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TART 2022
An Overview of
A Coupled Neutron-Photon
3-D, Combinatorial Geometry
Time Dependent
Monte Carlo Transport Code

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DISCLAIMER

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Abstract

This document is designed to provide an overview of TART 2022, a coupled neutron-photon, 3 Dimensional, combinatorial geometry, time dependent Monte Carlo radiation transport code. This code can run on **any modern computer**. It is a **complete system** to assist you with input preparation, running Monte Carlo calculations, and analysis of output results. TART 2022 is also **incredibly FAST**; if you have used similar codes, you will be amazed at how fast this code is compared to other similar codes. Use of the entire system can save you a great deal of time and energy, and most important it can improve your understanding.

This document only intended to announce the availability of TART2022, and it is **NOT THE USER'S MANUAL for TART**; indeed, there is nothing in this document that describes how to use TART. This document merely briefly provides an overview of the history and capability of TART and the contents of the TART 2022 DVD. **The actual code user's manual remains the documentation for the earlier published code TART2005**, supplemented by updates similar to this current TART2022 document, namely TART2012, and TART2016 updates.

TART 2022 is distributed on DVD. This DVD contains on-line documentation for all codes included in the system, the codes configured to run on a variety of computers, and many example problems that you can use to familiarize yourself with the system.

TART 2022 supersedes all older versions of TART, and it is strongly recommended that users only use the most recent version of TART 2022 and data files.

Overview

This announcement of the release of TART2022 supersedes ALL earlier TART announcements of earlier code releases, the most recent being 2016 [1], and 2012 [2]. The last complete documentation of the TART system was TART2005 [3], some 17 years ago, while I was employed at Lawrence Livermore National Laboratory (LLNL). Since that time, I retired from LLNL and there has been no code development, maintenance, or financial support for this code at LLNL. However, I have privately continued work to improve TART, based largely on feedback from TART users throughout the World. These users have kindly freely supplied me with their improvements, and I privately incorporated them into the code that today I call TART 2022 and briefly describe here. I say briefly describe because much of the TART2005, TART2012 and TART2016 documentation is still relevant, and as distributed with TART 2022 DVD.

Although none of the work on TART 2022 was performed at LLNL, David Heinrichs has kindly agreed to support publication of this report through LLNL, in order to reach the widest possible audience. Note, that ALL improvements in TART2022 were performed at no cost to LLNL, DOE or any other organization; these were done by me, privately, hopefully for the good of our TART community of users.

Acknowledgments

First I must acknowledge the major contributions of Fabrice Pelestor (DGA/Technique Naval, Toulon, France); he contributed many improvements to TART, particularly he contributed the 64 bit and multi-processing version, to greatly modernize the code and allow it to be efficiently used with today's computers. The code we have today, TART 2022, could not have been produced without his contributions.

I thank Dave Heinrichs (LLNL) for supporting publication of this report and agreeing to distribute TART 2022 within LLNL. Next I acknowledge the cooperation with other Monte Carlo code designer/users, in particular, Bob MacFarlane (LANL, MCNP), Rich Procassini (LLNL, MERCURY), Ed Lent (LLNL, COG) and Maurice Greene (ORNL); coordinated code comparisons have led to improvements in TART as well as ALL of these other codes. I cannot stress enough that modern transport codes are far too complex to allow true code verification without detailed comparisons to other similar codes.

I also thank the many users of earlier versions of TART who have supplied extremely useful feedback to me. Since the general release of TART2005, TART2012 and TART2016 the response from users in terms of feedback has been extremely useful in improving the code. These improvements have been in terms of correcting problems in the earlier releases of TART, and in terms of users proposing new or improved options to meet their needs, now incorporated in TART 2022. **Today virtually ALL improvements to TART are based on feedback to me from TART users. Therefore, I highly encourage all users to supply their feedback to me, so that ALL TART users can benefit from your experience, including yourself by including your ideas in future versions if TART**.

New in TART 2022 System

Here is a quick summary of what is now included in TART 2022 compared to the last published version TART2005; the summary is by year (this summary is also included inside the TART 2022 code as comments)

2006

1) Corrected S(a,b) coherent scatter to,
   scatter in the Lab (not CM) system.
   coherent scatter with no change speed.
2) Updated neutrons/fission sampling to include
   correction to conserve <nu>.
3) Corrected criticality flux by material normalization
   Now EXACTLY = Analog fission neutrons produce
   so, they sum to total analog flux.
4) Massive change to correct reactall and reacted.
   Now only analog - output also by ZA/C.
5) Added C=47-54 charged particle reactions

(Currently only C=48 in ZA=30000).
6) Changed weights to relative - insure each source
particle (neutron/photon) has a total weight = 1
7) Removed bias and biasg - only way to insure the total weight = 1

2007

1) Corrected high energy exponential spectra fit
2) Added stack to build for photon re-entry problem
3) High energy fission fit now E*Exp[-a*E]
4) Low energy fission fit sqrt(E) to higher energy

2008

1) Spectra sqrt(E) below 10 keV.
2) (n,n') near threshold, low energy extension.
3) Updated NEWCROSS (energy dependent cross sections) for ENDF/B-VII U238.
4) Updated for over 1,000,000 zones: extended output format (8 column zone numbers).
5) Corrected cneutal and cphotal (earlier these were ignored)
6) Sentl 60 Intermediate Resonances now standard

2012

1) Complete rewrite to incorporate all user feedback.
2) Made 64 bit compiler compatible.
3) Eliminated re-entrant coding.
4) Neutrons and photons sources now treated same.
5) sentl 1 = 3 (neutron AND photon sources) is no longer allowed
6) Because of the above, sentl 18 photon/neutron
source ratio no longer has any meaning (no longer used).
7) Data files updated based on ENDF/B-VII.1 data.

