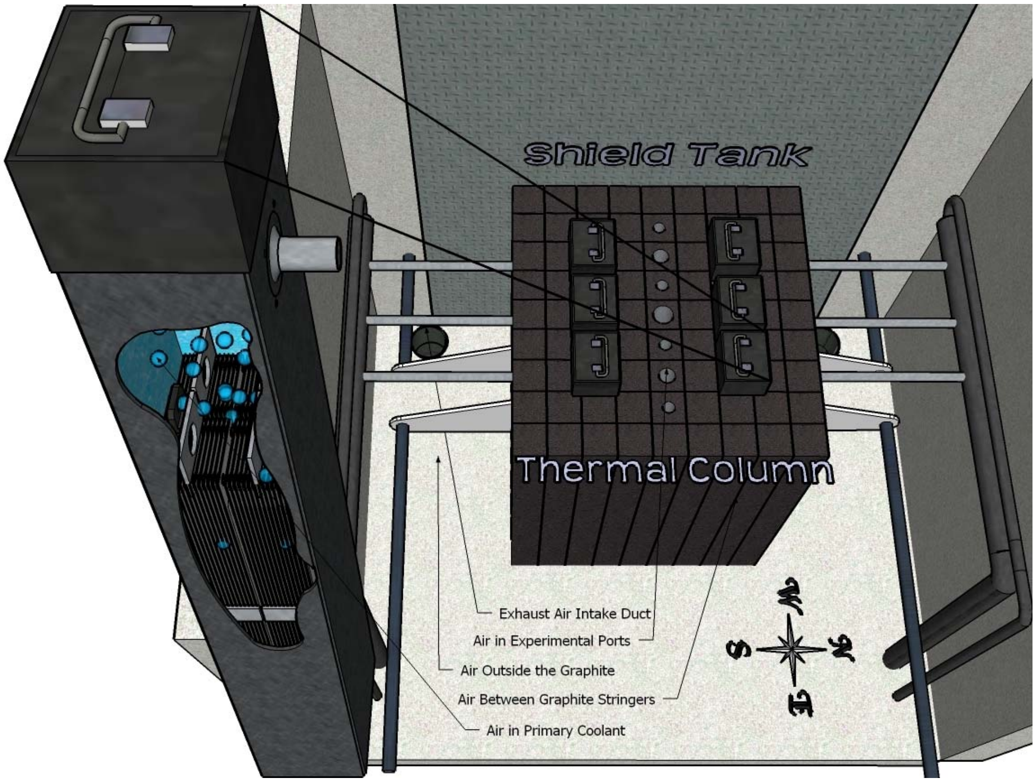

Figure 1-1 Locations of Air inside the UFTR, with Concrete Shielding Removed

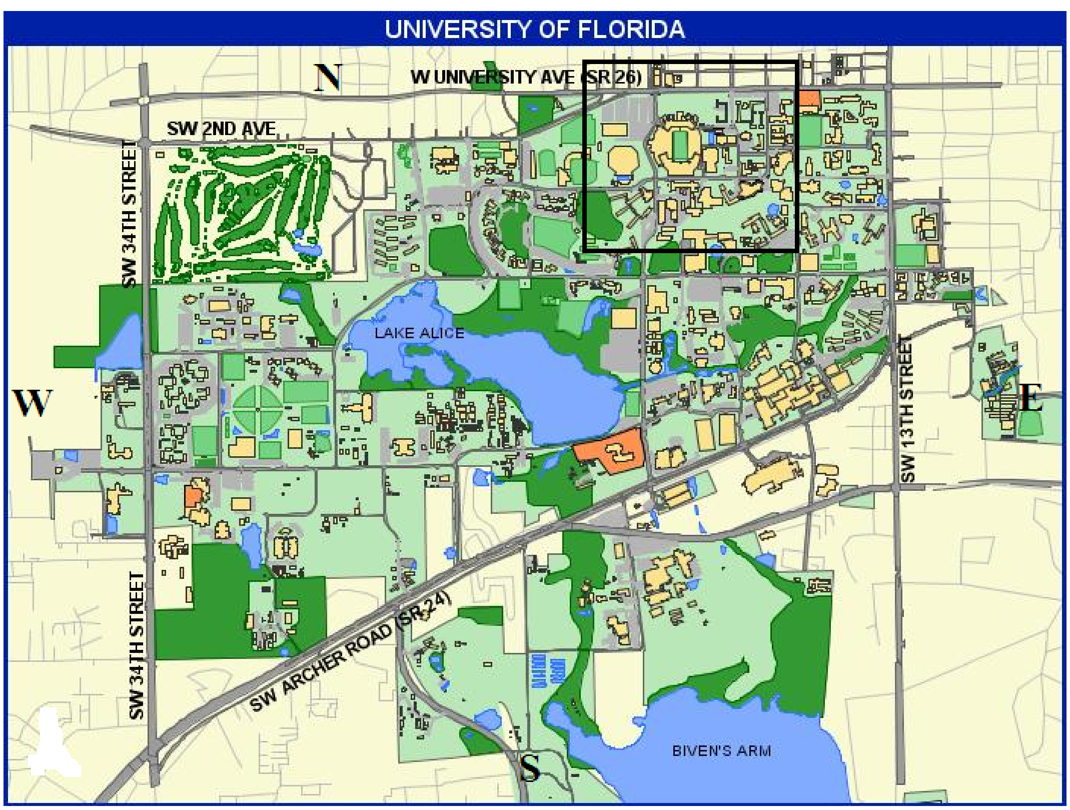

Figure 1-2 University of Florida Campus in Gainesville, Florida

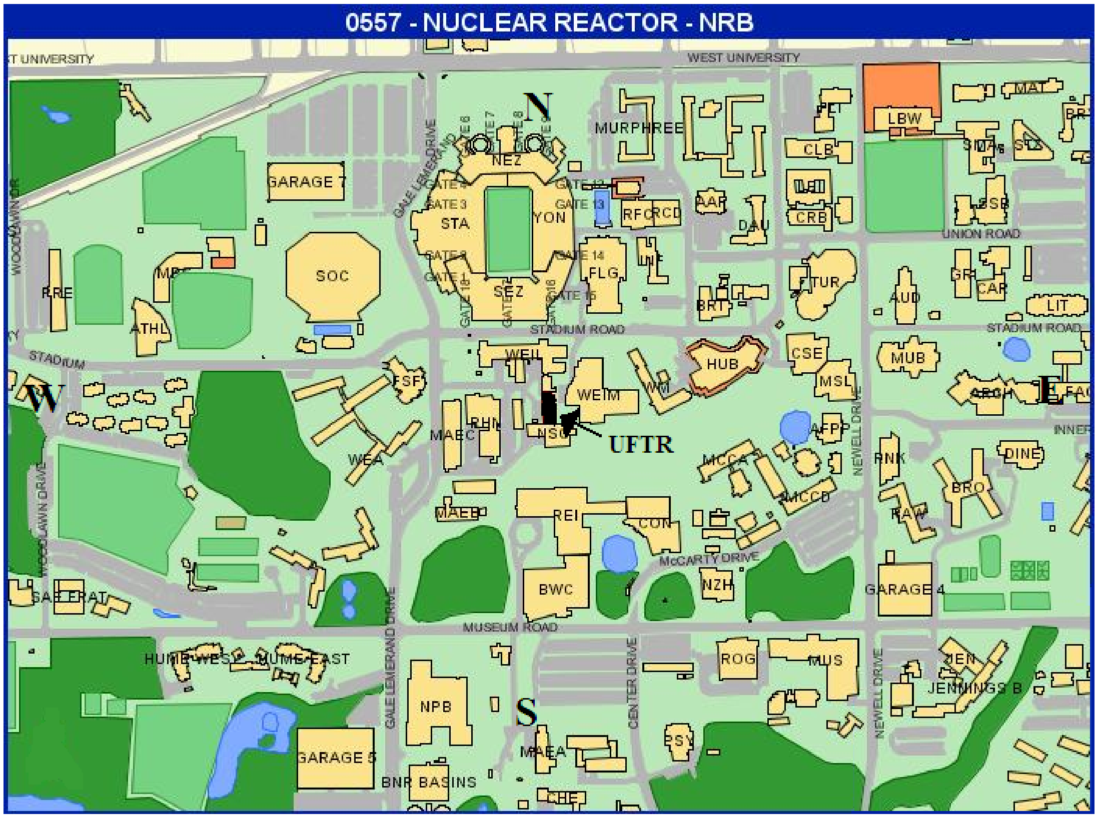

Figure 1-3 UFTR Location on the University of Florida Campus

CHAPTER 2
THEORY AND BASIS FOR EFFLUENT DISPERSION IN THE STAC2.1 CODE

Ar-41 concentrations, emitted from the UFTR stack, are calculated based on standard American Society for Mechanical Engineers (ASME) equations and Pasquill stability classes determined for atmospheric conditions, which are input parameters for STAC2.1 [1, 2, 4, 8]. The following sections describe these methodologies.

Gaussian Model

The Gaussian model, illustrated in Fig. 1, describes, in three-dimensions, the theoretical path of a plume emerging from the stack: straight downwind, horizontally, and vertically [4]. These directions correspond, respectively on a coordinate system, to the *x*-axis, *y*-axis, and *z*-axis. This system illustrates the basic plume shape and centerline (bold, dashed line parallel to the *x*-axis) is seen in Fig. 2-1 [4]. "H" represents the effective stack height to the plume centerline, and "h" is the height of the stack. The path of the plume is detailed with the elliptical and Gaussian-like parabolic sketches to demonstrate three dimensional depths.

General Wind and Terrain Effects

Wind constitutes the horizontal motion of air as it passes a defined point; it is characterized by wind speed and direction. Wind speed is typically measured in miles per hour, but for the purposes of this research, it is either reported in feet per second or meters per second. Wind direction is described to be the direction *from where* the wind is blowing, *not* the direction the wind is blowing towards. In addition, it is measured in compass heading azimuth degrees, 0^o to 360^0, where the 0^o starts at the North axis and spans to 360^o clockwise around the compass [18]. Fig. 2-2 illustrates a northeasterly wind direction of ~45^o on a compass rose [11, 18].

Also applied, in relation to frictional (drag) effects on wind speed, is the approximated terrain category of the region, which affects the surface velocity profile applied from the ground to the stack emission point. For the University of Florida (UF) campus, the terrain is conservatively assumed to be urban. The comparison between urban, suburban, and rural, for the effects of different terrain structure on wind speed profiling, is shown in Fig. 2-3 [1, 4]. As surface roughness decreases, the depth of the affected atmospheric layer becomes shallower, and the wind speed profile gets steeper. The numbers reflected in the curves refer to average normalized percentages of the gradient wind at varying heights.

Concentration Equations

For distances straight downwind from the stack, the concentration of the Ar-41, at ground level, is calculated in Eq. 2-1 by using the listed parameters. The variables for Eq. 2-1 are: concentration of effluent (Ar-41) released (χ) in Ci/m^3, release rate (Q) in Ci/s, effective stack height (h) in m, average wind speed (u_s) in m/s, horizontal standard deviation for the crosswind straight downwind (x-value) from the stack ($\sigma_y(x)$) in meters, and vertical standard deviation for the crosswind straight downwind (x-value) from the stack ($\sigma_z(x)$) in meters.

$$\chi(x,0,0) = \frac{Q}{\pi\, u_s\, \sigma_y(x)\, \sigma_z(x)} \exp\left(-\left[\frac{h^2}{2(\sigma_z(x))^2}\right]\right) \tag{2-1}$$

To account for *off-center* lateral dispersion in both directions, downwind from the stack, Eq. 2-2 is applied. Note Eq. 2-1 does not account for lateral movement; all y-values are implicitly equal to 0.0.

$$\chi(x,y,0) = \frac{Q}{\pi\, u_s\, \sigma_y(x)\, \sigma_z(x)} \exp\left(-\left[\frac{h^2}{(\sigma_z(x))^2} + \frac{y^2}{2(\sigma_y(x))^2}\right]\right) \tag{2-2}$$

The effective stack height (h) is calculated, as a conservative buoyant plume, by adding the height of the plume centerline above the source emission point at the stack (h_p) to the height of physical effluent discharged at the stack (h_s) as in Eq. 2-3. All heights are measured in meters.

$$h = h_p + h_s \tag{2-3}$$

STAC2.1

STAC2.1 is a one wind effluent dispersion code based on the fundamental methodologies first proposed by Pasquill, et al [1-4]. This code was used to determine the down-wind concentrations of Ar-41 effluent from the UFTR, and is evaluated for this purpose in this work. In STAC2.1, the height of the plume centerline (SHDLTA) is computed using the information in Tables 2-1 and 2-2 as well as Eq. 2-3 – 2-13. Note that variables in parentheses refer to variables used in the STAC2.1 code. In addition, (SHDLTA) is considered to be h_p in Eq. 2-3.

Table 2-1 shows the information calculated in STAC2.1 pertaining to the height of the plume centerline. Table 2-2 describes the input variables, their descriptions, the values specific to the UFTR, and the references for each; metric units were used. Note that the specific heat of Ar-41 was assumed to be that of argon then air; concentration results did not differ when the specific heat was altered.

Input parameters describing the characteristics of Ar-41 were:

- specific heat (CPEFF)
- density ratio to dry air (EDF)
- plume type (HASUME)
- molecular weight (MOLWT)
- release rate (QSC)
- half-life (THALF)

The specific heat of Argon was used as an approximation of that for Ar-41 (Appendix A). The release rate, in the code, was assumed to be 1.0 Ci/s to determine the general factors for each weather condition.

Terrain, for regions surrounding the UFTR, is described by the terrain type (TERTYP) and altitude above sea level (ZALT). The geographical reference points are described by:

- Universal Transverse Mercator (UTM) global center reference points (XGLOB, YGLOB)
- maximum distance straight downwind (XMAX)
- maximum distance laterally from the centerline (YMAX)

- UTM stack reference point (XSTAK and YSTAK)
- incremental step straight downwind (XSTEP)
- incremental step laterally from the centerline (YSTEP)

Weather input data is:

- height of the weather sensor (SMEAS)
- ambient temperature (TAMB)
- time of day (TIMREL)
- mean ground wind speed (UGND)
- Pasquill's weather classes (WCAT)
- wind direction (WINDIR)

In addition, the stack of the UFTR is characterized by:

- inner diameter of the stack (DISTAK)
- height of the stack (SHSTAK)
- temperature at the stack (TSTAK)
- velocity of the effluent exiting the stack (VSTAK)

Eq. 2-4 is the simple calculation used to find the height of the plume centerline above the UFTR stack. Eq. 2-5 – 2-13 compute the necessary pieces for each of the other equations. These calculations rely heavily on atmospheric conditions (Pasquill's Stability Classes, UGND, or TAMB), effluent information (VSTAK, EDF, or FBOUY), and stack information (ASTAK or ZALT). The equations originate or are derived from accepted standards for atmospheric dispersion [1 – 4, 7].

$$\text{SHDLTA} = (1.5*\text{DISTAK}*\text{VSTAK} + \text{FBUOY}) / \text{USTAK} \qquad (2\text{-}4)$$

$$\text{FBUOY} = 4.0\ \text{x}10^{-5}*\text{QHEFF} \qquad (2\text{-}5)$$

$$\text{UWV} = \text{UGND} / (-4.141\text{x}10^{-10}*\text{SMEAS}^4 + 3.668\text{x}10^{-7}*\text{SMEAS}^3 - 1.115\text{x}10^{-4}*\text{SMEAS}^2 + 0.01470*\text{SMEAS} + 0.04573) \qquad (2\text{-}6)$$

$$\text{USTAK} = -4.141\ \text{x}10^{-10}*\text{UWV}*\text{SHSTAK}^4 + 3.668\text{x}10^{-7}*\text{SHSTAK}^3 - 1.115\text{x}10^{-4}*\text{SHSTAK}^2 + 0.01470*\text{SHSTAK} + 0.04573 \qquad (2\text{-}7)$$

$$\text{QHEFF} = (\text{SMDOT}*\text{CPEFF} * (\text{TSTAK} - \text{TAMB}))/4.184 \qquad (2\text{-}8)$$

$$\text{SMDOT} = \text{EDF}*\text{ADEN}*\text{VSTAK}*\text{ASTAK} \qquad (2\text{-}9)$$

$$\mathrm{ADEN} = 0.5 * (\mathrm{ADENT} + \mathrm{ADENHT}) \tag{2-10}$$

$$\mathrm{ASTAK} = \mathrm{PI} * (\mathrm{DISTAK}/2.0)^2 \tag{2-11}$$

$$\mathrm{ADENT} = 16.019 * (-2.8124\mathrm{x}10^{-4}*\mathrm{TAMB} + 8.0467\mathrm{x}10^{-2}) \tag{2-12}$$

$$\mathrm{ADENHT} = 1.2975 - 1.6404\mathrm{x}10^{-4}*\mathrm{ZALT} + 6.4583\mathrm{x}10^{-9}*\mathrm{ZALT}^2 - 1.0594\mathrm{x}10^{-13}*\mathrm{ZALT}^3 \tag{2-13}$$

Pasquill Stability Classes

Also necessary, for Eq. 2-1 and 2-2, to find the effluent concentration, are the crosswind standard deviations, $\sigma_y(x)$ and $\sigma_z(x)$. These are determined by the atmospheric stability classes created by Pasquill, where A is the most unstable condition, and F is the most stable. Stability is determined by the amount of solar radiation, wind speed, outside temperature, relative lapse rate (0.65 ^{o}C/100m for the UFTR), and the time of day [1, 2]. Characteristically, *unstable* is considered warm and sunny (daytime) while stable is cool and overcast (nighttime). Tables 2-3 and 2-4 describe, in detail, the characteristics for each class. Typically, classes A, B, and C represent daytime conditions, while D, E, and F refer to the nighttime.