2013

1) Added Relativistic speed
2) Correct various typos
3) Treated LOST particles as leaked (extremely low probability events)

2016

1) Eliminated ALL computer dependence; identical for IBMPC, LINUX, MAC, etc.
2) Updated FORTRAN to allow improved optimization and speed.
3) Corrected assorted options
4) Neutron Data files based on the latest ENDF/B-VII data and preliminary ENDF/B-VIII
5) Photon Data files based on my EPICS2014; official ENDF/B electron and photon data
6) Added utility code TimeKeff we display sub-critica time dependent K-eff.

2022

17-1 (Mar. 2017) *Eliminated potential infinite loops in ubangi
(kinematics routine).
18-1 (July 2018) *Added RDTART1, RDINEUT1 and RDCNEUT1 to allow
scalar (one word) reads, rather than array.
*Added dimension (usually 1) to ALL array
arguments of subroutines.
(Oct. 2018) *Added unshielded and totally shielded cross
sections for method diagnostics = extension
of sentl 20 using
= 0 - unshielded multi-group
1 - multi-band
2 - continuous energy
(Added for diagnostics using multi-band data -
set all multi-band cross sections to the same
value to simulate Bonderenko self-shielded)
3 - multiband converted to unshielded
4 - multiband <sigma0> = 0
5 - multiband <sigma0> = totally unshielded
(Nov. 2018) *Corrected ERROR for photon only transport -
subroutine REFLECT was using VNOW instead
of CLIGHT.
*Ignore time change for FUDGE shift in
subroutine REFLECT.
*Combined gen2 and gen2kt into genxnd to have
only one neutron data generator for both
criticality and source problems.
*Reduced BSP neutron produced photon storage
from 15 to 13 words per photon.
*Corrected use of different atomic weights
for neutron and photon data.
*Added self-shielding models strictly for
theoretical purposes = WARNING: NOT INTENDED
FOR ANY REAL PRODUCTION APPLICATIONS.
19-1 (Mar. 2019) *Multi-Band: Intermediate Resonance (IR) Model
Allowed to replace Narrow Resonance (NR) -
1) Standard has IR turned off
2) Use sentl 60 1 to turn on IR
*WARNING - This is a dummy routine - the actual
IR method used by TART is proprietary software
only available by license.
21-1 (Aug. 2021 *Updated neutron and photon data files.
*Added PLOTTAB cross section output
*Added option with continuous energy cross
sections to turn off Unresolved Resonance
Region (URR) self-shielding.
*Extended Maxwellian up & down in energy

and 200 (from 100) bins per energy decade.
*Added unshielded and totally shielded cross
sections in the unresolved resonance region
for method diagnostics = extension sentl 20
= 0 - unshielded multi-group
1 - multi-band
2 - continuous energy

(-3,-4,-5 continuous energy (2) change in URR)

-3 - continuous + same 3 below, only in URR
-4 - continuous + same 4 below, only in URR
-5 - continuous + same 5 below, only in URR

(3, 4, 5 multiband (1) ALL energies
---
3 - multiband converted to unshielded
4 - multiband <sigma0> = 0
5 - multiband <sigma0> = totally unshielded

It is important to note that through all of these updates, the TART input format has NOT BEEN CHANGED in any significant way, so that the INPUT documentation for TART2005 is still relevant and is distributed with TART 2022 and virtually all older TART input decks will still run with TART2022, but you might want to review the options used by older input decks, to insure that you are now using the BEST INPUT (see below for details).

The remainder of this document is more or less a copy of the TART2005 [3], TART2012 [2 r2] and TART2016 [1]documents, with changes only where it was necessary to reflect changes in TART2022 or my status as retired.

32 versus 64 Bit Executables

Here we must distinguish between arithmetic, which in TART 2022 is always performed using 64 bits, and the compiler options, you, the user, may employ to create TART 2022 executables. TART 2022 executables are 100% 32 versus 64 bits compatible; not one line of coding need be changed to create either 32 or 64 bit executables. But so far I have not found any significant advantage of 64 bit executables, except for very large problems that exceed the 4 GB, 32 bit limit. In deciding what is BEST FOR YOUR USE here are a few points to consider,

1) For most problems both 32 and 64 bit executables give EXACTLY the same answer; so, in terms of accuracy there is no advantage to one versus the other.
2) A 32 executable is slightly faster; this surprised me; a definite advantage to 32 bit executables.
3) 32 bit executables run on either 32 or 64 bit computers. In contrast 64 bit executables only run on 64 bit computer; another advantage for 32 bit executables.

The bottom line is that at least so far I have not found any significant advantage to using 64 bit executables rather than 32 bits. **If YOU, THE CODE USER finds an advantage PLEASE tell me, so that your experience can be included in future versions of TART.**

New in TART2005 System

Here is a quick summary of what is new in TART2005,

1) **Continuous energy cross sections, including multi-band self-shielding in the unresolved resonance energy region.**
2) **Delayed neutron, time, and energy distributions.**
3) **Improved thermal scattering law, S(a,b), data.**
4) **Improved fission spectra.**
5) **Improved sub-critical system simulation.**
6) **Alpha static criticality calculations.**
7) **Output summary of events by reaction type (capture, n,2n, etc.), as well as neutron production and removal.**
8) **Output complete comparison of expected and analog results.**
9) **General corrections and improvements, e.g., checking input parameters.**

BEST PHYSICS

In addition, TART now uses the "BEST" physics concept, to set ALL input default values to provide users with the "BEST" available physics. With this concept users need only prepare the minimum TART input, focusing on the physics problems they are interested in, and relying on TART to provide the "BEST" available physics to meet their needs.

WARNING – users should review their older TART input decks to ensure that they do not include options that override the default "BEST" values; in which case if you wish to use the "BEST" options, you need merely delete the now extraneous input parameters from your TART input decks.

The TART2005 System

This report is intended merely as a brief introduction to TART2005. The on-line documentation for the TART2005 system codes, distributed on the current TART2022 DVD, has been coordinated to illustrate combined use of the codes to make your job simpler and your work easier to accomplish, in particular extensive use of interactive graphics. If you have not used interactive graphics before you are only making your job harder, and your tasks will take longer to accomplish.

Overview of This Report

2022 Update: ALL of the documentation described here is still relevant and is planned to be distributed with the TART 2022 DVD. The remainder of this section is copied from the original TART2005 report.

This report describes all major changes in TART since TART95 [4]. As such this report supersedes the reports of TART96 [5], TART97 [6], TART98 [7], TART2000 [8], and TART2002 [9]. However, the TART95 report [4] is still the most comprehensive report on TART.

This report is divided into a number of parts, with each part describing one part of the TART2022 DVD system. The parts are,
Part 1: TART2022 - Monte Carlo Calculations
Part 2: Input Parameters - Description of all Input Parameters
Part 3: TARTCHEK - Check TART Input and Display TART Results
Part 4: TARTAID – Interactively create TART Input
Part 5: EPICSHOW - Display Atomic and Nuclear data used by TART
Part 6: PLOTTAB - General Plotting Code to Display TART Output
Part 7: EDITOR - Text editor for use with TART
Part 8: Utility Codes - A collection of Useful Codes
Part 9: IMAGES – Using TART for medical and industrial imaging
Part 10: Criticality – Using TART to calculate critical systems

I Strongly Recommend that you read the on-line documentation for all parts of this system, to get a better overall picture of how this entire code system fits together and can help you. The TART2005 on-line documentation is available in Microsoft Word and Adobe PDF formats and includes black and white as well as color graphic results. Only when you start using the codes in combination will you realize that this is a complete system that can really assist you in your work.

Computer Requirements

TART2005 will run on any modern Computer, with at Least 20 Megabytes Memory and 60 Megabytes Disk Space**. Dynamic memory management allows TART to run problems on virtually any size computer; up to 4 GB for 32 bit executables, and beyond this limit with 64 bit executables.** This puppy can run on virtually any computer; see, the below table of running times on a variety of computers.

TART 2022 DVD

TART 2022 is distributed on DVD. This DVD contains on-line documentation for all codes included in the system, the codes configured to run on a variety of computers, and many example problems that you can use to familiarize yourself with the system.

TART Home Page

Since I retired there is no longer an up-to-date TART Home Page at Lawrence Livermore National Laboratory. The BEST contact and source of information, reports and announcement is my current personal e.mail address **RedCullen1@comcast.net** and website **http://redcullen1.net/homepage.new** [10]**.**

TART documentation is now available on the TART 2022 DVD; it is currently not available on-line, but the virtual identical TART 2012 and TART 2016 documents are now freely available online within LLNL: **https://e-reports-ext.llnl.gov/pdf/630173.pdf.** TART users should periodically check my website **http://redcullen1.net/homepage.new** [10] for the latest news and on-line TART tutorials that are designed to aid TART users

TART Hot Line

Well, not exactly a hot line, but at least a place to turn to when you need help. If you have any difficulties setting up TART input, running it, or analyzing output, you can contact me at home. Although I am retired I am still willing to try to help TART users. But please be aware that this will be strictly on my own time and not related in anyway to my previous employment at LLNL, so please keep your requests within reason. To contact me use my current personal e.mail address **RedCullen1@comcast.net** and website **http://redcullen1.net/homepage.new** [10]

Background: Legacy, Schmegacy

Because TART has a history of over fifty years one might think that today's TART code is an old legacy code that is very much out-of-date and is teetering on its last legs. Nothing could be further from the truth. Today's TART code has been completely re-written in the last few years, and is now one of the most modern, up-to-date Monte Carlo radiation transport codes available. All that remains of the earlier code, **TARTND**, is the user input and output interface, and the many hundreds of person-years of experience accumulated in using TART over the last fifty years.

The earlier **TARTND** code was written in the LRLTRAN language (unique to Livermore), which limited the code for use only on Livermore's CRAY computers. TARTND was basically a high energy neutron and photon transport code. It was limited to high energy neutrons because it used unshielded, multi-group cross sections, and as such did not account for resonance self-shielding, and it had an extremely limited thermal scattering treatment, and only a hand full of groups at low energy; none below a milli-eV. In addition, its use of Livermore's Evaluated Nuclear Data Library (ENDL) for neutron data further restricted TARTND to high energy neutron problems; as the author of ENDL, Robert J. Howerton stated [11] that ENDL was never intended for use in slow neutron applications and gives poor results if it is misused in slow neutron applications. In addition, TARTND was designed to run on the small computers that were available decades ago, e.g., geometry that could be modeled only in fairly limited detail.