The actual standard deviations arrive from using the equations in Table 2-5, which generate the curves in Fig. 2-4 and 2-5. These equations are derived by Briggs, from Pasquill's original graphs constructed from data strenuously gathered over time [1 – 4]. In general, the standard deviations increase in an exponential trend as distance from the stack increases. X-values are the actual distances straight downwind from the stack in any designated wind direction. Also, these apply to any relative concentration of effluent, Ar-41, released.

This chapter established the essential equations and approach used in the atmospheric concentration prediction code STAC2.1. The next discussion includes the validation methods employed for STAC2.1: manual and a comparison with a detailed physics treatment using CALPUFF.

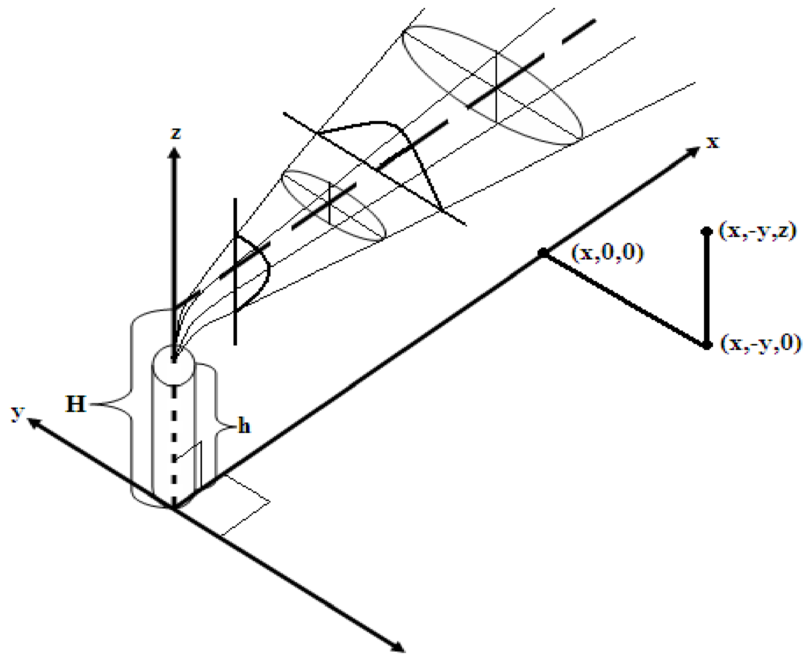

Figure 2-1 Coordinate System of Gaussian distributions straight downwind, horizontal, and vertical

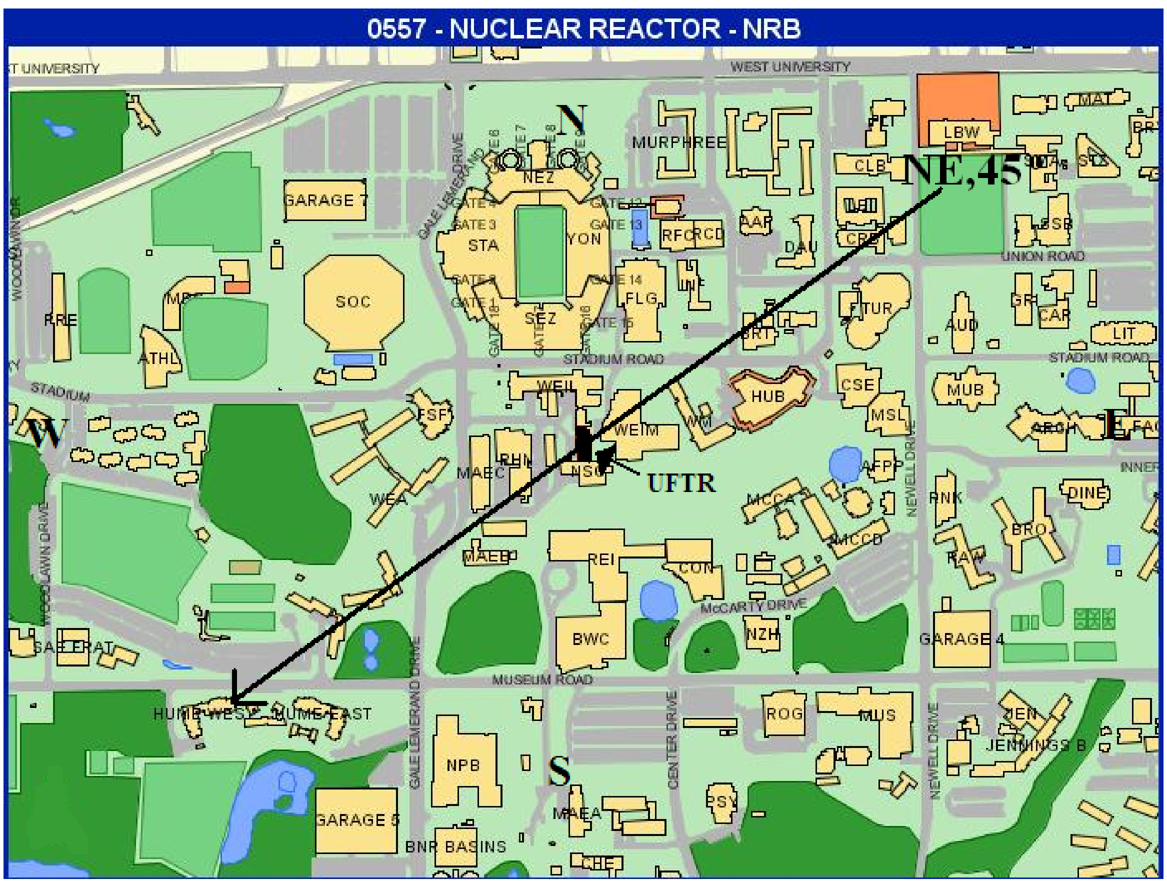

Figure 2-2 Northeasterly wind direction

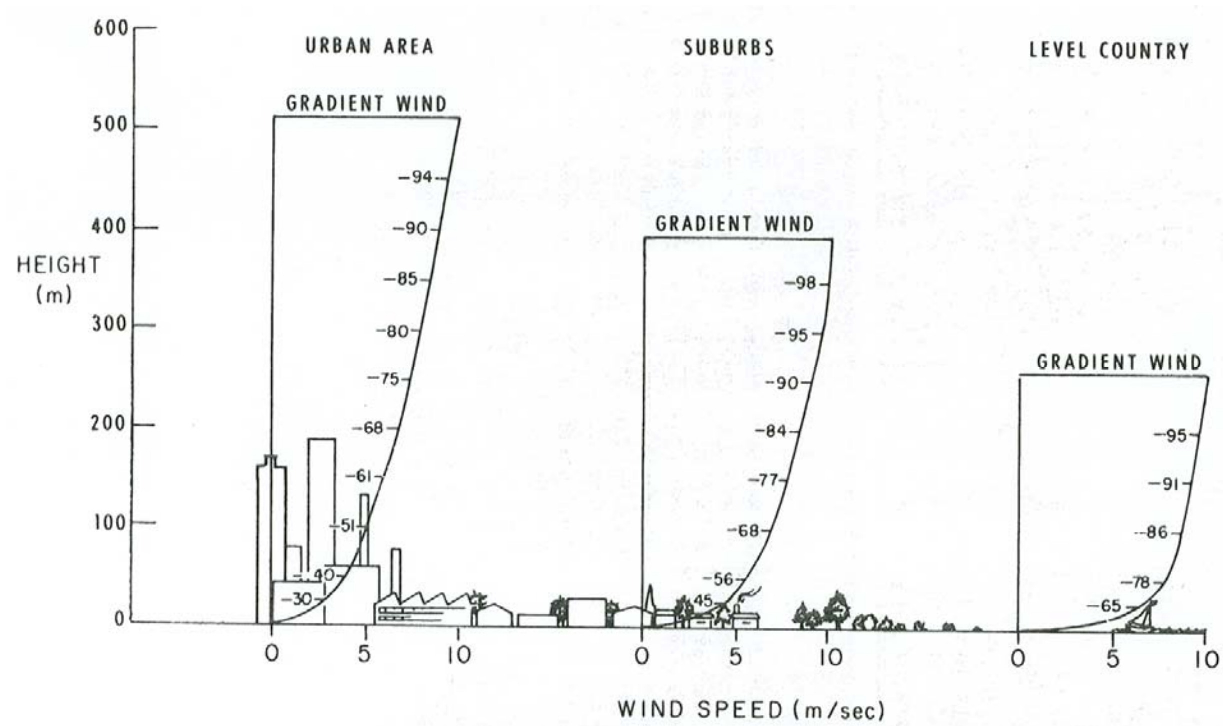

Figure 2-3 Effect of Terrain Roughness on the General Wind Speed Profile

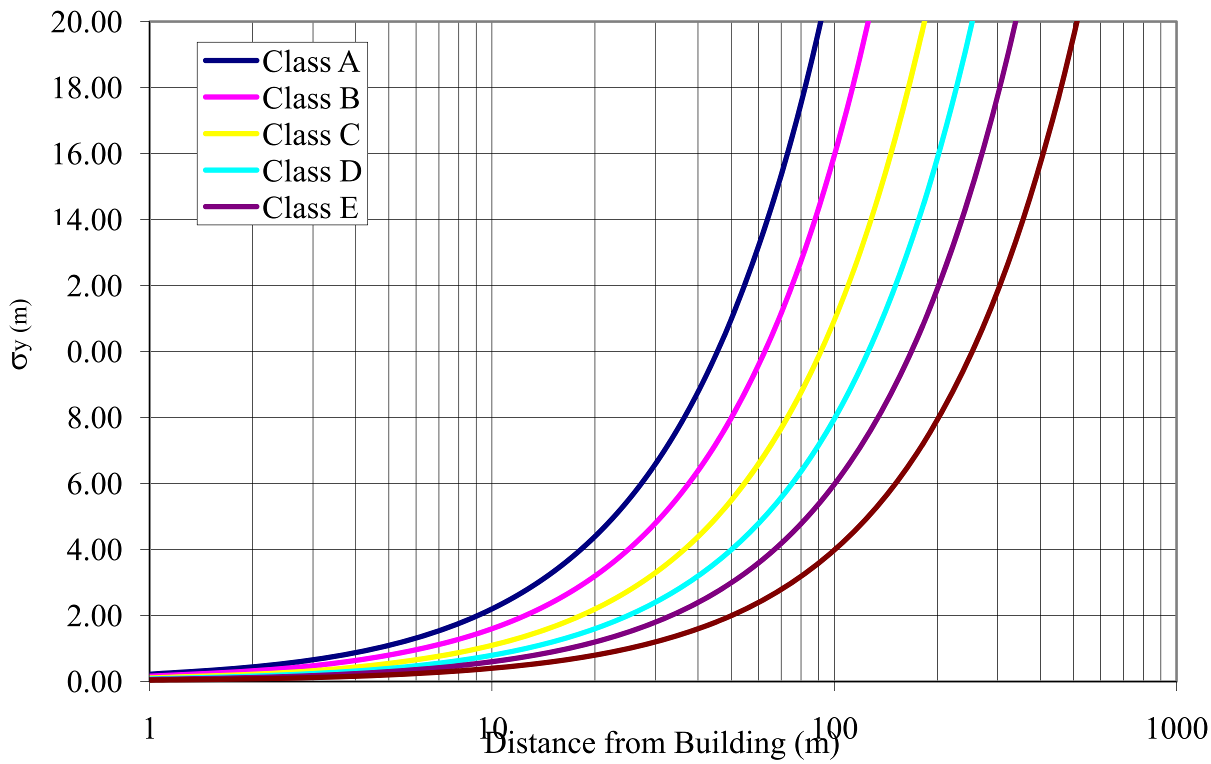

Figure 2-4 Distance from building vs. $\sigma_y(x)$ with results varying as Pasquill's stability classes

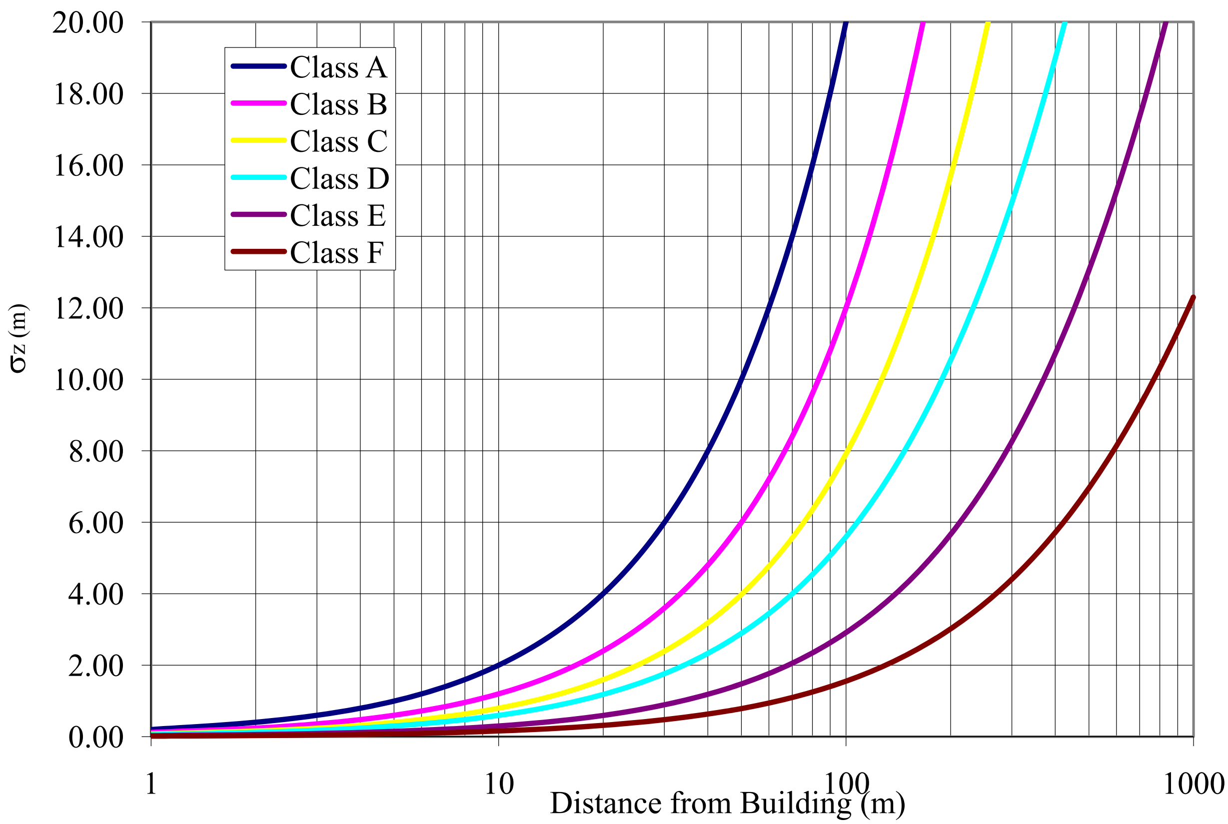

Figure 2-5 Distance from building vs. $\sigma_z(x)$ with results varying as Pasquill's stability classes

Table 2-1 STAC2.1 Variables for Height of the Plume Centerline Calculated in Code

Variables	Variable Descriptions
ADEN	Air density
ADENHT	Altitude, above sea level, for air density
ASTAK	Stack cross sectional area
FBOUY	Effluent buoyancy factor
QHEFF	Heat emission
SMDOT	Mass flow rate
SHEFF	Effective stack height (Eq. 2-3)
SHDLTA	Height of the plume centerline above the source
USTAK	Mean wind velocity at the stack
UWV	Upper maximum wind velocity

Table 2-2 STAC2.1 Code Input Variables and Values

Variables	Variable Descriptions	Values	Reference
CPEFF	Specific heat of effluent (Air =1004.83 J/kg-°C)	520 J/kg-°C	[1,19] Appendix A
DISTAK	Inner discharge diameter of stack	0.860 m	[20] Appendix A
EDF	Effluent density factor: ratio of effluent density to air density	1.4	[19] Appendix A

Table 2-2 Continued

Variables	Variable Descriptions	Values	Reference
HASUME	Plume type: Momentum jet (M), Buoyant plume (B), Conservative buoyant plume (C)	C	Assumed
MOLWT	Molecular weight of effluent	40.96 g/mol	[21]
QSC	Effluent release rate	1.0	Assumed
SMEAS	Height of the weather sensor	3.56 m	[9]
SHSTAK	Stack height	9.04 m	[20] Appendix A
TAMB	Ambient temperature	29.23 ^oC	[9]
TERTYP	Terrain type: Urban = 1, Suburban = 2, Level Country = 3	1	Assumed
THALFH	Effluent half life	1.83 hrs	[21]
TIMREL	Day or night conditions (determines velocity gradient)	D	Assumed
TSTAK	Temperature at the stack	29.23 ^oC	[9]
UGND	Mean ground wind speed	1.87 m/s	[9]
UNITS	Sets units to English or Metric Note that Ci can be substituted for g or lb.	M	Assumed
VSTAK	Vertical effluent velocity	12.81 m/s	[20] Appendix A
WCAT	Pasquill's Stability Classes: A (most unstable) through F (most stable)	A	Assumed
WINDIR	Wind direction (0^o – 360^o)	178.4 ^{o}	[9]
XGLOB	UTM Global reference center x-coordinate	17	Assumed
XMAX	Maximum distance straight downwind from stack	2501.0 m	Assumed
XSTAK	UTM Reference stack x-coordinate	0	Assumed
XSTEP	Incremental step straight downwind from stack	5.0 m	Assumed
YGLOB	UTM Global reference center y-coordinate	0	Assumed
YMAX	Maximum distance laterally from stack	301.0 m	Assumed
YSTAK	UTM Reference stack y-coordinate	0	Assumed
YSTEP	Incremental step laterally from stack	100 m	Assumed
ZALT	Altitude, above sea level, of modeled location	41.76 m	[22]

Table 2-3 Pasquill Weather Condition Categories

Category	Typical Conditions	Weather Descriptions	Wind m/s	Wind Direction – Stand. Dev.
A	Extremely Unstable	Very Sunny Summer	1	+- 25 deg
B	Moderately Unstable	Sunny and Warm	2	+- 20 deg
C	Slightly Unstable	Average Daytime	5	+- 15 deg
D	Neutral Stability	Overcast Day/Night	5	+- 10 deg
E	Slightly Stable	Average Nighttime	3	+- 5 deg
F	Moderately Stable	Clear Nighttime	2	+- 3 deg

These Tables describe the Pasquill Stability Classes used in the STAC2.1 Program: acquired from Pasquill's Atmospheric Diffusion [2]

Table 2-4 Pasquill's Relations to Weather Categories

Surface Wind	Day Solar Radiation			Night Cloudiness		Lapse Rate	
Speed m/s	Strong	Moderate	Slight	>=50%	<=50%	Deg C(F)/100m	
<2	A	A-B	B	--	--	A-B	-1.9(-3.5)
2	A-B	B	C	E	F	B-C	-1.8(-3.3)
4	B	B-C	C	D	E	C-D	-1.6(-2.9)
6	C	C	D	D	D	D-E	-1.0(-1.8)
>6	C	C	D	D	D	E-F	>0.5(>0.9)

These Tables describe the Pasquill Stability Classes used in the STAC2.1 Program: acquired from Pasquill's *Atmospheric Diffusion* [2]

Table 2-5 Briggs Derived Formulas for Standard Deviations of Horizontal ($\sigma_y(x)$) and Vertical ($\sigma_z(x)$) Crosswinds Based on Pasquill's Stability Classes

Stability Class	σ_y, meters	σ_z, meters
A	$0.22\ x\ (1 + 0.0001x)^{-1/2}$	$0.20\ x$
B	$0.16\ x\ (1 + 0.0001x)^{-1/2}$	$0.12\ x$
C	$0.11\ x\ (1 + 0.0001x)^{-1/2}$	$0.08\ x\ (1 + 0.0002x)^{-1/2}$
D	$0.08\ x\ (1 + 0.0001x)^{-1/2}$	$0.06\ x\ (1 + 0.0015x)^{-1/2}$
E	$0.06\ x\ (1 + 0.0001x)^{-1/2}$	$0.03\ x\ (1 + 0.0003x)^{-1}$
F	$0.04\ x\ (1 + 0.0001x)^{-1/2}$	$0.016\ x\ (1 + 0.0003x)^{-1}$

CHAPTER 3
VALIDATION OF STAC2.1 RESULTS: MANUALLY AND USING CALPUFF

With the essentials of the STAC2.1 code presented in Chapter 2, how STAC2.1 was applied to the case of the UFTR is presented here. Because STAC2.1 is an in-house code, a manual method validation and an independent validation of results were accomplished using the CALPUFF suite. This was completed by comparing results to those from the CALPUFF package. The following sections described the UFTR Ar-41 release rate, the manual validation method, and details of the CALPUFF package, and results comparison between STAC2.1 and the two validation methods.

Release Rate Calculation

The release rate, specific to the UFTR at full power, was calculated to be 9.228 x10^{-5} Ci/s ($\dot{R}$). The details of this release source term are depicted in Eq. 3-1 – 3-3 [1, 2, 4, 20, 23, 24]. Additional parameters in these equations, relative to the UFTR reactor, are: the undiluted volumetric release rate of Ar-41 from the reactor at 100kW (full power) (8.147 x10^{-4} Ci/m^3), the total stack flow rate for Ar-41 from the core vent and dilution fan ($\dot{f}$) (15772 ft^3/min or 7.44 m^3/s), the dilution factor (Λ) from the dilution fan and core vent (dimensionless) (0.0152168), and the flow diluted release concentration at the top of the stack (ψ = 1.24x10^{-5} Ci/m^3) [23, 24]. The fan flow rate value was determined as a result of the most recent service to the dilution fan. This dilution factor (Λ) takes into account that Ar-41 comes from the core (reactor) via the core vent, which is then dispersed by both the core vent and the dilution fan [23, 24].

$$\Lambda = \frac{\text{Core Vent Flow Rate} \ \frac{ft^3}{min}}{\dot{f} \ \frac{ft^3}{min}} \tag{3-1}$$

$$\dot{R}\ \frac{Ci}{s} = \psi\ \frac{Ci}{m^3} * \dot{f}\ \frac{m^3}{s} \tag{3-2}$$

$$\psi \frac{\text{Ci}}{\text{m}^3} = 8.147 \times 10^{-4} \frac{\text{Ci}}{\text{m}^3} * \Lambda \tag{3-3}$$

In STAC2.1, a unity source (1.0 Ci/s) was used to calculate general maximum multipliers (M) for straight downwind from the stack. Final maximum concentrations of Ar-41 (C), from STAC2.1, were calculated by multiplying these general concentrations by the specific release rate, 9.228×10^{-5} Ci/s; as shown in Eq. 3-4.

$$C = M * 9.228 \times 10^{-5} \tag{3-4}$$

Manual Validation Method

A manual validation of STAC2.1 was performed. Selected calculations were verified, independently, manually, as shown in Table 3.1. Tabulated values for $\sigma_y(x)$ and $\sigma_z(x)$, atmospheric conditions for Gainesville, Fl, and the stack height and release rate for the UFTR were applied to Eq. 2-2 for the hand calculation. Concentrations were compared for various ground level distances from the UFTR versus those computed using STAC2.1 for the year between July 2004 and July 2005, assuming extremely unstable conditions.

Note that the temperature of the effluent was assumed to be the same as the average ambient temperature; 23.05^{o}C. The average daytime wind azimuth direction for the year was a vector from 167.11^{o}, and the average ground wind speed was 2.42 m/s. In addition, the effective stack height and wind speed at the stack were calculated [1, 4], then assumed to be the same for each of the three trials. The effective stack height was calculated from Eq. 2-3 and 2-4, and the wind speed at the stack was from Eq. 2-6 and 2-7. Lastly, for daytime conditions, the Pasquill stability class was assumed to A.

As shown in the last row of Table 3.1, the differences in concentration as determined using tabular manual values and STAC2.1 code runs was less than 3.61% within 500m, and less than 0.77% within 100m downwind of the stack. To explain the differences, the manual computations do not account for all of the physics (buoyant plume rise with temperature, decay at time of arrival, etc), and are less robust than used in the STAC2.1 calculations [7].

Note that all percent differences, from Table 3.1 and in future, were calculated from the general formula shown in Eq. 3-5. For Table 3.1, the theoretical value was considered to be the manual term, and the experimental value was from STAC2.1.

$$\% \text{Difference} = \frac{\text{Experimental Value} - \text{Theoretical Value}}{\text{Theoretical Value}} * 100 \tag{3-5}$$

CALPUFF and Related Programs

CALPUFF and its related programs are an EPA approved generalized non-steady-state air quality modeling system; the main two related programs are CALMET and CALPOST. Note that the package does include many pre-processors for interfacing standard, readily-available meteorological data [24, 25]. Originally, CALPUFF and CALMET were developed by the California Air Resources Board, and then were updated to satisfy the Interagency Workgroup on Air Quality Modeling (IWAQM), EPA, United States Department of Agriculture (USDA) Forest Service, Environmental Protection Authority of Victoria (Australia), and private industry in both the United States and abroad [25]. The order of execution of the three main programs is: CALMET, CALPUFF, and then CALPOST.

CALMET is the initial, main portion of the modeling system. It is a meteorological model which develops hourly temperature and wind data in a three-dimensional domain. Two-dimensional fields of surface characteristics, mixing heights, and dispersion properties are also included [25, 26]. Two necessary input files into CALMET are: geo.dat and surf.dat. Geo.dat contains all of the land use and corresponding elevation data, in a gridded format. Surf.dat contains the surface weather data, for various weather stations.

CALPUFF is a transport and dispersion modeling program for concentration and effluent spread prediction over complicated terrain while accounting for atmospheric effects from CALMET (sole input file) [25]. The transport and dispersion is simulated using puffs or slugs. Puffs are circular, Gaussian mappings of effluent concentrations, while slugs are elongations of these puffs using Lagrangian and Gaussian methods. CALPUFF produces hourly concentrations or deposition fluxes at selected receptor locations. CALPOST processes these hourly concentrations into tabulations of the highest and second highest 3-hour averages for each receptor [25].

CALPUFF Package Model for STAC2.1 Comparison

A CALPUFF package input deck was fashioned to model the case of atmospheric transport of Ar-41 from the UFTR. Four cases were designed using combinations of two wind extrapolation theories from CALMET (Similarity Theory and Power Law) mixed with the two effluent transport and dispersion options from CALPUFF (puff and slug).

General characteristics throughout the model were: 24 hour run time, a 17 x 17 grid, a grid spacing of 0.05 km, and six vertical layers in the atmosphere. In addition, all elevation and coordinates pertinent to the UFTR were obtained from the Magellan Explorist 300 handheld global positioning system receiver. The following information was employed in gathering this data, and then input into the CALMET and CALPUFF input files: a datum based on WGS-84, zone 17, Eastern Time zone, and a UTM projection in the northern hemisphere. The latitude and longitude gathered was an easting of 369.530 km and a northing of 3280.494 km. The elevation was ~41.76 m at the northeast corner of the UFTR. The following two sections describe additional pertinent details in CALMET and CALPUFF files.

CALMET Details

In the CALMET input files, general assumptions were made regarding terrain and weather conditions. Although the UF campus in Gainesville, FL does not have perfectly flat terrain, it is also not completely urban. Therefore, the assumption of flat terrain with an urban landscape is a near approximation accounting for the slightly sloping landscape with buildings of varying heights around the UFTR. The assumption of no overwater effects is made since no large bodies of water are within about a kilometer of the stack and the maximum concentrations in the spread of effluent are less than a kilometer from the stack as well.

CALMET's geo.dat input file (Appendix B) contained the terrain and land use data in 17 x 17 grids. All land use values were assumed to be 10 (urban or built up land); Appendix C contains the land use table from the CALMET manual [26]. The elevation levels were all set to 41.76 m above sea level, which was the estimated altitude of UFTR.

The surf.dat input file for CALMET contained the weather data and was designed for a warm summer day. All of the weather data in surf.dat was averaged, as described in Table 3.2, for input into STAC2.1.

In the four models for the STAC2.1 comparison, the surface wind observations were varied between two extrapolation methods: similarity theory and power law. Similarity theory extends the influences of wind speed and direction from the surface to the upper layers. The wind speed ($U(z)$) is expressed using inverse Monin-Obukhov length ($1/L$), roughness length (z_o), anemometer height (z_1), atmospheric stability function (ψ_m), and measured wind speed at the anemometer height ($U(z_1)$) as depicted in Eq. 3-6. For further explanation, refer to the CALMET manual p. 2-12 – 2-14 [26].

$$U(z) = U(z_1)\left(\frac{\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)}{\ln\left(\frac{z_1}{z_o}\right) - \psi_m\left(\frac{z_1}{L}\right)}\right) \tag{3-6}$$

The Power law approach is a more simple method of adjusting the wind using existing wind and height measurements as a function of a power as shown in Eq. 3-7. Variables are the adjusted wind (u_z), the measured wind value (z_m), measured height of the measured wind observation (u_m), and the midpoint of the CALMET grid option (z).

$$u_z = u_m * \left(\frac{z}{z_m}\right)^{0.143} \tag{3-7}$$

CALPUFF Details

Three main characteristics, focused on in CALPUFF, were: puff versus slug option, addition of Ar-41 to the species section, and input of the UFTR stack parameters. As mentioned before, the puff and slug models were mixed with the similarity theory and power-law for the comparison.

Ar-41 was input as a dry deposited gas; the characteristic values are described in Table 3.3 [25, 27, 28]. The diffusivity of Ar-41 through air is described by Eq. 3-8, which include temperature in Kelvin (T), molecular weights of the species in g/mol (M), molecular volume in cm^3/g-mol ($\tilde{V}$), pressure in atm (P), and the gas constant in atm-cm^3/g-mol-K (R) [27]. Alpha star, reactivity (non-radioactive reference), and mesophyll resistance were assumed to be similar to low values of other species such as SO_2 [25]. The Henry’s Law constant for Ar-41 was assumed to be similar to that of argon [28].

$$D = 1.8\,x10^{-4}\,\frac{\sqrt{T}}{\left(\sqrt{\tilde{V}_{Ar41}} + \sqrt{\tilde{V}_{Air}}\right)^2} * \frac{M_{Ar41}\,P}{R\,T}\sqrt{\frac{1}{M_{Ar41}} + \frac{1}{M_{Air}}} \tag{3-8}$$

The stack information for CALPUFF is illustrated in Table 3.4, and matches that of the UFTR [1 – 4, 19, 24].

As described above, four CALPUFF package models were created with these four combinations of wind extrapolation methods and effluent transport and dispersion theory: similarity theory and puff dispersion, similarity theory and slug dispersion, power law and puff dispersion, and power law and slug dispersion. Results of the comparison with STAC 2.1 are described in the next section.

STAC2.1 and CALPUFF Results Comparison

Four CALPUFF models were created using summer weather conditions (Table 3.2), details for the UFTR stack, Ar-41 characteristics, a flat, uniform terrain associated with Gainesville, FL, no over water effects, and using an urban wind model. The four studies included combinations of the transport dispersion models (puff and slug) with two different wind extrapolation methods (power law and similarity theory). The four model combinations were: puff and similarity theory, puff and power law, slug and similarity theory, and slug and power law. A STAC2.1 model was created to match the average weather conditions, flat terrain, and urban model, as well as the UFTR and Ar-41 parameters used in CALPUFF, and then compared to each of the four cases. The results of this comparison are given in Tables 3.5 and 3.6.

Maximum concentrations computed using STAC2.1 and CALPUFF software models were compared for each of the cases. It was found that the relative *distance* where the maximum concentration occurred varied as much as 31% different between the two models. The distance of the maximum concentration was identical in all four CALPUFF models. The maximum concentrations differed from between ~19 and 31%, depending on whether a puff or slug model, or wind extrapolation power law or similarity theory was employed. STAC2.1 results most closely matched the slug, power law model. Comparisons between concentrations for the same distances differed between the codes by ~1 to 6 %.

The best model relative to a comparison with STAC2.1 is the CALPUFF slug and wind extrapolation power law model which resulted in a percent difference of ~-19%. This illustrates that STAC2.1 yields conservative results, by ~19%, and creates an upper bound for Ar-41 full-power peak ground concentrations straight down-wind from the UFTR.

The validation methods and corresponding results from comparing STAC2.1 to a manual method as well as a comparing it with the CALPUFF package was described above. Chapter 4 describes the results from STAC2.1 for concentrations, dose rates, and other pertinent calculations for the UFTR. Note that STAC2.1 values are always greater than CALPUFF results therefore STAC2.1 yields conservative results by ~19%.