In contrast today's TART code is written in such standard FORTRAN that it runs on everything from large central computers to UNIX workstations, to MACs and PCs, using Windows or LINUX – like I said: this puppy runs on any computer. It also includes the multi-band method to manage resonance self-shielding [12], and a very accuracy and efficient method to manage free atom scattering [13], as well as thermal scattering law data to manage bound atom scattering [14]. **Added with TART2005 are continuous energy cross sections.** Whereas the old TARTND code used 176 neutron energy groups, mostly clustered at high energy, today's TART code uses 700 neutron energy groups for tallies, 50 per energy decade, uniformly spaced in the log of the neutron energy between 10^{-5} eV and 1 GeV; only the 616 groups up to 20 MeV are currently used. Compared to the hand full of low energy groups used by TARTND, today's TART code has 250 groups below 1 eV. In addition, TART now uses the most up-to-date evaluated nuclear data, namely the ENDF/B-VIII [15]. It also uses the most modern evaluated photon interaction data, EPICS2017 [16], which is now the official ENDF/B-VIII photon interaction data library. In addition, today's code is designed to run on today's computers – and tomorrow's computers; there is now no limit on any input parameters, e.g., geometry can be modeled using as much detail as needed, be it using one spatial zone, or millions of spatial zones, TART2022 can efficiently manage both extremes. In an attempt to try and make your life simpler when you do include more geometric details, you will find that TART2022 now includes many more input options that can simplify how you define geometry **(note, that the geometry included with TART2005 is so general that no additional geometry was added for TART 2022).**

One thing that today's code has managed to carryover from the older TARTND code, is incredible speed. If you compare TART to other Monte Carlo radiation transport codes you will be amazed at how much faster TART is. But be assured that this speed is not accomplished by compromising accuracy; we have always used Howerton's first theorem, **"We are in no rush for the wrong answer."** The combination of speed and accuracy is achieved by using all appropriate methods that we learned in graduate school and beyond. For example, where other codes may ignore everything we learned and try to solve transport problems starting from basic principles, TART uses very efficient and accurate methods to account for resonance self-shielding, bound and free atom scattering, and an assortment of nuclear and atomic models, which allow transport calculations to be accelerated, with no loss in accuracy. Indeed, it is fair to says that over a given, fixed

period of running time TART's results are more accurate than other codes that start from basic principles, and as a consequence these other codes can end up converging extremely slowly, and when they do eventually converge it is usually to the TART answer that you can obtain much sooner.

Continuous Energy Cross Sections

With today's TART2022, the user has the choice to use: 1) multi-group, unshielded cross sections, or 2) multi-band cross sections to account for self-shielding, or 3) the new (2005) continuous energy cross sections (no groups), that include all of the details of cross sections. This choice can be used as a teaching tool, to determine the importance of multi-group and self-shielding for your applications, or if you wish, to minimize running time. It is NOT recommended that you try to minimize running time at the expense of accuracy, but for quick, initial calculations users may decide to use these options. The running time using these various representations of the cross sections are roughly in the ratio: 1) multi-group = 1, 2) multi-band = 1.3, 3) continuous energy = 2, e.g., the difference in running time between multi-group and continuous energy is only a factor of 2, so there is not a great deal of benefit to using anything except continuous energy cross sections; but the choice is yours.

This combination of a modern up-to-date code that runs on any computer, and the best available nuclear models, and nuclear and atomic data, makes today's TART system hard to beat for performance speed and accuracy. The transition from the older **TARTND** code to today's **TART2022** code did not take place overnight; basically, this transition began years ago with the release of **TART95**.

The original **TARTND** code has been used and distributed from Lawrence Livermore National Laboratory for many years but was always limited because it was written in the Livermore LLLTRAN language and designed only to run on CRAY computers. **TART95**, released in July 1995, was the first version of the code written in very conservative standard FORTRAN, designed to be used on virtually any computer. Subsequent release of **TART96, TART97, TART2000** and **TART2002** were designed to extend the general utility of the code to more areas of application, by concentrating on improving the physics used by the code, particularly with respect to newer neutron data, and more detailed neutron data. **TART2000** and **TART2002** further improved the physics, particularly with respect to newer photon data, and more detailed photon data [16]. **TART2005** was a major step forward in terms of generalizing the nuclear and atomic data used, and greatly expanding the options available to define geometry. TART2005's **continuous energy cross sections** and input options, and greatly improved consistency checking are designed to make the code more user friendly and to improve the reliability of results.

TART2022 completely supersedes all older versions of TART, and it is strongly recommended that users only use the most recent version of TART2022 and its data files. **Today the recommendation is to use only TART 2022.**

For a historical review of the improvements in TART since the release of the first computer independent version, TART95, see also the TART2002 report [9]. Here I only

describe where we are today, in terms of currently available features, and I review the new conventions and input options; for complete details of input, see chapter 2 of this report on Input Parameters.

Features of TART2005

A COMPLETE SYSTEM: The TART system is not merely one single code to run Monte Carlo radiation transport calculations. It is a complete system, that helps you check your input before you run calculations (this greatly improves reliability), simplifying running calculations (no complicated system dependent conventions to remember), and helps you analyze results, by using interactive graphics, allowing you to overlay your results onto your geometry (**this gives you the "big picture", that allows you to see the overall variation of energy deposition, flux…**).

Part of this complete system is one, and only one, set of neutron and photon data for use in your applications. I have used my over 50 years of expertise to select what I consider to be the BEST data for use in applications, and this is what is supplied with TART. TART is designed as an application system, including the BEST code using the BEST options and BEST neutron and photon data that I can provide. There are any number of codes available that can be used to investigate the results based upon using one or another set of nuclear data; **TART is not one of these codes**. If you want to investigate the effect of using one cross section versus another I suggest you use some other code. Once you have verified that one set of cross sections is better than the data used by TART, PLEASE, let me know, and I will consider revising TART's data bases.

Basically, if you are interested in neutron and/or photon applications and obtaining the answer to your problems as accurately and as quickly as possible, then the TART system is designed for you.

COMPUTER INDEPENDENT: TART2022 today, runs on every computer: large central computers, a variety of UNIX workstations (SUN, SGI, HP, DEC Alpha, Meiko, and IBM RISC), Power MACs and IBM PCs using Windows or LINUX. TART is written in such simple and standard FORTRAN that I feel confident to say that not only does TART run on all computers today, but it will also run on new computers as they become available; so, you can be sure that TART will be available for your use not only today, but also well into the future. **Note, that today TART 2022 has extended this computer independence to allow one single version of TART 2022 to be used to produce 32 bit or 64 bit executables, for use on any computer; it always uses 64 arithmatic for maximum accuracy.**

It was not too long ago that Monte Carlo radiation transport codes could only be run on multi-million dollar central computers. Today my lap top computer allows me to take TART with me anywhere and to run enormous problems in a small fraction of the time it took on large central computers just a few years ago. Not only is TART handy as far as its portability, but you should also note the economic advantage of today's TART over the old TARTND code that only ran on CRAY computer. For example, my $2,000, 1200 MHz Laptop computer runs TART2005 over **forty** times as fast as TARTND on a multi-million dollar CRAY-YMP.

This speed is even further enhanced with TART 2022; see the summary of the speed of TART at my website, http://redcullen1.net/homepage.new/speed.htm. It is also interesting to note how far Personal Computers have come in the last few years. When TART95 was released in 1996 the then fastest available 486dx2/66 PC took 18,487 seconds to run a set of benchmark problems. Today's best time of 14 seconds is an incredible 1.320 times faster - this is due to advances in computer speed, compiler design, and TART design. Think about what this means. A problem that in 1996 took an entire 9 to 5, 8 hour (480 minute) work day to complete, now takes LESS THAN 22 SECONDS!!!

The last point concerning computer independence that I will mention relates to the many users who have asked me: **isn't it more time consuming and inefficient to make TART so computer independent? The answer is, no it is not.** If anything, being able to assess TART using many different computer/compiler combinations makes my job easier and makes TART far more dependable. Different compilers check for different possible errors or inconsistencies, so that I can find and fix as many problems as possible by using as many different computer/complier combinations as possible, making TART more dependable, and ultimately saving myself time and energy.

BEST OPTIONS USED AS DEFAULTS: In the past to use TART the users had to be aware of and set all sorts of options and insure they were set correctly in their input files. Now the defaults for ALL options are what I consider to be the "BEST" set of options, so you need no longer be concerned with them in your input, i.e., if you do not define ANY given option by input you can be sure TART will provide the BEST available option. These options include ALL energy limits for transporting and scoring neutrons and photons; these limits are now automatically set by the code to track and score over the entire energy range of the data in the neutron and photon data files. In addition, the important options for resonance self-shielding, thermal scattering, and fluorescence, are initially to have these features turned on.

NEW INPUT OPTIONS: have been added to TART2005 to allow reactor noise analysis calculations (**sentl 54 and 55**), easier simulation of detectors (**sentl 56**), use either total or prompt nu-bar (**sentl 57**), and definition of zone volumes by user input (**volume**). Options have also been added to extend TART's capabilities for geometry, as well as to simplify and make input more user friendly. These options include **cubic and quartic (e.g., torus) surfaces,** as well as macro "surfaces" **xyzbox, xcan, xconic**, and macro "volumes," **xsurf**, new **rotation** and **spatial translation**, **surface cloning**, new neutron, and photon **sources**, see, **Appendix D: Summary of New Conventions and Options. Note, that ALL of these input options were included in TART2005 and were found to be so general that no additional options were added for TART 2022.**

ENDF/B NEUTRON AND PHOTON CROSS SECTIONS: Older versions of TART only used the Livermore ENDL library neutron data, which was primarily designed for use in high energy neutron applications. In contrast the ENDF/B-VI, VII and VIII, neutron data are designed for widespread use at all energies [15]. Therefore, using this data allows the code to be accurately used in a wider range of applications. **TART 2022 data was updated based on ENDF/B-VIII, for both neutrons and photons.**

TART2005 used ENDF/B-VI data, whereas currently TART 2022 uses the ENDF/B-VIII [15], as well as the EPICS2017 photon interaction data, which has been adopted as the ENDF/B-VIII standard [16].

If you are a fan of the older ENDL data, sorry, but this is no longer supported by TART. You should consider that most of the evaluations in ENDL were done by R.J. Howerton prior to his retirement in 1986 – let me repeat that – 1986 – 36 years ago. ENDL was great in its day, but compared to more modern evaluations, ENDL is now completely out-of-date.