Table 3-1 Urban Pasquill Class A Ground Level Concentration of Ar-41 Manual Calculation vs. STAC2.1 Results at Various Distances from the UFTR (July 2004 – July 2005)

Parameters	Trial 1	Trial 2	Trial 3
Distance from building (m)	50	100	500
σ_y (m)	10.97	21.89	107.35
σ_z (m)	10.00	20.00	100.00
Manual Concentration: (Ci/m^3)	3.15×10^{-8}	1.39×10^{-8}	6.81×10^{-10}
STAC2.1 Multiplier	3.39×10^{-4}	1.50×10^{-4}	7.11×10^{-6}
STAC2.1 Concentration (Ci/m^3)	3.13×10^{-8}	1.38×10^{-8}	6.56×10^{-10}
% Difference: STAC2.1 vs. Manual	-0.70%	-0.77%	-3.61%

Table 3-2 Average weather conditions from CALMET test case for STAC2.1 use

Time of Year	Wind Speed (m/s)	Direction (Deg)	Temp (K)	Temp (C)
Summer	3.87	188.91	301.86	28.86

Table 3-3 Characteristics of Ar-41 as input in CALPUFF

Species	Diffusivity cm^2/s	Alpha Star N/A	Reactivity N/A	Mesophyll Resistance s/cm	Henry's Law Dimensionless
Ar-41	0.1535	1	0	0	3.425×10^{-2}

Table 3-4 CALPUFF Stack Parameter Input

Parameter	Value
Source Number	1
X Coordinate (km)	369.530
Y Coordinate (km)	3280.494
Stack Height (m)	9.04
Base Elevation (m)	41.76
Stack Diameter (m)	0.86
Exit Velocity (m/s)	12.81
Exit Temperature (K)	302.1
Building Downwash	0
Emission Rates (Ci/s)	1.0×10^{0}
Sigma y	0.22
Sigma z	0.2

Table 3-5 STAC 2.1 and CALPUFF Comparison with a Puff Model

Models	Similarity Theory			Power Law		
	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)
STAC2.1 (Maximum)	1.83×10^{-8}	30.71	103	1.83×10^{-8}	19.61	103
STAC2.1	1.49×10^{-8}	6.43	79	1.49×10^{-8}	-2.61	79
CALPUFF (Maximum)	1.40×10^{-8}	N/A	79	1.53×10^{-8}	N/A	79

Table 3-6 STAC 2.1 and CALPUFF Comparison with a Slug Model

Models	Similarity Theory			Power Law		
	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)
STAC2.1 (Maximum)	1.83×10^{-8}	23.65	103	1.83×10^{-8}	18.83	103
STAC2.1	1.49×10^{-8}	0.68	79	1.49×10^{-8}	-3.25	79
CALPUFF (Maximum)	1.48×10^{-8}	N/A	79	1.54×10^{-8}	N/A	79

CHAPTER 4
STAC2.1 RESULTS

Previously, the program methodology, theory, and validation for both STAC 2.1 and CALPUFF were discussed. The Gaussian modeling feature of CALPUFF was used to validate the simple STAC2.1 one-wind, Gaussian model. Results are described below.

STAC2.1 was used to calculate conservative concentrations. Remember that the highest daytime concentrations, closest to the stack, occur for Pasquill class A, the most unstable condition. In addition, for class "C", while the concentrations are lower over-all, the continuous, full-power concentrations remain above the limit further away from the stack. To ascertain the Ar-41 concentrations for the UFTR, while accounting for atmospheric influences, local weather condition measurements were acquired from the local conditions recorded daily by the Department of Physics Weather Station [2, 4]. The information in Tables 4.1 and 4.2 are the average temperatures, wind directions, wind speeds, and Pasquill Classes attributed for yearly periods between July 2004 and July 2005 surrounding the UF campus. Table 4.1 contains daytime, 7am – 7pm, results, while Table 4.2 has the nighttime, 8pm – 6am, information.

Concentrations

The full-power peak Ar-41 concentrations released, for each set of individual data, using possible different population and Pasquill Class combinations, as well as the distance from the building where these peaks occur, are illustrated in Table 4.3. Stability classes A, B, and C are used for daytime, while the F stability class is used for nighttime. Note that highlighted concentrations reflect the average daytime stability classes for each time period; the average nighttime stability class (F) is the only nighttime category shown. Concentrations, for each time period averaged Pasquill Class, are illustrated in Fig. 4-1.

Dose Rates

The total effective dose equivalent limit for Ar-41 is 50 mrem per year at a maximum concentration of 1.00×10^{-8} Ci/m^3, inhaled or ingested continuously over a year [29]. Dose rate is linearly related to Ar-41 concentration as shown in Eq. 4-1. Maximum full-power dose rates and corresponding concentrations, for the quarterly and yearly Pasquill Class averages, are shown in Table 4.4. The full-power dose rate trends, for each average Pasquill Class for each time period, is illustrated in Fig. 4-2.

$$\text{Dose}\,\frac{\text{mrem}}{\text{yr}} = \chi\,\frac{\text{Ci}}{\text{m}^3} * \frac{50\,\text{mrem}}{1.00\,\text{x}10^{-8}\,\frac{\text{Ci}}{\text{m}^3}} \tag{4-1}$$

Table 4.5 shows possible limiting case scenario full-power concentrations and doses for several buildings near the UFTR based on a continuous operation concentration with dedicated winds using the April 2005 – July 2005 data. The wind directions were assumed to vector to each building.

Operation Hours

Peak, full-power concentrations show that when the UFTR is assumed to operate at 100% power for 24 hours per day, then the allowable maximum concentrations and doses of Ar-41 for dedicated wind directions exceed 1.00×10^{-8} Ci/m^3 and 50 mrem/yr. This implies that a “reactor duty cycle” must be applied to bring the monthly average concentration of Ar-41 below the maximum allowable concentrations.

Using the calculated peak, full-power concentrations of Ar-41, the UFTR Effective Full Power Hours (EFPH), are shown in Table 4.6 for daytime conditions, since daytime is when the reactor is most likely to be run. In considering the peak concentrations, this will decrease limit exceeding concentrations to below 1.00×10^{-8} Ci/m^3 [16, 29]. EFPH are calculated using Eq. 4-2 [20, 23, 24]. Ar-41 concentrations (χ) are in Ci/m^3. For units of kW-hours month or kW-hours/week, multiply by 100kW. The 720 hours/month is standard assuming 24 hours/day, 7 days/ week, and ~4.286 wk/month [20]. Note that the EFPH limit based on license requirements is 235.00 hours/month or 55.56 hours/week [20].

$$\mathrm{EFPH}\,\frac{\mathrm{hrs}}{\mathrm{mo}} = \frac{1.00\,\mathrm{x}10^{-8}\ \frac{\mathrm{Ci}}{\mathrm{m}^3}}{\chi\ \frac{\mathrm{Ci}}{\mathrm{m}^3}} * 720\ \frac{\mathrm{hrs}}{\mathrm{mo}} \tag{4-2}$$

Therefore, on average, to remain below the annual limit of 1.00x10^{-8}Ci/m3, the UFTR may be run up ~307 hours/month at full power for the year, with a restriction of running up to ~240 hours/month during the late spring and summer months. Since the additional restriction is 235.00 hours/month, the UFTR may be run up 235.00 hours/month (55.56 hours/week) all year long. This is a significant increase from the current EFPH for the UFTR of ~116 hours/month [20].

Dilution Factors

The flow diluted release concentration of Ar-41 (ψ) at the top of the stack, before being affected by the environment, is approximately 1.24x10^{-5} Ci/m^3 from Eq. 3-3. Dilution factors are calculated by dividing concentrations in question by 1.24x10^{-5} Ci/m^3, shown in Eq. 4-3. Table 4.7 shows the dilution factors for the site boundary, the distance where maximum concentration occurs, and the distance where the closest residence housing is located (East Hall at 190m). The concentrations were calculated using the limiting case conditions for April 2005 – July 2005, with a wind direction towards East Hall (80$^{\mathrm{o}}$).

$$\mathrm{Dilution\,Factor} = \frac{\chi\ \frac{\mathrm{Ci}}{\mathrm{m}^3}}{1.24\,\mathrm{x}10^{-5}\ \frac{\mathrm{Ci}}{\mathrm{m}^3}} \tag{4-3}$$

Consider that the dilution ratio for the maximum concentration (415:1) is also the maximum case instantaneous release concentration from the UFTR stack. The dilution ratio, currently used by the UFTR, is 200:1 [16]. Note that 200:1 is extremely conservative compared to the computed value of 415:1 based on results from STAC2.1.

Table 4.8 illustrates the difference between the two ratios using the concentration calculated from the UFTR SOP ($6.20x10^{-8}$ Ci/m^3) [20, 23, 24], and the maximum concentration as determined by STAC2.1. It is shown that the 200:1 ratio is approximately 2.07 times more conservative than the 415:1 ratio.

Stack Height Comparison

A study was conducted to determine whether or not the physical stack height could be raised to increase atmospheric dilution and decrease the peak concentration of Ar-41 from the UFTR to below the limits of $1.00x10^{-8}$ Ci/m3 and 50 mrem/yr. This was relevant in consideration of eliminating the requirement to limit how long the UFTR may be operated per month. Weather conditions from April 2005 – July 2005 were applied in these models, using a wind direction of 80^o pointed towards East Hall (the closest student residence hall). These weather conditions represented a limiting scenario with the highest overall concentrations and dose rates.

The following heights were initially modeled for a general comparison: 8.00 m, 9.04 m, 10.00 m, 15.00 m, 20.00 m, and 25.00 m. Table 4.9 shows the peak, full-power concentrations and dose rates for each stack height modeled. Between 15.00 m and 20.00 m, the concentrations and dose rates dip below the limits. Fig. 4-3 and 4-4 illustrate the concentration and dose rate distributions, respectively, for each stack height model.

Additional models were completed at stack heights of 16.00 m, 16.50 m, 17.00 m, and 18.08 m in order to determine a stack height which will yield full-power concentrations and doses below the limits without limiting operations hours. Table 4.10 shows the maximum, full-power concentrations and dose rates, and Fig. 4-5 and 4-6 depict the concentration and dose rate distributions respectively. From these comparisons, any stack height above 16.50 m will yield concentrations and dose rates below the limits. Conservatively, the stack height may be doubled from 9.04 m to 18.08 m, for operation 24 hours per day, 7 days a week.

Results from STAC2.1 were described in this chapter for full-power concentrations, corresponding dose rates, and other pertinent calculations for the UFTR. This was based on theory and validations covered in previous chapters. The next discussion covers the final summary and conclusions of this work.

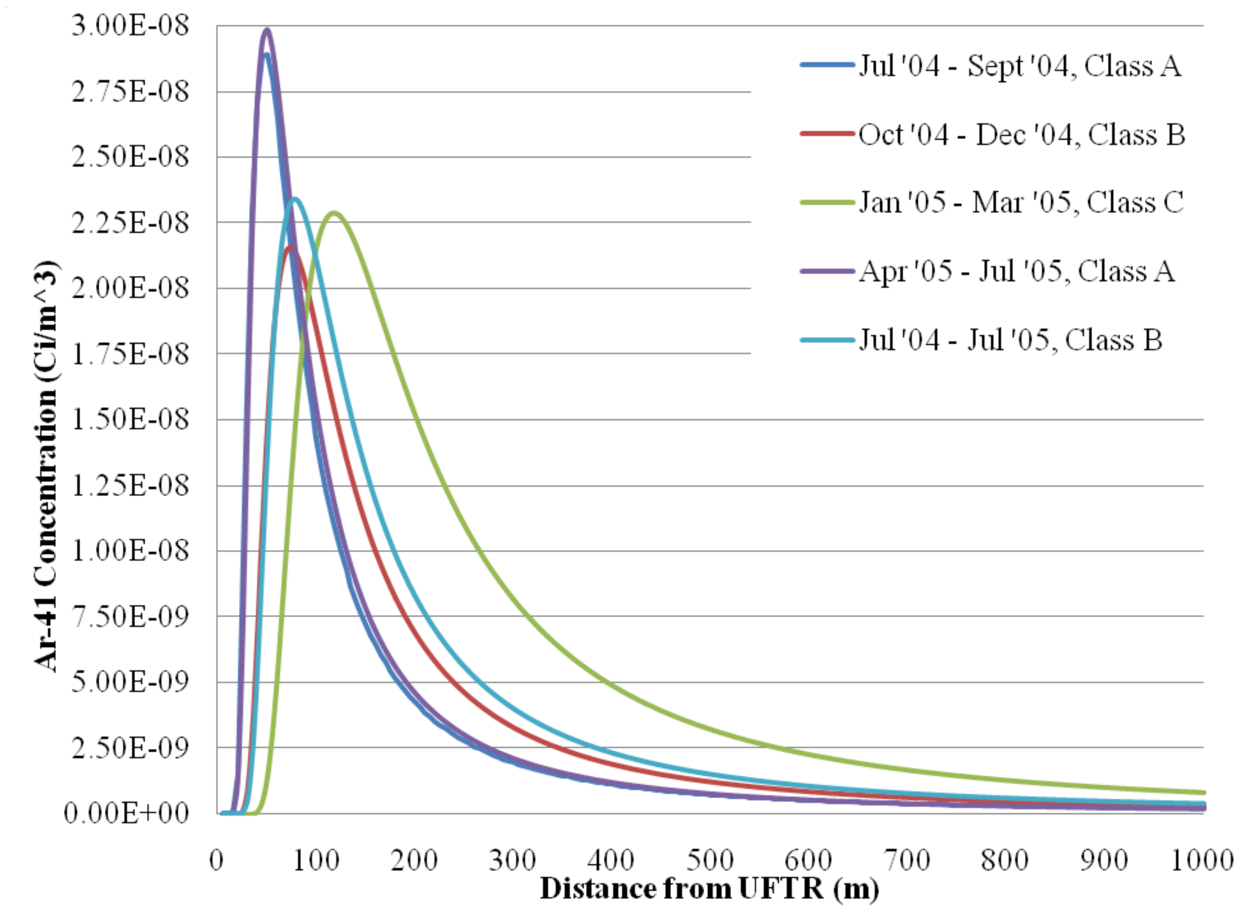

Figure 4-1 Ground Peak Concentrations (Ci/m^3) and Distance (m) from the UFTR for Average Pasquill Classes for each Time Period

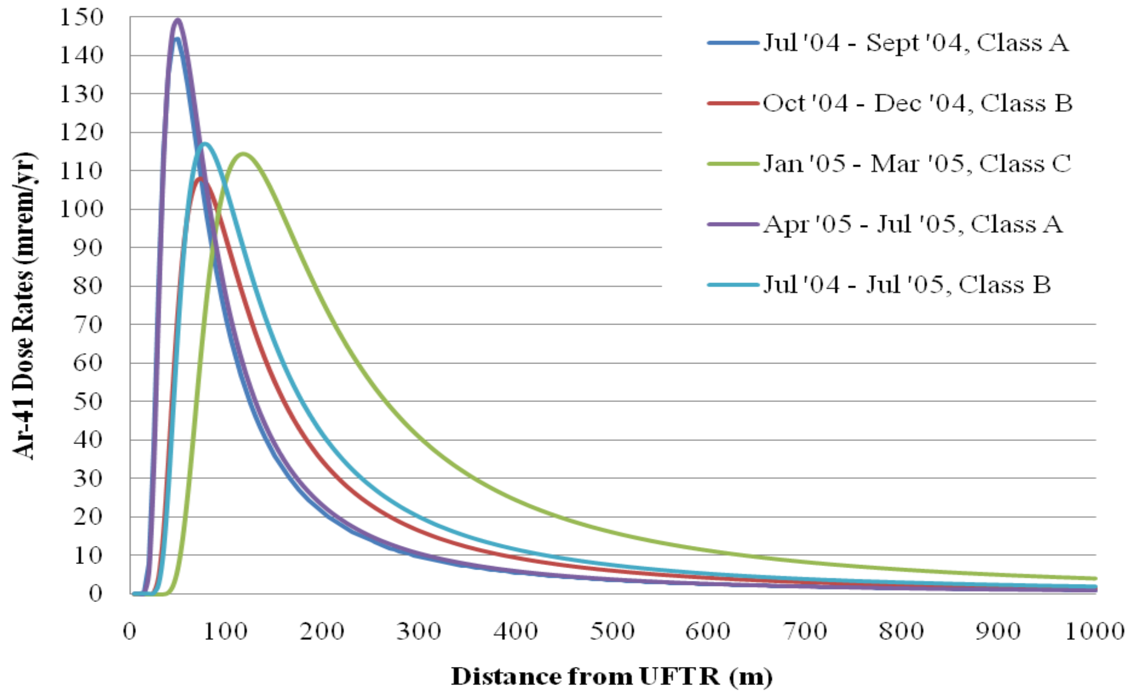

Figure 4-2 Dose Rates (mrem/yr) and Distance (m) from the UFTR for Average Pasquill Classes for each Time Period