TEMPERATURE DEPENDENT NEUTRON DATA: In the past TART has always used nominally room temperature (293.6 Kelvin) neutron cross sections, and the standard distributed DVD still includes data only for room temperature. We can now prepare additional data files at virtually any temperature to meet programmatic needs [17]. **PLEASE remember that I am now retired, so I cannot guarantee to meet your needs for data at other temperatures, but if you have a need please feel free to contact me and we can talk – but I cannot promise anything.**

NEUTRON 700 GROUP TREATMENT: for cross sections over the energy range 10^{-5} eV up to 1 GeV. Older versions of the code used a 175 group treatment from 1.309 10^{-3} eV up to 20 MeV, with most of the groups concentrated at higher energy: this limited accurate use of the code to higher energy applications. In contrast the current 700 group treatment is designed to accurately treat the entire neutron energy range, thereby allowing the code to be used for a wider range of applications. The 700 group structure is 50 groups per energy decade, equally spaced in the log of the energy, from10^{-5} eV up to 1 GeV. As yet neutron data is only generally available up to 20 MeV, but when higher energy data becomes generally available TART is ready to use it. Note, that this 700 group structure is used both to define multi-group cross sections, and to use as tally bins.

If you are a fan of the older 175 group treatment, sorry, but this no longer supported by TART. The objective is to continue to make TART useful in an ever wider spectrum of applications, and the limitation of the old 175 groups, which were intended only for use in high energy neutron applications, simply was incompatible with this objective.

PHOTON 701 POINT TREATMENT: for cross sections over the energy range 100 eV up to 1 GeV**.** older versions of the code used a 176 point treatment from 100 eV up to 30 MeV, with most of the points concentrated at higher energy: this limited accurate use of the code to higher energy applications. As with the 700 group neutron treatment, this new treatment of the photon cross sections is designed to accurately treat the entire energy range, allowing the code to be used for a wider range of applications. The 701 points is a fixed set of energy points, 100 points per energy decade, equally spaced in the log of the energy, from 100 eV up to 1 GeV. Currently photon data in my EPICS2017 [16] data libraries is available up to 1 GeV, so that all 701 points are currently used by TART.

If you are a fan of the older 176 point photon treatment, sorry, but this no longer supported by TART.

IMPROVED NEUTRON FISSION TREATMENT: TART includes continuous energy sampling of fission spectra. Earlier versions of TART used equally probable energy bins; equally probable energy bins lead to rather large errors in sampling low probability ranges at low and high energy emission of neutrons. This is a win-win improvement in TART, where the sampling is now both more accurate and faster. TART also includes the option to use either the average number of neutrons emitted per fission, or to sample from the distribution of the number of neutrons emitted per fission (**sentl 54**). Also included in TART is an option to allow spontaneous fission sources (**sentl 55**). The combination of allowing spontaneous fission sources and sampling from the distribution of the number of neutrons emitted per fission, **allows TART to be used to simulate reactor noise analysis problems** involving neutron emission correlation effects. You now also have your choice to use either total nu-bar (prompt plus delayed), or prompt (ignoring delayed); this is controlled by **sentl 57**, with the default being total nu-bar. You now have the option to include a separate energy and time dependence for delayed neutrons, also controlled by **sentl 57**. Appendix C illustrates the effect on reactivity of using total versus prompt nu-bar.

UNRESOLVED RESONANCE REGION SELF-SHIELDING: TART includes an extension of the multiband self-shielding method [12] to the unresolved resonance region. See Appendix A for an illustration of the effect that this has on neutron cross sections. This unresolved resonance region treatment is used with the multi-band method as well as with continuous energy cross sections; this option is controlled by sentl 20.

IMPROVED THERMAL SCATTERING TREATMENT: for both bound and free atom scattering. ENDF/B thermal scattering law data is only available for a few materials [14]. TART now includes six of these in its neutron data library,

ZA =	1801	H bound in H2O
	1901	H bound in CH2
	1902	D bound in D2O
	4809	Be bound in Be metal
	4909	Be bound in BeO
	6912	C bound in graphite
	8916	O bound in BeO

To use these in your applications you need merely specify the above ZA in place of the normal ZA when defining your materials in TART input. For example, for free H in H2O the input is two parts ZA = 1001 (H) and one part ZA = 8016 (O); for bound H in H2O, you need merely specify two parts ZA = 1801 (H bound in H2O) and one part ZA = 8016 (O). The exception being that for bound BeO you must specify both Z = 4909 (Be bound in BeO) and ZA = 8916 (O bound in BeO) – the above list includes seven items, but really only includes data for six materials, since for BeO both Be, and O MUST be defined as bound.

Since thermal scattering law data is available only for a few materials, free atom scattering is still important since it is used for all other materials. The major advantages of the new free atom thermal scattering treatment include improved accuracy of sampling, and greatly improved speed of execution [13].

PHOTON SCATTERING TREATMENT: TART includes an improved treatment of photon coherent and incoherent scattering. The current treatment has the advantage that it is both more accurate, and faster to use, than the older treatment.

IMPROVED GEOMETRIC EXPERT SYSTEM: TART has always included an expert system that learns what your geometry looks like as your problem runs. This allows tracking through your geometry to accelerate during any given TART run. TART allows you to carry this learned information forward to successive TART runs. The information defining the connectivity of your geometry is automatically output to a file named **GEOLINKS**, and if you run a problem using the same geometry in the future, this information is read by TART, to allow it to use the previously learned information and continue to accumulate experience and accelerate even further with each successive TART run.

IMPROVED NO UPPER OR LOWER LIMITS: on anything you can define by input. TART uses dynamic memory, to accommodate virtually any sized problems. Unlike earlier versions of TART, which had a maximum allowed number of zones, surfaces, etc., today's TART has no limits at all. For example, earlier versions of the code were limited to a maximum of 1,000 spatial zones. Since then, the spatial detail used in TART problems has increased enormously. The largest TART problem that I know of involved 27 million (27,000,000) spatial zones. Of course, TART can still accommodate even the simplest problem, such as a one zone spherical ball. In all cases from smallest to largest TART automatically sizes itself to accommodate each individual problem run. **With the extension to 64 bit executables the number of spatial zones can be even further increased to meet virtually any need, e.g., even beyond the 4 GB memory/address 32-bit limit.**

LONG RUN RANDOM NUMBER GENERATOR: The current random number generator uses 128 bits arithmetic and includes over 2,500 different random number sequences, each sequence a trillion (10^{12}) random numbers displaced from the preceding sequence. With a modern computer we can generate a trillion random numbers in about one day, if that is all a code is doing. With TART each random number sequence should take about 10 to 20 days to use one complete trillion number sequence. Therefore, the currently available 2,500 sequences should keep you busy for years; and if you need more, just ask for them.

MULTIPROCESSING: The TART utility codes **MULTIPRO** and **TARTSUM** are now routinely used to perform multiprocessing. This approach to multiprocessing is so simple, straightforward, and general that virtually all TART users can use it. With this approach if you have a computer with thousands of processors you can use **MULTIPRO** to create everything that you need to use as many processors as you want and then average the results together using **TARTSUM**. Even if you do not have a computer with many processors, but you do have access to a number of computers, you can use all available computers to run problems (they do not even have to be the same type of computer), and again use **TARTSUM** to average all of the results together. This approach is completely computer independent, and in the example case of using 250 processors, you can compress 250 days of work into a single day (more than a year of

working days into one day). With the new random number generator, using different random number sequences for each run, you can make over 2,500 statistically independent runs and combine the results.

Unlike the approaches used by other codes that are tied to specific computers, and have overhead due to communications between processors, with TART's approach you can use as many processors as are available, all at the same time, or at different time one after another, and there is no overhead due to communications between processors, since each run is independent and contributes to the final results. You can do this simply by running the same problem with different random number sequences, either using multiprocessing, or any number of single processor computers that you have access to, or a single processor repeatedly, if you just want to run more histories to improve your results. This gives you the ultimate flexibility as far as how to best use the computer resources available to you.

IMPROVED INPUT CHECKING: to catch more input errors before the calculation begins. As described below, this checking is now incorporated in both TART and TARTCHEK. TART continues the TART traditions to support all older TART input parameters. For example, if you have a twenty year old TART input problem, you will still be able to use it today with TART. However, TART and TARTCHEK are now much cleverer at finding errors in TART input, with the result that you may find that TART input decks that ran earlier, will now cause TART to stop, with detailed ERROR messages asking you to correct your input before proceeding.

MODULAR CODING: TART is also very **modular**, so that portions of the code can be used in other codes. For example, TART and TARTCHEK use exactly the same input and geometry package; this assures that when you use TARTCHEK to check your geometry, when you run TART it will interpret your geometry in exactly the same manner.

INTERNAL CONSISTENCY CHECKING: No code is perfect, and for any complicated code, such as TART, which has many possible paths through it, it is virtually impossible to manually check all possible paths. The code now includes internal consistency checking; it does its own checking every time it runs. For example, every single array in the code is checked for misuse, in an attempt to find as many errors as possible, so we can fix them before you, and user, runs into them. You would not believe how effective this internal checking has been over the last few years at finding and allowing us to eliminate potential problems, resulting in a much more reliable code. This internal consistency checking has been so effective that since the release of TART98 not one single internal consistency problem has occurred. However, I have left the internal consistency checking in place within the code, so that any changes or new additions to the code are automatically checked and verified.

FULL OPTIMIZATION: One general improvement worth noting, is that based on communications with a variety of FORTRAN compiler designers, TART's has been re-designed to allow it to be compiled at the **highest level of optimization** on most computers, which can greatly reduce running time, without sacrificing accuracy; indeed by understanding how the optimizers are designed, I have made TART much more

reliable as far as its coding not being misinterpreted by compiler optimizers. Today's TART2022 has been updated to be FORTRAN 2018 compatible.

CONTINUATION OF ANY INPUT LINE: Any input line can now be continued onto any number of continuation lines. With earlier versions of TART some input, particularly complicated sources, could not be continued from one line to another, which made input preparation difficult. You will find that being able to continue any input line, it is much easier to prepare input. **Some of the following new options, such as cloning, rotation and spatial translation, were recommended by TART users, and are also designed to simplify preparation of TART input. If you have ideas to simplify input preparation even further, I would love to hear them.**