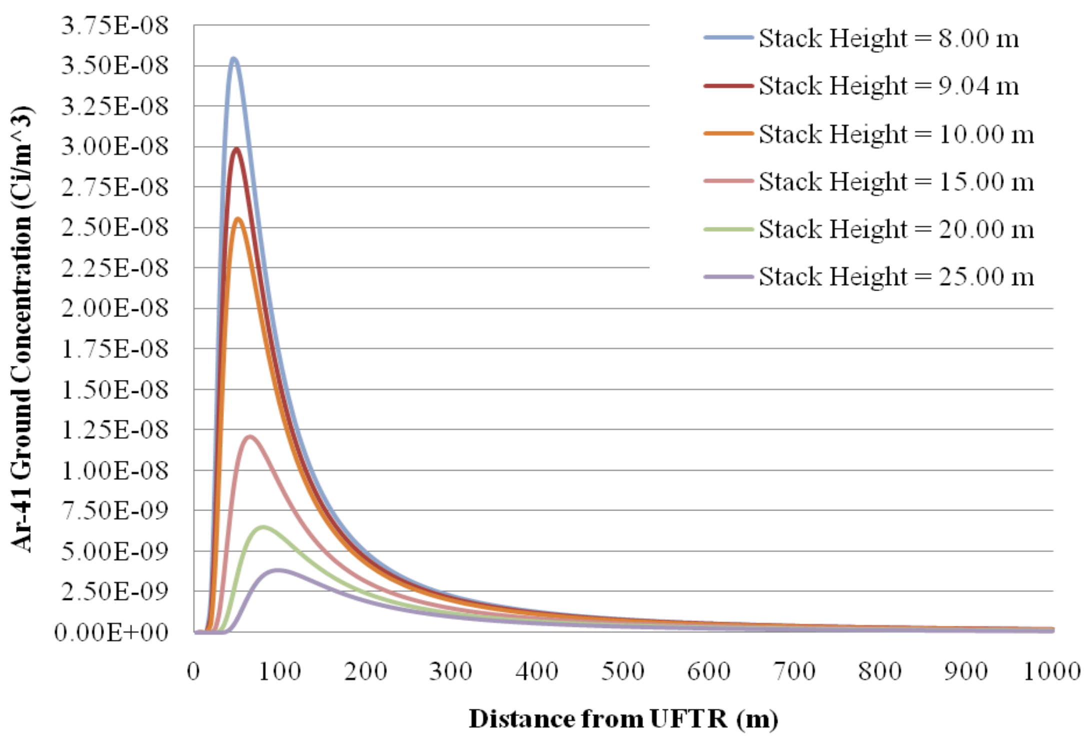

Figure 4-3 Ar-41 Ground Concentrations (Ci/m^3) and Distance (m) from the UFTR for Various Stack Heights

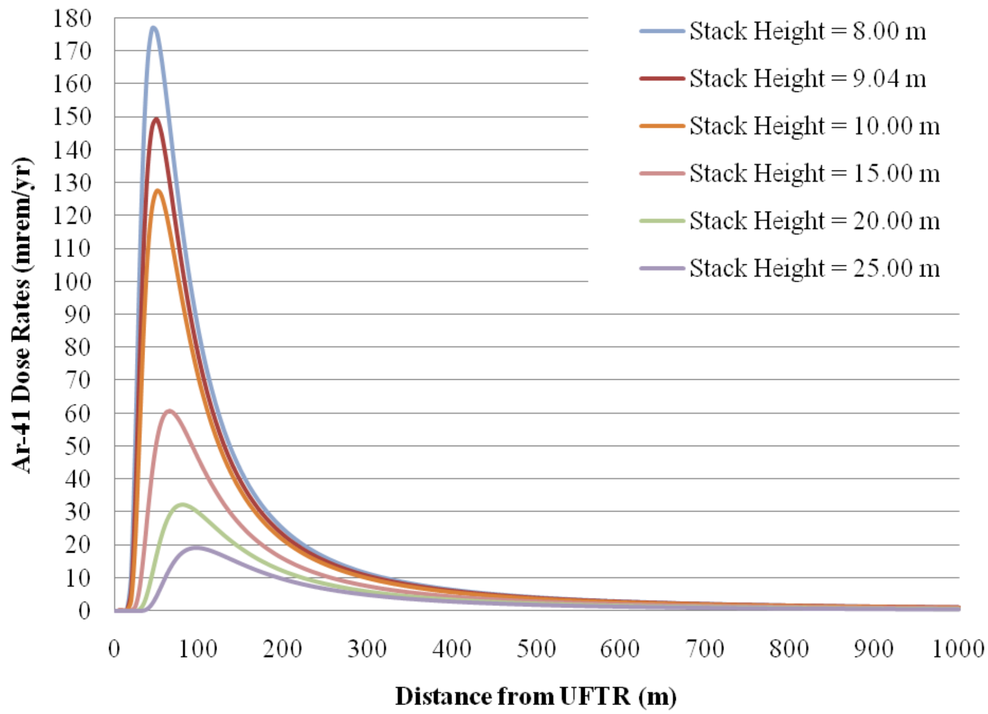

Figure 4-4 Ar-41 Dose Rates (mrem/yr) and Distance (m) from the UFTR for Various Stack Heights

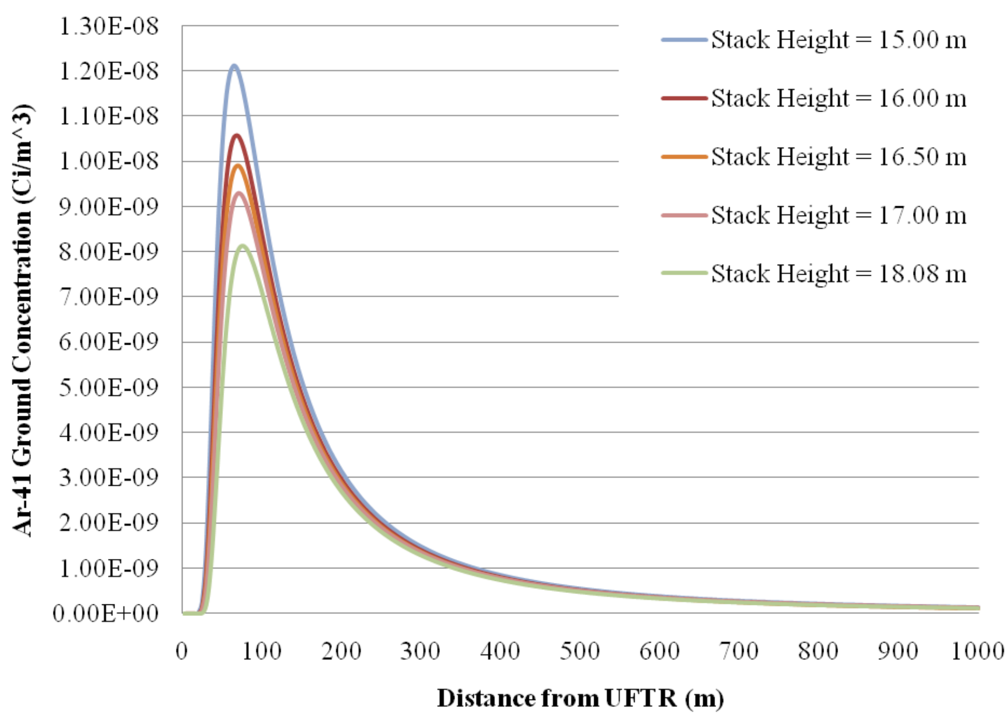

Figure 4-5 Ar-41 Ground Concentrations (Ci/m^3) and Distance (m) from the UFTR for Stack Heights around the Concentration Limit (1.00x10-8 Ci/m^3)

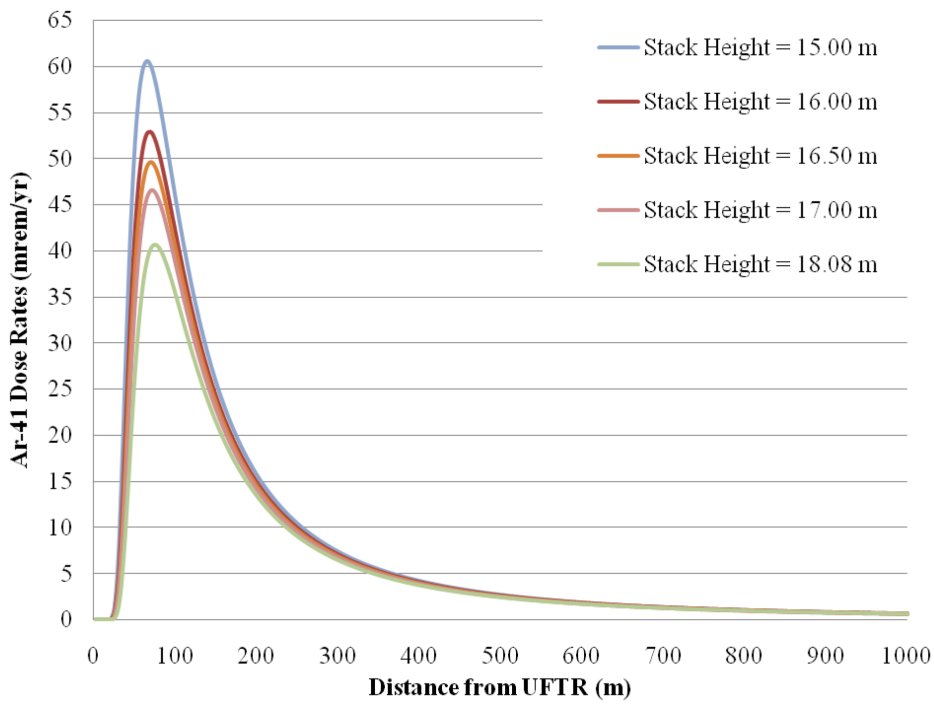

Figure 4-6 Ar-41 Dose Rates (mrem/yr) and Distance (m) from the UFTR for Stack Heights around the Concentration Limit ($1.00x10^{-8}$ Ci/m^3)

Table 4-1 Daytime Monthly, Quarterly, & Yearly Atmospheric Averages

Monthly Quarters, & Year	Temperature F	Temperature C	Wind Direction Degrees	Wind Speed mph	Wind Speed m/s	Pasquill Classes
Jul ‘04-Sept ‘04	83.38	28.54	160.77	5.09	2.28	A
Oct ‘04-Dec ‘04	69.21	20.67	143.81	6.63	2.96	B
Jan ‘05-Mar ‘05	63.73	17.63	182.61	5.31	2.37	C
Apr ‘05-Jul ‘05	77.63	25.35	181.25	4.66	2.08	A
Jul ‘04-Jul ‘05	73.49	23.05	167.11	5.42	2.42	B

Table 4-2 Nighttime Monthly, Quarterly, & Yearly Atmospheric Averages

Monthly Quarters, & Year	Temperature F	Temperature C	Wind Direction Degrees	Wind Speed mph	Wind Speed m/s	Pasquill Classes
Jul ‘04-Sept ‘04	77.89	25.50	158.09	3.10	1.39	F
Oct ‘04-Dec ‘04	62.94	17.19	134.13	2.47	1.10	F
Jan ‘05-Mar ‘05	57.34	14.08	183.31	3.31	1.48	F
Apr ‘05-Jul ‘05	70.90	21.61	166.16	2.66	1.19	F
Jul ‘04-Jul ‘05	67.27	19.59	160.42	2.89	1.29	F

Table 4-3 Urban Ground Peak Ar-41 Concentrations (Ci/m^3) and Distance (m) from the UFTR

Stability Classes	Jul04-Sep04 Ci/m^3	m	Oct04-Dec04 Ci/m^3	m	Jan05-Mar05 Ci/m^3	m	April05-Jul05 Ci/m^3	m	Jul04-Jul05 Ci/m^3	m
A	$2.89x10^{-8}$	50	$2.62x10^{-8}$	44	$2.86x10^{-8}$	47	$2.99x10^{-8}$	50	$2.83x10^{-8}$	45
B	$2.39x10^{-8}$	79	$2.16x10^{-8}$	75	$2.36x10^{-8}$	78	$2.46x10^{-8}$	82	$2.34x10^{-8}$	80
C	$2.32x10^{-8}$	119	$2.09x10^{-8}$	111	$2.28x10^{-8}$	120	$2.39x10^{-8}$	123	$2.27x10^{-8}$	115
F	$1.09x10^{-8}$	775	$1.08x10^{-8}$	865	$1.08x10^{-8}$	750	$1.09x10^{-8}$	835	$1.09x10^{-8}$	800

Table 4-4 Total Effective Dose Rate and Maximum Concentration Values for the Monthly and Yearly Averages for 2004-2005, Assuming Full-Power Continuous Operation

Monthly Quarters, & Year	Day Pasquill Classes	Max Conc. & Dist. from UFTR Ci/m^3	m	Total Effective Dose Rate mrem/year
Jul '04-Sept '04	A	2.89×10^{-8}	50	145
Oct '04-Dec '04	B	2.16×10^{-8}	75	108
Jan '05-Mar '05	C	2.28×10^{-8}	120	114
Apr '05-Jul '05	A	2.99×10^{-8}	50	150
Jul '04-Jul '05	B	2.34×10^{-8}	80	117

Table 4-5 Total Effective Dose Rate and Peak Concentrations for Buildings near the UFTR, Assuming Full-Power, Continuous Operation

Buildings on Campus	~Distance from UFTR (m)	~Wind Direction (deg)	Max. Conc. (Ci/m^3)	Dose (mrem/yr)
Reed Lab. (RLA)	20	180	7.14×10^{-10}	4
Weimer Hall (WEIM)	40	265	2.65×10^{-8}	133
Weil Hall (WEIL) Main Eng.	63	170	2.89×10^{-8}	145
Rhines Hall (RHN) Mat. Sci.	91	80	1.96×10^{-8}	98
Reitz Student Union (REI)	133	0	1.09×10^{-8}	55
Mech.& Aerospace Eng. C (MAEC)	137	80	1.03×10^{-8}	52
Mat. Eng. (MAE)	160	40	7.87×10^{-9}	39
East Hall (EAS) (Closest Housing)	190	80	5.75×10^{-9}	29
Gator Corner Dining (FSF)	183	95	6.16×10^{-9}	31
Mech. & Aerospace Eng. B (MAEB)	200	40	5.22×10^{-9}	26
North Hall (NOR) Housing	229	93	4.04×10^{-9}	20
Ben Hill Griffin Stadium (STA) Football	250	170	3.42×10^{-9}	17
Weaver Hall (WEA) Housing	251	80	3.39×10^{-9}	17
Riker Hall (RIK) Housing	274	85	2.86×10^{-9}	14
Van Fleet Hall (VAN) ROTC	298	110	2.43×10^{-9}	12
Tolbert Hall (TOL) Housing	309	93	2.27×10^{-9}	11
Graham Hall Housing (GRA)	320	50	2.12×10^{-9}	11
O'Connell Center (SOC) Swim & Sports	331	125	1.98×10^{-9}	10
Carse Swim/ Dive (SWIM) Athletics	343	115	1.85×10^{-9}	9
Trusler Hall (TRU) Housing	411	50	1.29×10^{-9}	6
Simpson Hall (SIM) Housing	417	55	1.26×10^{-9}	6
Parking Garage VII (OCONNEL)	463	135	1.02×10^{-9}	5

Table 4-6 UFTR Hours of Operation Based on Peak Ar-41 Concentrations (Ci/m^3) for Daytime Atmospheric Conditions

Monthly Quarters, & Year	Day Pasquill Classes	Max. Conc. & Dist. from UFTR Ci/m^3	m	EFPH hrs/mo	kW-hrs/mo	hrs/wk	kW-hrs/wk
Jul '04-Sept '04	A	2.89×10^{-8}	50	249.13	24913.49	58.90	5889.72
Oct '04-Dec '04	B	2.16×10^{-8}	75	333.33	33333.33	78.80	7880.22

Table 4-6 Continued

Monthly Quarters, & Year	Day Pasquill Classes	Max. Conc. & Dist. from UFTR Ci/m^3	m	EFPH hrs/mo	kW-hrs/mo	hrs/wk	kW-hrs/wk
Jan '05-Mar '05	C	2.28×10^{-8}	120	315.79	31578.95	74.65	7465.47
Apr '05-Jul '05	A	2.99×10^{-8}	50	240.80	24080.27	56.93	5692.73
Jul '04-Jul '05	B	2.34×10^{-8}	80	307.69	30769.23	72.74	7274.05

Table 4-7 Dilution Ratios based on Concentrations and Relevant Campus Locations

Campus Relevance	Distance from UFTR m	Concentration Ci/m^3	Dilution Ratio (Value:1)
UFTR Site Boundary	30	1.48×10^{-8}	838
Maximum Concentration	50	2.99×10^{-8}	415
East Hall (Closest Dorm)	190	5.75×10^{-9}	2157

Table 4-8 Dilution Ratio Comparison

Location	Concentration (Ci/m^3)	Dilution Ratio (Top of stack: Other)	Difference Ratio (STAC2.1:SOP)
UFTR SOP (Using 200:1)	6.20×10^{-8}	200	2.07
Maximum Concentration	2.99×10^{-8}	415	

Table 4-9 Maximum Concentrations, Dose Rates, and Corresponding Distances from the UFTR per Stack Height

Stack Height m	Distance from UFTR m	Maximum Concentration Ci/m3	Maximum Dose Rate mrem/year
8.00	45	3.54×10^{-8}	177
9.04	50	2.99×10^{-8}	149
10.00	50	2.55×10^{-8}	128
15.00	65	1.21×10^{-8}	61
20.00	80	6.49×10^{-9}	32
25.00	97	3.84×10^{-9}	19

Table 4-10 Maximum Concentrations, Dose Rates and, Corresponding Distances from the UFTR per Stack Height

Stack Height M	Distance from UFTR m	Maximum Concentration Ci/m3	Maximum Dose Rate mrem/year
15.00	65	1.21E-08	61
16.00	70	1.06E-08	53
16.50	70	9.93E-09	50
17.00	70	9.30E-09	47
18.08	75	8.14E-09	41

CHAPTER 5
SUMMARY AND CONCLUSIONS

Results Summary and Conclusions

In summary, University of Florida (UF) researchers performed a detailed assessment of the Ar-41 concentration and dose generated by operation of the University of Florida Training Reactor (UFTR) for relicensing requirements for the NRC (Appendix D). Specifically, yearly maximum predicted concentrations, dose rates, operational limits, and dilution factors were calculated for the UFTR with impact assessments assuming dedicated wind directions to nearby campus buildings at 100% full power (100kW). In addition, a stack height study was conducted to determine the height necessary to reduce the Ar-41 concentration without limiting operation times. Note that the total effective dose equivalent limit for Ar-41 is 50 mrem per year at a maximum concentration of $1.00\text{x}10^{-8}$ Ci/m^3, inhaled or ingested continuously over a year.

A Gaussian plume model based code, STAC2.1, developed and benchmarked by UF researchers, was employed to calculate the maximum concentrations and corresponding distances. Average daytime atmospheric conditions for UF (2004-2005), UFTR discharge stack parameters, and Ar-41 characteristics were established as input parameters for the code. Manual Pasquill plume calculations and detailed CALPUFF computations were used to successfully validate STAC2.1 results. The percent differences from the manual method ranged from 0.70 to 3.61%, and the percent differences from CALPUFF models aliased using STAC2.1 were within ~-19%. In addition, since the STAC2.1 results are greater than those from CALPUFF, it can be concluded that STAC2.1 results are conservative and yield an upper bound for the full-power peak concentrations of Ar-41 straight down-wind from the UFTR.

Based on the available data and results from STAC2.1, the *average* yearly maximum, down-wind, assuming 100% full power Ar-41 concentration for the UFTR was 2.34 $\text{x}10^{-8}$ Ci/m^3

at 80m (117 mrem/yr), while the highest full power concentration (April 2005 – July 2005) was 2.99×10^{-8} Ci/m^3 at 50m (150 mrem/yr). Note this assumes continuous full power operation, and the highest maximum concentration was used as the limiting value for all other calculations in determining reactor operational constraints so as to be in compliance with the mean dose of 50 mrem/year.

Concerning the buildings on campus, only buildings within ~150m of the UFTR could experience concentrations and dose rates greater than the limits if the reactor were continuously operated at full power; this included Weimer Hall (2.65×10^{-8} Ci/m^3), Weil Hall (2.89×10^{-8} Ci/m^3), Rhines Hall (1.96×10^{-8} Ci/m^3), Reitz Student Union (1.09×10^{-8} Ci/m^3), and the Mechanical and Aerospace Engineering C building (1.03×10^{-8} Ci/m^3). The student residence hall closest to the UFTR, East Hall, located 190m away, had both the concentration and dose rate below the annual full operation limit: 5.75×10^{-9} Ci/m^3. In order to reduce the maximum concentrations (and corresponding doses) to acceptable limits, the number of allowable full power hours of operation per month was calculated. The allowable number of hours, averaged for the year, was ~307 hours/month, with a further restriction during the summer of ~240 full power hours/month. Therefore, based on an additional license restriction of 235.00 hours/month, from Ar-41 emissions, the UFTR may be run up 235.00 hours/month (55.56 hours/week) all year long during the daylight hours. This is a significant increase from the current EFPH for the UFTR of ~116 hours/month [24]. In addition, since nighttime concentrations and resultant doses are lower than for daytime, the reactor may be run 48 hours/week continuously without exceeding limit requirements; ~7 hour/week would still be available as well.

Based on an analysis of the STAC2.1 results, the estimated 200:1 ratio, used in the UFTR standard operational procedures established for the past 50 years, was ~2 times more conservative than the calculated ~415:1 dilution ratio.

Finally, several models were evaluated with varying stack heights to see the effects on Ar-41 concentrations and dose; fan speeds were kept constant. Initially stack heights of 8.00m, 9.04m (current stack height), 10.00m, 15.00, 20.00, and 25.00m were modeled. The results showed that between 15.00m and 20.00m the concentration dropped below the limit. Further models at 15.00m, 16.00m, 16.50m, 17.00m, and 18.08m were performed. Results indicated that increasing the stack height from the current height of 9.04 m to effluent discharge levels greater than ~16.50 m would yield continuous peak full-power Ar-41 concentrations below the limit of 1.00×10^{-8} Ci/m^3 anywhere on campus.

All results and analyses were used for the NRC re-licensing of the UFTR. Further work could be done to add to the depth of this thesis; several ideas are described in the next section.

Possible Future Works

Future comparisons with STAC2.1, involving CALPUFF, could be performed. One idea is to consider a wider variation of terrain and weather conditions to gain additional understanding of these model effects in CALPUFF. Note that if flat terrain data is criticized then one would need detailed detection point on a street canyon basis. Some additional concepts pertaining to CALPUFF which may be explored are: using high resolution datasets, more detailed inspection of the wind vector results, and a more precise one day, one-wind model created in CALMET. Another concept is linking CALMET data with Pennsylvania State University / National Center for Atmospheric Research mesoscale model (MM5) [25, 26, 30] or the Weather Research and Forecasting model (WRF) [31, 32] for comparison with STAC2.1. All of these possible comparisons entail looking at the accuracy of the one-wind model and the locations of the concentrations as the Ar-41 plume spreads away from the UFTR.

Other programs, such as COMPLY, may be used to model the UFTR and be compared to the results from STAC2.1 and CALPUFF. COMPLY is another EPA approved model [12].

In addition, further analyses of Ar-41 concentrations and necessary modifications for a possible UFTR power upgrade from 100kW to 500kW may be considered. A multi-faceted study was performed as part of another effort. It included two modifications for reducing Ar-41 concentrations emitted at the higher power: adding neutron absorbing shields on the north and south sides of the UFTR (where the least graphite and concrete shielding are present), and increasing the stack height to at least 40 m [33]. For this stack height comparison, additional vertical analysis of upper floors of the atmosphere, regarding Pasquill stability classes in STAC2.1 may need to be considered.

APPENDIX A
STAC2.1 INPUT VARIABLE CALCULATIONS

Ratio of Densities

Ar-41 density at room temperature at STP: 40.96 g/mol*1mol/22.4L =1.8286 g/l = 1.8286 kg/m^3

Assuming constant volume, and using Ideal gas laws:

$$\frac{\rho_1 T_1}{P_1} = \frac{\rho_2 T_2}{P_2} \tag{A-1}$$

$$\rho_2 = \frac{\rho_1 T_1 P_2}{T_2 P_1} \tag{A-2}$$

$$\rho_2 = \frac{\left(1.8286 \frac{\mathrm{kg}}{\mathrm{m}^3}\right)(273\,\mathrm{K})(100\,\mathrm{kPa})}{(298\,\mathrm{K})(101.325\,\mathrm{kPa})} \tag{A-3}$$

Ar-41 density: 1.653 kg/m^3

Air density: 1.169 kg/m^3

$$\text{Ratio} = \frac{\left(1.653 \ \frac{\text{kg}}{\text{m}^3}\right)}{\left(1.169 \ \frac{\text{kg}}{\text{m}^3}\right)} = 1.4 \qquad \text{(A-4)}$$

Specific Heat

Assumed the specific heat of Ar-41 is approximated by the specific heat of Argon (520 J/kg-^{o}C).

Inner Diameter of Stack Calculation

Length of square stack side: 2 ft 6 in = 0.762m

Standard Deviation: 0.25in = 0.0064m

Measured area of rectangular stack opening: 6.35 ft^2 = 0.581m^2

Conversion to circular dimensions: $A = \pi r^2$ = 0.581m^2

Radius is: 0.430m

Diameter is: 0.860m

Height of the Stack

The height was measured from inside the stack opening to the floor of the stack.

Stack height: 29 ft 8 in = 29.67 ft = 9.04m

Efflux velocity from Stack

Total volumetric flow rate (core vent + dilution fan): 15772 ft^3/min = 7.4436 m^3/s

$$\text{Air Flow Velocity} = \frac{\text{Volumetric Flow Rate}}{\text{Cross} - \text{sectional Area of Stack Opening}} = \frac{7.4436 \ \frac{\text{m}^3}{\text{s}}}{0.581 \ \text{m}^2} = 12.81 \ \frac{\text{m}}{\text{s}} \qquad \text{(A-5)}$$

APPENDIX B

GEO.DAT FILE FOR CALMET INPUT

```
GEO.DAT         2.0             Header structure with coordinate parameters
   2
Produced by MAKEGEO Version: 2.2  Level: 030402
simplified GEO.DAT for use with test case
UTM
  17N
WGS-84   10-10-2002
     17      17     369.530    3280.494       0.050       0.050
KM  M
0          - LAND USE DATA - (0 = default categories)
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
    1.00000    -- Terrain heights - HTFAC - conversion to meters
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76   41.76
   41.76   41.76   41.76   41.76   41.76   41.76   41.76
```

41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			
41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76	41.76
41.76	41.76	41.76	41.76	41.76	41.76	41.76			

0 - default z0 field
0 - default albedo field
0 - default Bowen ratio field
0 - default soil heat flux parameters
0 - default anthropogenic heat flux field
0 - default leaf area index field

APPENDIX C
LANDUSE TABLE FOR GEO.DAT FILE FOR CALMET INPUT

Land Use Type	Description	Surface Roughness (m)	Albedo	Bowen Ratio	Soil Heat Flux Parameter	Anthropogenic Heat Flux (W/m^2)	Leaf Area Index
10	Urban or Built-up Land	1.0	0.18	1.5	.25	0.0	0.2
20	Agricultural Land - Unirrigated	0.25	0.15	1.0	.15	0.0	3.0
-20*	Agricultural Land - Irrigated	0.25	0.15	0.5	.15	0.0	3.0
30	Rangeland	0.05	0.25	1.0	.15	0.0	0.5
40	Forest Land	1.0	0.10	1.0	.15	0.0	7.0
51	Small Water Body	0.001	0.10	0.0	1.0	0.0	0.0
54	Bays and Estuaries	0.001	0.10	0.0	1.0	0.0	0.0
55	Large Water Body	0.001	0.10	0.0	1.0	0.0	0.0
60	Wetland	1.0	0.10	0.5	.25	0.0	2.0
61	Forested Wetland	1.0	0.1	0.5	0.25	0.0	2.0
62	Nonforested Wetland	0.2	0.1	0.1	0.25	0.0	1.0
70	Barren Land	0.05	0.30	1.0	.15	0.0	0.05
80	Tundra	.20	0.30	0.5	.15	0.0	0.0
90	Perennial Snow or Ice	.20	0.70	0.5	.15	0.0	0.0

* Negative values indicate "irrigated" land use

[26]

APPENDIX D
APPENDIX SUBMITTED TO THE NRC: APPENDIX E

By
V.S. Cornelison and G. E. Sjoden
Nuclear and Radiological Engineering Department, University of Florida

Introduction

Atmospheric plume dispersion modeling, integrating atmospheric statistical dynamics, diffusion, and meteorological data may be applied to achieve an estimate of the downwind concentration of Ar-41 effluent released during steady state operation of the University of Florida Training Reactor (UFTR). The atmospheric modeling approach utilized to determine effluent levels is based on the methods constructed by Pasquill and further expounded upon by Briggs and Turner [1 – 4], with related methodologies applied in US Atomic Energy Commission studies [34]. We note that these methods have been adopted and used as a basis for methodologies adopted by the Environmental Protection Agency, Federal Coordinator of Meteorology, and the American Society for Mechanical Engineers [1, 4, 6, 8].

Wind direction and atmospheric conditions such as temperature, solar radiation, and wind speed distinctly affect the path of effluents dispersed from an exhaust stack [1 – 4, 7]. The specific time of day versus night conditions are important, due to environmental changes in the lapse rate from the combined effects of heating and cloud cover. These varying conditions, along with the accepted mathematical models, allow the concentration of Ar-41 to be conservatively estimated with a simple one-wind, Gaussian computer code employing proper model physics: STAC2 (Version 2.1) Build 1.5b (hereafter referred to as 'STAC2.1') [8]. Note that while wind speed and temperature specifically affect effluent concentration, wind direction simply determines the vector location along which the effluent flows. The basis of STAC2.1 is a Gaussian plume model. The Gaussian model, illustrated in Figure D-1, describes, in three-dimensions, the theoretical path of a plume emerging from the stack: straight downwind, horizontally, and vertically [4]. These directions correspond, respectively to a coordinate system along the x-axis (parallel to the wind vector), y-axis, and z-axis. Figure D-1 illustrates the basic plume and plume centerline (bold, dashed line parallel to the x-axis). The “H” in the figure represents the effective stack height relative to the plume centerline, and “h” is the physical height of the stack. The profile of the plume is detailed with the elliptical and parabolic sketches to demonstrate three dimensional depths.

In addition, frictional (drag) effects on wind speed can be approximated using a terrain category typical of the region where the atmospheric transport is occurring. For the University of Florida campus, the terrain is assumed to be urban with a flat landscape. The comparison between urban, suburban, and rural, to capture specific effects of different terrain on wind speed profiles, is shown in Figure D-2 [1, 4]. As surface roughness decreases, the depth of the affected atmospheric layer becomes more shallow, and the wind speed profile becomes steeper. The numbers reflected in the curves refer to normalized percentages of the wind gradient at various heights.

The UFTR, an Argonaut design, produces Ar-41 by neutron activation in the course of operations. This effluent is discharged from the air handling equipment from the exhaust stack adjacent to the reactor building. The limiting parameter for the operating duty cycle of the UFTR is the concentration of Ar-41; monthly concentration averages in uncontrolled spaces for Ar-41 must not exceed 1.00E-8 Ci/m^3 (note: 1 Ci/m^3 = 1μCi/mL), at 100% reactor power, per state and federal guidelines (10CFR20) [16, 17]. The UFTR is in close proximity to many building structures on the Florida campus, including the Ben Hill Griffin Football Stadium, other engineering departments, parking garages, and students' residence halls. The closest student residence hall, East Hall, is located approximately 190m west-southwest of the UFTR.

Calculation Theory Implemented in STAC2.1: Gauss, Pasquill, and Briggs

The Ar-41 concentrations, emitted from the UFTR stack, are calculated based on standard ASME effluent diffusion equations and Pasquill stability classes determined from atmospheric conditions, which are cast as input parameters for STAC2.1 [1, 2, 4, 8]. The principal governing equation for the determination of down-wind ground concentration is given in Eq. (1), with variables cast as: concentration of effluent (Ar-41) released (χ) in Ci/m^3, release rate (Q) in Ci/s, effective stack height (h) in m, average wind speed (u_s) in m/s, horizontal standard dispersion coefficient ($\sigma_y = \sigma_y(x)$) as a function of (x) distance from the stack in meters, vertical dispersion coefficient ($\sigma_z = \sigma_z(x)$) as a function of distance from the stack in meters, and horizontal shift from the centerline (y) in m. As can be seen by inspection of Eq. (1), the maximum predicted ground (z=0) concentrations occur immediately downwind from the stack, where there is no horizontal shift (y = 0).

$$\chi(x,y) = \frac{Q}{\pi\sigma_y(x)\sigma_z(x)u_s}\exp\left\{-\left[\frac{h^2}{2\sigma_z(x)^2}+\frac{y^2}{2\sigma_y(x)^2}\right]\right\} \qquad (1)$$

An "effective" stack height (h), in meters, is calculated, using a conservative buoyant plume estimate, and is the height of the plume centerline above the source accounting for the rise of the physical effluent discharged at the stack. The height of the plume centerline is computed by STAC2.1, while the height of the physical stack is an input parameter. The crosswind dispersion coefficients, σ_y and σ_z are determined by the atmospheric stability classes ("A" through "F") and were originally created by Pasquill, where "A" is the most *unstable* condition, and "F" is the most *stable*.

Relative "stability" is determined by the amount of solar radiation, wind speed, outside temperature, relative lapse rate (0.65 ^{o}C/100m for the case of the UFTR), and the effluent release time of day (day or night) [1, 2]. Characteristically, "unstable" is considered warm and sunny (daytime), while "stable" is cool and overcast (nighttime). Table D-1 describes, in general, the characteristics attributed to each class.

In addition, with regard to the effluent (Ar-41), STAC 2.1 takes into account the half-life, density ratio to air, specific heat of the bulk effluent, and the molecular weight (for ppt-v determinations, if required). In addition, STAC2.1 accounts for general terrain altitude as a tunable parameter for density corrections.

Validation of STAC2.1 Results both "By-Hand" and using CALPUFF

The release rate, specific to the UFTR, was calculated to be 9.228 E-5 Ci/s ( ). The details of this release source term are depicted in Eq. (2) – (4) [1, 2, 4, 11, 20, 24]. Additional parameters in these equations, relative to the UFTR reactor, are: the undiluted release rate of Ar-41 from the reactor at 100kW (full power) (8.147 E-4 Ci/m^3), the total stack flow rate for Ar-41 from the core vent and dilution fan ($\dot{f}$) (15772 ft^3/min or 7.444 m^3/s), the dilution factor (Λ) from the dilution fan and core vent (dimensionless) (0.0152168), and the flow diluted release concentration at the top of the stack (ψ = 1.24E-5 Ci/m^3) [20, 24]. The fan flow rate value was determined as a result of the most recent service to the dilution fan. This dilution factor (Λ) takes into account that Ar-41 comes from the core (reactor) via the core vent, which is then dispersed by both the core vent and the dilution fan [20, 24].

$$\Lambda = \frac{\text{Core Vent Flow Rate } \frac{ft^3}{min}}{\dot{f} \frac{ft^3}{min}} \tag{2}$$

$$\psi \frac{Ci}{m^3} = 8.147\,E-4 \frac{Ci}{m^3} * \Lambda \tag{3}$$

$$\dot{R}\,\frac{\mathrm{Ci}}{\mathrm{s}} = \psi\,\frac{\mathrm{Ci}}{\mathrm{m}^3} * \dot{f}\,\frac{\mathrm{m}^3}{\mathrm{s}} \tag{4}$$

In STAC2.1, the release rate was initially modeled assuming a unit source to calculate general maximum concentrations straight downwind from the stack. Final concentrations of Ar-41, for the UFTR, were calculated by multiplying these general concentrations by the specific release rate, 9.228 x 10^{-5} Ci/s.

All calculations were verified, independently, by hand, as shown in Table D-1. Tabulated values for σ_y and σ_z, atmospheric conditions for Gainesville, Florida, and the stack height and release rate for the UFTR were applied to Eq. (1) for the hand calculation. Concentrations were compared for various distances from the UFTR versus those computed using STAC2.1 for the year between July 2004 and July 2005 assuming extremely unstable conditions.

In addition, we note that the temperature of the effluent was assumed to be the same as the average ambient temperature; 23.05^{o}C. The average *daytime* wind azimuth direction for the year was from 167.11^{o}, and the average ground wind speed was 2.42 m/s. As shown in the last row of Table D-2, the differences in the concentrations determined via tabular “by-hand” values or STAC2.1 code runs were less than 3.61% within 500m, and less than 0.77% within 100m downwind of the stack. To explain the differences, the “by-hand” computations do not account for all of the physics (buoyant plume rise with temperature, decay at time of arrival, etc), and are less robust than used in the STAC2.1 calculations [9].

‘CALPUFF’ is an EPA approved California puff and slug atmospheric dispersion modeling program for accurate concentration and effluent spread prediction over complicated terrain [26]. Puffs are circular, Gaussian mappings of effluent concentrations, while slugs are elongations of these puffs using Lagrangian and Gaussian methods. Four CALPUFF models were created using summer weather conditions, details for the UFTR stack, Ar-41 characteristics, a flat, uniform terrain associated with Gainesville, FL, no "over water" effects, and using an urban wind model. The four studies included combinations of puff and slug models with two different wind extrapolation methods; power law and similarity methods. A STAC2.1model was created to match the average weather conditions, flat terrain, and urban model, as well as the UFTR and Ar-41 parameters used in CALPUFF, and then compared to each of the four cases. The results of this comparison are given in Tables D-3 and D-4.

Maximum concentrations computed using STAC2.1 and CALPUFF software models were compared for each of the cases. It was found that the *relative distance* where the *maximum concentration occurred* was as much as 31% different between the two models. This distance of the maximum concentration was identical in all four CALPUFF models. The maximum concentration values differed from between ~19% and 31%, depending on whether a puff or slug model, or wind extrapolation power law or similarity theory was employed. STAC2.1 results most closely matched the slug, power law model. Comparisons between concentrations for the same downwind distances differed between the codes by only ~1% to 6 %. The best model relative to a comparison with STAC2.1 is the 'CALGROUP slug and wind extrapolation power law model,' which resulted in a percent difference of +/- ~19%.

Overall, the amalgam of all of these results demonstrate that STAC2.1 yields a conservative and reasonable estimate for the effluent concentration of Ar-41 downwind from the stack, and can therefore be used in establishing Ar-41 concentrations for UFTR operations.

STAC2.1 Concentration and Dose Results for the UFTR

STAC2.1 was used to calculate conservative concentrations. Remember that the highest daytime concentrations, closest to the stack, occur for Pasquill class "A," the most unstable condition. In addition, for class "C", while the concentrations are lower overall, the concentrations remain above the prescribed limit further from the stack. To ascertain the Ar-41 concentrations for the UFTR, while accounting for atmospheric influences, local weather condition measurements were acquired from the local conditions recorded daily by the Department of Physics Weather Station [2, 4]. The information located in Tables D-5 and D-6 are the average temperatures, wind directions, wind speeds, and Pasquill Classes attributed for the yearly period between July 2004 and July 2005 surrounding the UF campus. Table D-5 contains daytime, 7am – 7pm, results, while Table D-6 has the nighttime, 8pm – 6am, information. The tables also include mean values for quarterly periods and the total year. Again, we note that the monthly average computed for Ar-41 based on operation of the reactor must not exceed the maximum limit of 1.00E-8 Ci/m^3 [16].

The peak Ar-41 concentrations released, for each set of individual data, using possible different Population and Pasquill Class combinations, as well as the distance from the building where these peaks occur, are illustrated in Table D-7. Note that highlighted concentrations reflect the average stability classes for each time period.

The total effective dose equivalent limit determined for Ar-41 is 50 mrem per year at a maximum concentration of 1.00E-8 Ci/m^3, inhaled or ingested continuously over a year [29]. Dose is linearly related to concentration as shown in Eq. (5). Results for the quarterly averages are shown in Table D-8. Table D-9 shows possible limiting case scenario concentrations and doses for several buildings near the UFTR based on a continuous operation concentration with dedicated winds using the April 2005 – July 2005 data. For this exercise, the wind directions were assumed to vector toward each building.

$$\text{Dose}\,\frac{\text{mrem}}{\text{yr}} = \chi\,\frac{\text{Ci}}{\text{m}^3} * \frac{50\,\text{mrem}}{1.00\,\text{E}-08\,\frac{\text{Ci}}{\text{m}^3}} \tag{5}$$

Peak concentrations show that when the UFTR is assumed to operate at 100% power for 24 hours per day, then the allowable maximum concentrations and doses of Ar-41 for dedicated wind directions exceed 1.00E-8 Ci/m^3 and 50mrem/yr. This implies a “reactor duty cycle” is needed to bring the monthly average concentration of Ar-41 below the maximum allowable concentrations.

Operation Hours for the UFTR

Using the calculated peak concentrations of Ar-41, the UFTR Effective Full Power Hours (EFPH), are shown in Table D-10 for daytime conditions, since daytime is when the reactor is most likely to be run. In considering the peak concentrations, this will decrease all limit exceeding concentrations to below 1.00E-8 Ci/m^3 [16, 29]. EFPH are calculated using Eq. (6) [20, 24].

$$\mathrm{EFPH}\,\frac{\mathrm{hrs}}{\mathrm{mo}} = \frac{1.00\,\mathrm{E}-08\ \frac{\mathrm{Ci}}{\mathrm{m}^3}}{\chi\ \frac{\mathrm{Ci}}{\mathrm{m}^3}} * 720\,\frac{\mathrm{hrs}}{\mathrm{mo}} \tag{6}$$

Ar-41 concentrations (χ) are in Ci/m^3. For units of kW-hours month or kW-hours/week, one can multiply by 100kW. The 720 hours/month is a standard, assuming 24 hours/day, 7 days/week, and ~4.286 weeks/month [20]. Note that the EFPH limit based on license requirements is 235.00 hours/month or 55.56 hours/week [20].

Therefore, on average, to remain below the annual limit of 1.00E-8 Ci/m^3, the UFTR could be run up ~307 hours/month at full power for the year, with a restriction of running up to ~240 hours/month during the late spring and summer months. However, since the additional licensing restriction is 235.00 hours/month, the UFTR may be run up 235.00 hours/month (or 55.56 hours/week) all year long.

Moreover, since nighttime concentrations are lower than for daytime concentrations, the UFTR can be operated at any time of day, day or night, up to a total of 55.56 hours per week. This is a significant increase from the current EFPH for the UFTR of ~116 hours/month [20].

Dilution Factor for the UFTR

The flow diluted release concentration of Ar-41 (ψ) at the top of the stack, before being affected by the environment, is approximately 1.24E-5Ci/m^3 from Eq. (5). Dilution factors are calculated by dividing concentrations in question by 1.24E-5Ci/m^3. Table D-11 shows the dilution factors for the site boundary, the distance where maximum concentration occurs, and the distance where the closest residence housing is located (East Hall at a range of 190m). The concentrations were calculated using the limiting case conditions for April 2005 – July 2005, with a wind direction towards East Hall (80^o).

Consider that the dilution ratio for the maximum concentration (415:1) is also the maximum case instantaneous release concentration from the UFTR stack. The dilution ratio, currently used by the UFTR, is 200:1 [20]. Note that 200:1 is extremely conservative compared to the computed value of 415:1 based on results from STAC2.1, which has been shown to be conservative. Table D-12 illustrates the difference between the two ratios using the concentration calculated from the UFTR SOP (6.20E-8 Ci/m^3) [20, 24], and the maximum concentration as determined by STAC2.1. It is shown that the 200:1 ratio is approximately 2.07 times more conservative than the 415:1 ratio.

Summary and Conclusions

In summary, UF researchers performed a detailed assessment of the Ar-41 dose generated by operation of the University of Florida Training Reactor (UFTR). In particular, yearly maximum predicted concentrations, dose rates, operational limits, and dilution factors were calculated for the UFTR with impact assessments assuming dedicated wind directions to nearby campus buildings at 100% full power (100kW). Note that the total effective dose equivalent limit for Ar-41 is 50 mrem per year at a maximum concentration of 1.00E-8 Ci/m^3, inhaled or ingested continuously over a year. A Gaussian plume model based code, STAC2.1, developed and benchmarked by UF researchers, was employed to calculate the maximum concentrations and the distances where they occurred. Average daytime atmospheric conditions for the University of Florida in Gainesville, FL from 2004-2005, UFTR discharge stack parameters, and Ar-41 characteristics were established as input parameters for the code. "By Hand" Pasquill plume calculations, and detailed CALPUFF (a detailed physics model) computations were used to successfully validate STAC2.1 results; the percent differences from the "By Hand" method ranged from 0.70% to 3.61% (Table D-2), and the percent differences from CALPUFF models aliased using STAC2.1 were within +/- 19% (Tables D-3 – D-4).

Based on the available data, the *average* maximum Ar-41 concentration determined using STAC2.1 for the reactor at full power for the year was 2.34E-8 Ci/m^3 down-wind 80m from the UFTR (D-7). The period from April 2005 – July 2005, the warmest months with the slowest wind conditions, resulted in the highest maximum concentration of 2.99E-8 Ci/m^3 at a down-wind location 50m from the UFTR. This time period and highest maximum concentration was used as the limiting value for the dilution factors, dose rates, and concentrations for the other buildings on campus, as well as the limiting value for full power hours of operation. Concerning the buildings on campus, only buildings within ~150m of the UFTR could experience concentrations and dose rates greater than the limits (Table D-9) if the reactor were continuously operated at full power; this included Weimer Hall (2.65E-8 Ci/m^3), Weil Hall (2.89E-8 Ci/m^3), Rhines Hall (1.96E-8 Ci/m^3), Reitz Student Union (1.09E-8 Ci/m^3), and the Mechanical and Aerospace Engineering C building (1.03E-8 Ci/m^3). The student residence hall closest to the UFTR, East Hall, located 190m away, had both the concentration and dose rate below the annual full operation limit: 5. 75E-9 Ci/m^3. In order to reduce the maximum concentrations (and corresponding doses) to acceptable limits, the number of allowable full power hours of operation per month were calculated (Table D-10). The allowable number of hours, averaged for the year, was ~307 hours/month, with a further restriction during the summer of ~240 full power hours/month. Therefore, based on the current license restriction of 235.00 hours/month, for Ar-41 emissions, the UFTR may be run up 235.00 hours/month (55.56 hours/week) all year long. This is a significant increase from the current EFPH for the UFTR of ~116 hours/month [13]. In addition, since nighttime concentrations and resultant doses are lower than for daytime, the reactor may be run 55 hours/week continuously without exceeding limit requirements.

Finally, the current dilution factor used in the UFTR SOP is 200:1 to account for atmospheric effects. Based on an analysis of the STAC2.1 results, the limiting dilution ratio is ~415:1 (Table D-11). As a result, the 200:1 ratio using in the first half century of licensing was more than twice as conservative given the actual ratio of 415:1 (Table D-12).

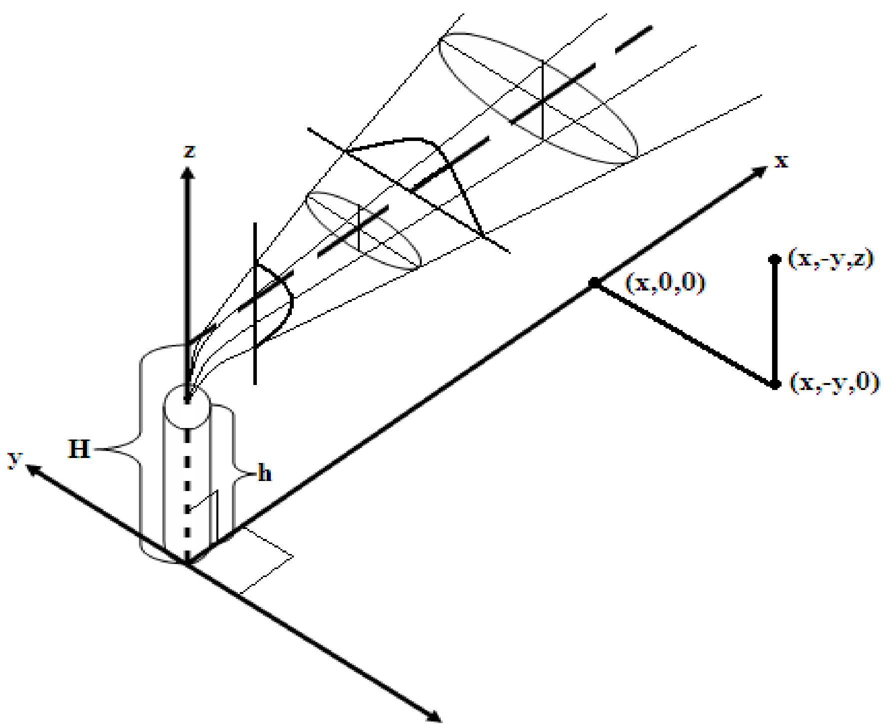

Figure D-1 Coordinate System of Gaussian distributions straight downwind, horizontal, and vertical

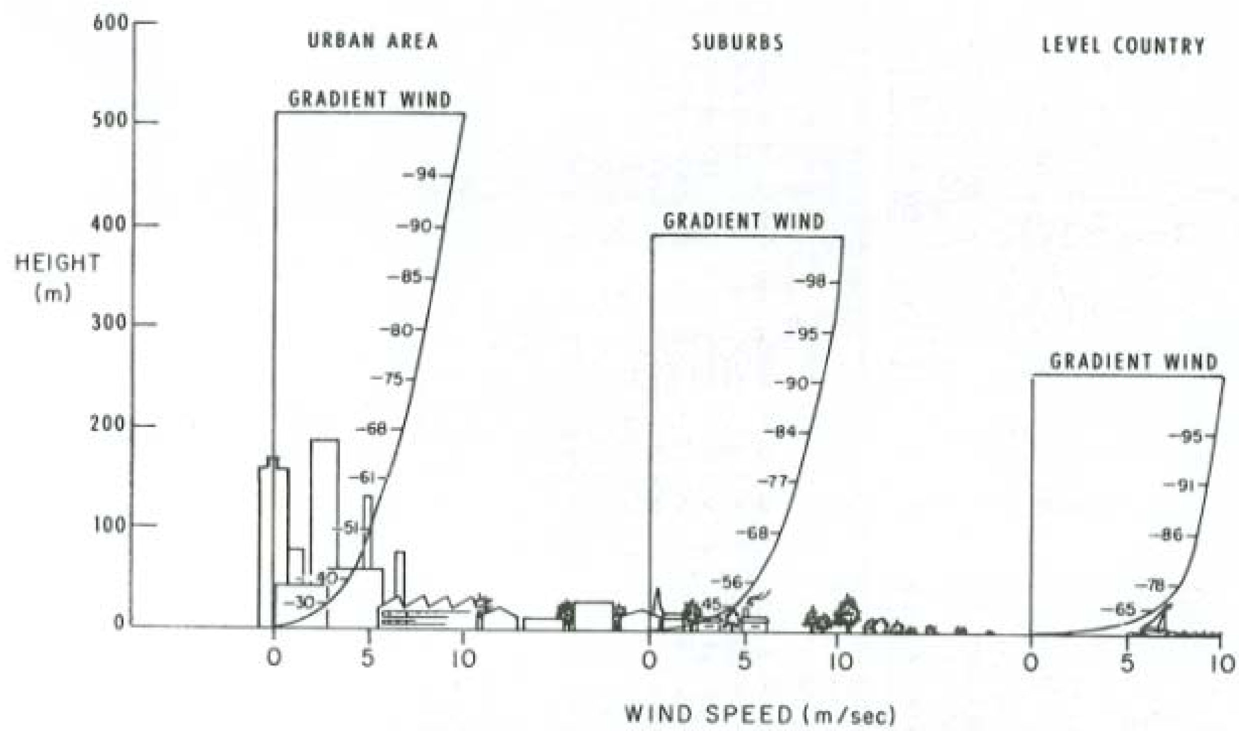

Figure D-2 Effect of Terrain Roughness on the General Wind Speed Profile

Table D-1 Pasquill Weather Condition Categories

Category	Time of day	Typical Conditions	Weather Descriptions	Wind m/s	Wind Direction – Stand. Dev.
A	Day	Extremely Unstable	Very Sunny Summer	1	+- 25 deg
B		Moderately Unstable	Sunny and Warm	2	+- 20 deg
C		Slightly Unstable	Average Daytime	5	+- 15 deg
D	Night	Neutral Stability	Overcast Day/Night	5	+- 10 deg
E		Slightly Stable	Average Nighttime	3	+- 5 deg
F		Moderately Stable	Clear Nighttime	2	+- 3 deg

Table D-2 Urban Pasquill Class "A" Ground Level Concentration of Ar-41 Hand Calculation vs. STAC2.1 Results at Various Distances from the UFTR (July 2004 – July 2005)

Distance from Building (m)	50	100	500	References
UFTR release rate (Ci/s)	9.228E-05	9.228E-05	9.228E-05	Calculated
Effective height of effluent release (m)	12.3	12.3	12.3	[12]
Pasquill Category (Daytime)	A	A	A	Assumed
Wind speed at the stack (m/s)	3.99	3.99	3.99	[12]
Sigma y (m)	10.97	21.89	107.35	[1, 4]
Sigma z (m)	10.00	20.00	100.00	[1, 4]
By Hand Concentration: (Ci/m^3) (Eq. 1)	3.15E-08	1.39E-08	6.81E-10	[1, 4]
STAC2.1 Multiplier: Release Rate is Unity	3.39E-04	1.50E-04	7.11E-06	Calculation
STAC2.1 Concentration: Multiplier * UFTR Release Rate (9.228E-5 Ci/m^3)	3.13E-08	1.38E-08	6.56E-10	Calculation
% Difference: STAC2.1 vs. By Hand	-0.70%	-0.77%	-3.61%	Calculation

Table D-3 STAC 2.1 and CALPUFF/CALGROUP Comparison with a Puff Model

Models	Similarity Theory			Power Law		
	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)
STAC2.1 (Maximum)	1.83E-08	30.71	103	1.83E-08	19.61	103
STAC2.1 (Same Distance as CALPUFF)	1.49E-08	6.43	79	1.49E-08	-2.61	79
CALPUFF/CALGROUP	1.40E-08	N/A	79	1.53E-08	N/A	79

Table D-4 STAC 2.1 and CALPUFF/CALPGROUP Comparison with a Slug Model

Models	Similarity Theory			Power Law		
	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)	Maximum Conc. (Ci/m^3)	% Diff. in Conc.	Distance from Stack (m)
STAC2.1 (Maximum)	1.83E-08	23.65	103	1.83E-08	18.83	103
STAC2.1 (Same Distance as CALPUFF)	1.49E-08	0.68	79	1.49E-08	-3.25	79
CALPUFF/CALGROUP	1.48E-08	N/A	79	1.54E-08	N/A	79

Table D-5 Daytime Monthly, Quarterly, & Yearly Atmospheric Averages (July 2004-2005)

Monthly Quarters, & Year	Temp		Wind Direction	Ground Wind Speed		Pasquill Classes
	F	C	Degrees	mph	m/s	
Jul ‘04-Sept ‘04	83.38	28.54	160.77	5.09	2.28	A
Oct ‘04-Dec ‘04	69.21	20.67	143.81	6.63	2.96	B
Jan ‘05-Mar ‘05	63.73	17.63	182.61	5.31	2.37	C
Apr ‘05-Jul ‘05	77.63	25.35	181.25	4.66	2.08	A
Jul ‘04-Jul ‘05	73.49	23.05	167.11	5.42	2.42	B

Table D-6 *Nighttime* Monthly, Quarterly, & Yearly Atmospheric Averages (July 2004-2005)

Monthly Quarters, & Year	Temperature		Wind Direction	Wind Speed		Pasquill Classes
	F	C	Degrees	mph	m/s	
Jul ‘04-Sept ‘04	77.89	25.50	158.09	3.10	1.39	F
Oct ‘04-Dec ‘04	62.94	17.19	134.13	2.47	1.10	F
Jan ‘05-Mar ‘05	57.34	14.08	183.31	3.31	1.48	F
Apr ‘05-Jul ‘05	70.90	21.61	166.16	2.66	1.19	F
Jul ‘04-Jul ‘05	67.27	19.59	160.42	2.89	1.29	F

Table D-7 STAC2.1 Urban Ground Peak Ar-41 Concentrations (Ci/m^3) and Distance (m) from UFTR

Time	Average Stability Classes	Jul04-Sep04		Oct04-Dec04		Jan05-Mar05		April05-Jul05		Jul04-Jul05	
		Ci/m^3	m	Ci/m^3	m	Ci/m^3	m	Ci/m^3	m	Ci/m^3	m
Day	A	2.89E-08	50	2.62E-08	44	2.86E-08	47	2.99E-08	50	2.83E-08	45
	B	2.39E-08	79	2.16E-08	75	2.36E-08	78	2.46E-08	82	2.34E-08	80
	C	2.32E-08	119	2.09E-08	111	2.28E-08	120	2.39E-08	123	2.27E-08	115
Night	F	1.09E-08	775	1.08E-08	865	1.08E-08	750	1.09E-08	835	1.09E-08	800

Highlighted concentrations reflect the average stability classes for each time period

Table D-8 Total Effective Dose Rate and Maximum STAC2.1 Concentration Values for the Monthly and Yearly Averages for 2004-2005, Assuming Full Power Continuous Operation

Monthly Quarters, & Year	Day Pasquill Classes	Max Day Conc. & Dist. from UFTR		Total Effective Dose Rate
		Ci/m^3	m	mrem/year
Jul '04-Sept '04	A	2.89E-08	50	145
Oct '04-Dec '04	B	2.16E-08	75	108
Jan '05-Mar '05	C	2.28E-08	120	114
Apr '05-Jul '05	A	2.99E-08	50	150
Jul '04-Jul '05	B	2.34E-08	80	117

Table D-9 STAC2.1 Total Effective Dose Rate Assuming Peak Concentration Values for Buildings near the UFTR Assuming dedicated 100% Wind Vectors from the UFTR Stack to the Building

Buildings on Campus	~Distance from UFTR (m)	~Wind Direction (deg)	Max. Conc. (Ci/m^3)	Dose (mrem/yr)
Reed Lab. (RLA)	20	180	7.14E-10	4
Weimer Hall (WEIM)	40	265	2.65E-08	133
Weil Hall (WEIL) Main Eng.	63	170	2.89E-08	145
Rhines Hall (RHN) Mat. Sci.	91	80	1.96E-08	98
Reitz Student Union (REI)	133	0	1.09E-08	55
Mech.& Aerospace Eng. C (MAEC)	137	80	1.03E-08	52
Mat. Eng. (MAE)	160	40	7.87E-09	39
East Hall (EAS) (Closest Housing)	190	80	5.75E-09	29
Gator Corner Dining (FSF)	183	95	6.16E-09	31
Mech. & Aerospace Eng. B (MAEB)	200	40	5.22E-09	26
North Hall (NOR) Housing	229	93	4.04E-09	20
Ben Hill Griffin Stadium (STA) Football	250	170	3.42E-09	17
Riker Hall (RIK) Housing	274	85	2.86E-09	14
Van Fleet Hall (VAN) ROTC	298	110	2.43E-09	12
Tolbert Hall (TOL) Housing	309	93	2.27E-09	11
Graham Hall Housing (GRA)	320	50	2.12E-09	11
O'Connell Center (SOC) Swim & Sports	331	125	1.98E-09	10
Carse Swim/ Dive (SWIM) Athletics	343	115	1.85E-09	9
Trusler Hall (TRU) Housing	411	50	1.29E-09	6
Simpson Hall (SIM) Housing	417	55	1.26E-09	6
Parking Garage VII (OCONNEL)	463	135	1.02E-09	5

Table D-10 UFTR Hours of Operation Based on Peak Ar-41 Concentrations (Ci/m^3) for Daytime Atmospheric Conditions

Monthly Quarters, & Year	Day Pasquill Classes	Daytime Max. Conc. & Dist. from UFTR		EFPH			
		Ci/m^3	m	hrs/mo	kW-hrs/mo	hrs/wk	kW-hrs/wk
Jul '04-Sept '04	A	2.89E-08	50	249.13	24913.49	58.90	5889.72

Table D-10 Continued

Monthly Quarters, & Year	Day Pasquill Classes	Daytime Max. Conc. & Dist. from UFTR Ci/m^3	m	EFPH hrs/mo	kW-hrs/mo	hrs/wk	kW-hrs/wk
Oct ‘04-Dec ‘04	B	2.16E-08	75	333.33	33333.33	78.80	7880.22
Jan ‘05-Mar ‘05	C	2.28E-08	120	315.79	31578.95	74.65	7465.47
Apr ‘05-Jul ‘05	A	2.99E-08	50	240.80	24080.27	56.93	5692.73
Jul ‘04-Jul ‘05	B	2.34E-08	80	307.69	30769.23	72.74	7274.05

Table D-11 Dilution Ratios based on Concentrations and Relevant Campus Locations

Campus Relevance	Distance from UFTR m	Concentration Ci/m^3	Dilution Ratio (Value:1)
UFTR Site Boundary	30	1.48E-08	838
Maximum Concentration	50	2.99E-08	415
East Hall (Closest Dorm)	190	5.75E-09	2157

Table D-12 Dilution Ratio Comparison

Location	Concentration (Ci/m^3)	Dilution Ratio (Top of stack: Other)	Dilution Ratio (STAC2.1:SOP)
Top of Stack	1.24E-05	N/A	N/A
UFTR SOP (Using 200:1)	6.20E-08	200	2.07
Maximum Concentration	2.99E-08	415	

LIST OF REFERENCES

[1] Smith, M.E, 1979: Recommended guide for the prediction of the dispersion of airborne effluents. New York, American Society for Mechanical Engineers, 3rd Ed.

[2] Pasquill, F, 1974: Atmospheric diffusion of the dispersion of windborne material from industrial and other sources. Chichester: Ellis, Horwood Limited, 2nd Ed.

[3] Briggs, G.A, 1969: Plume rise. Springfield, VA, U.S. Atomic Energy Commission, National Technical Information Service, TID-25075.

[4] Turner, B.D, 1973: Workbook of atmospheric dispersion estimates. North Carolina, Environmental Protection Agency, Office of Air Programs, 6th Ed.

[5] Meteorology and Atomic Energy--1968, US AEC Report TID-24190.

[6] Office of the Federal Coordinator for Meteorology. OFCM directory of atmospheric transport and diffusion consequence assessment models. Retrieved from the Internet 8-8-05, http://www.ofcm.gov/atd_dir/pdf/frontpage.htm

[7] U.S. Environmental Protection Agency: 1995. User guide for the Industrial Source Complex (ISC3) dispersion models volume II: Description of model algorithms. EPA – 454/ B – 95 – 003b. Retrieved from the Internet 8-10-05, http://www.epa.gov/ttn/scram/userg/regmod/isc3v2.pdf

[8] Sjoden G., and V. S. Cornelison, 2005-2008. STAC2.1 Build 1.5b, STAC2.1 exhaust stack effluent dispersion model. Florida Institute of Nuclear Detection and Security.

[9] University of Florida Department of Physics Weather Station. Historical text summaries. Retrieved from the Internet 7-1-05, http://www.phys.ufl.edu/weather/

[10] Los Alamos National Labs Chemistry Division. Argon. Retrieved from the Internet 4-30-08, http://periodic.lanl.gov/elements/18.html

[11] University of Florida campus map. Retrieved from the Internet on 8-5-05, http://campusmap.ufl.edu/

[12] U. S. Nuclear Regulatory Commission, 1873: Environmental impact statement for license renewal of the National Bureau of Standards reactor final report. NUREG-1873. December 2007. Retrieved from the Internet 5-1-08, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1873/sr1873.pdf

[13] Korean Atomic Energy Research Institute. 18-Argon. Retrieved from the Internet 4-30-08, http://atom.kaeri.re.kr/ton/index.html

[14] University of Florida Nuclear and Radiological Engineering Department. The University of Florida Training Reactor. Retrieved from the Internet 5-5-08, http://www.nre.ufl.edu/facilities/uftraHistory.php

[15] Yenatsky, M, May 2008: Private communication.

[16] U. S. Nuclear Regulatory Commission. 10CFR20 – Standards for Protection Against Radiation. Retrieved from the Internet 7-23-05, http://www.nrc.gov.edgesuite.net/reading-rm/doc-collections/cfr/part020/full-text.html#part020-1001

[17] U. S. Nuclear Regulatory Commission. 10CFR40 – Protection of environment, Part 61. Retrieved from the Internet 8-8-05, http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=c096bfbe27e56312fde493e740c75117&rgn=div5&view=text&node=40:8.0.1.1.1&idno=40

[18] NOAA. Glossary. Retrieved from the Internet 5-12-08, http://www.crh.noaa.gov/glossary.php?letter=w

[19] Sonntag, R.E., C. Borgnakke, and G.J. Van Wylen, 2003: Fundamentals of thermodynamics. 6th Ed., 658.

[20] Vernetson, W. G., November 30, 2007: Limitation on UFTR equivalent full-power hours of operation. Memorandum. University of Florida.

[21] Korean Atomic Energy Research Institute (KAERI). Table of Nuclides: Ar-41. Retrieved from Internet on June 2004, http://atom.kaeri.re.kr/ton/index.html

[22] Keane, C. University of Florida physical plant architectural and engineering division. blueprints of the University of Florida Training Reactor: Building 557.

[23] Chen, W, January, 1981: UFTR safety analysis report copy 8. University of Florida.

[24] October 2003. UFTR operation procedure E.6. University of Florida.

[25] Scire, J.S., D.G. Strimaitis, and R.J. Yamartino, January 2000: A user's guide for the CALPUFF dispersion model (Version 5). Concord, MA.

[26] Scire, J.S., Strimaitis, D.G, and Yamartino, R.J., January 2000: A user's guide for the CALMET meteorological model (Version 5). Concord, MA.

[27] Hesketh, H.E, March 1996. Air pollution control: Traditional and hazardous pollutants. CRC Press, Revised Edition.

[28] Henry's Law. Retrieved from the Internet 3-12-08, http://en.wikipedia.org/wiki/Henry's_law

[29] U. S. Nuclear Regulatory Commission. 10CFR20 Appendix B– Annual limits of intake and derived air concentrations of radionuclides for occupational exposure, effluent concentrations, and concentrations for release to sewerage. Retrieved from the Internet 3-18-08, http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-appb.html

[30] Kotroni, V. and K. Lagouvardos, November 2004: Evaluation of MM5 high-resolution real-time forecasts over the urban area of Athens, Greece. *Journal of Applied Meteorology*. **43**, No. 11, 1666-78.

[31] Holt, T. and J. Pullen, May 2007: Urban canopy modeling of the New York City metropolitan area: A comparison and validation of single- and multilayer parameterizations. *Monthly Weather Review*. **135**, No. 5, 1906-30.

[32] American Meteorological Society, November 2006: Weather forecast accuracy gets boost with new computer model. *Bulletin of the American Meteorological Society*. **87**, No.11, 1477-8. Retrieved from the Internet 5-29-08, http://vnweb.hwwilsonweb.com/hww/results/results_single.jhtml;hwwilsonid=GEL4NZQNWBIW3QA3DILSFF4ADUNGIIV0

[33] Ayres, D., C. Cohen, M. Greene, Yenatsky, M., April 25, 2008: Private Communication. UFTR Modifications: Final Proposal.

[34] Slade, D.H., ed., 1968: *Meteorology and Atomic Energy--1968*, US AEC Report TID-24190.

BIOGRAPHICAL SKETCH

Victoria Spring Cornelison was born in Atlanta, GA. Her family moved around and settled in Fort Myers, where she attended high school as Cypress Lake High School. Following high school, she attended Florida Gulf Coast University (FGCU) and graduated with her Bachelor of Arts in mathematics in 2002. While teaching high school mathematics at Estero High School in Estero, FL, she also earned her Master of Arts in Teaching, with a concentration in secondary education, from FGCU in 2004. After teaching high school for two years, in 2005, she decided she needed a change in careers and moved to Gainesville, FL to attend the University of Florida (UF). She has her Master of Science in nuclear engineering at UF, and her next step is to work on her Ph. D. at UF in Nuclear Engineering.