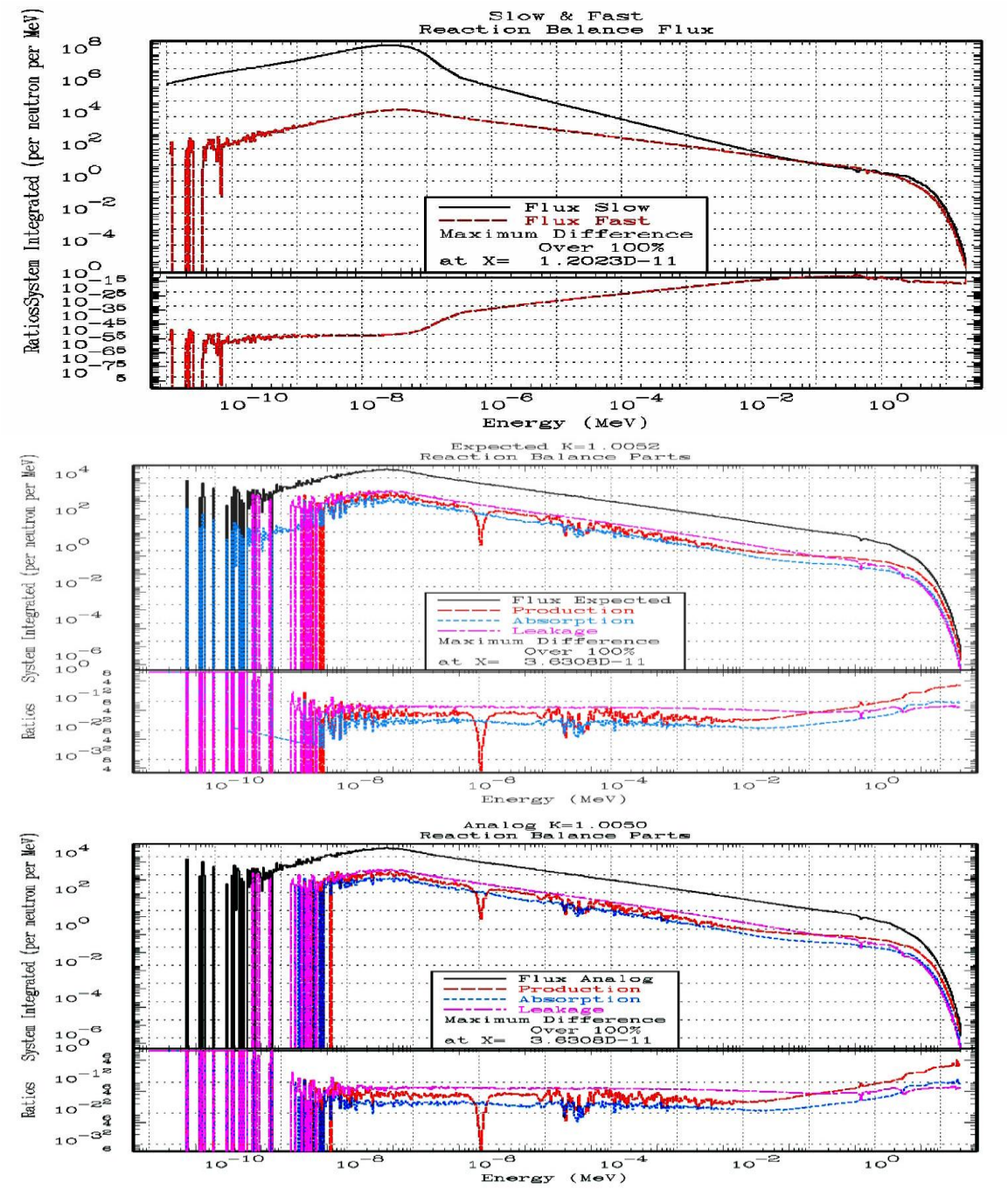
GENERAL IMPROVEMENTS: TART is based on the older TARTND code but required massive changes to the code to make it the modern, computer independent code that it is today. As such there were bound to be some growing pains with this essentially new code. Over the last few years, feedback from the many code users has led to general improvements in the code, both in terms of locating and correcting problem areas, as well as in adding and improving code options to meet the needs of users. Examples of overall corrections and improvements include,

1) Corrected Be-9 (n,2n) neutron emission spectra, which were incorrect.
2) Corrected Z cone Reflection.
3) Corrected addxyz input.
4) Added zone volume user input option.
5) Added the option with tally types 11 and 12, to tally in zone neutron absorption, rather than every time a neutron enters a zone.
6) Allowed type 11 and 12 for empty (no material assigned) zones.
7) Added improved reflected calculations.

EXPERIENCE: Lastly I will mention is the other important change is EXPERIENCE!!! Again, I cannot stress how important this is for any code. In the case of TART each successive version of the code includes the operating experience of the many people who are now using the code. With each passing version of TART reliability and accuracy are improved, mostly based on feedback from users - **such as you – so keep that feedback coming. Even though I am retired I do try to keep us with user feedback, in the hope of improving future versions of TART.**

GRAPHICS: I have always believed that "One picture is worth a thousand word," so an important part of the TART system has always included extensive use of graphics, from the most obvious TARTCHEK, to check TART input decks before you run TART, to a collection of utility codes that display results, e.g., flux, energy deposit, etc. Adding to this collection for 2022 is KeffPLOT (Keff PLOT), for use with criticality calculations, to display system integrated: Flux, production, absorption, and leakage versus neutron energy. This has turned out to be extremely useful in adding to our knowledge of what is happening inside a critical system, particularly so that you can "see" which energy ranges are important – or not important.

For example, the results from criticality calculations were included in tabulated form for earlier versions of TART, but KeffPLOT allows you to "see" and compare EXPECTED and ANALOG results, and the effect of changing TART input options, e.g., thermal scattering ON/OFF. Below are two examples of KeffPLOT results: In the first case comparing the flux in a slow (thermal) system to that in a fast system, followed by a comparison EXPECTED and ANALOG results for a same fast critical system.



Running Time

The below table presents results obtained using a collection of 68 TART benchmark problems. All 68 problems were run on each computer using only one processor. This table summarizes timing results for the older TARTND code that only runs on CRAY computers, as well as all released versions of TART, on a variety of computers. **Most of this list is from the TART2005 report, and is now somewhat out of date, but will help to give first time readers of this report some idea of the advances that we have seen over the years. The original TARTND running times from many years ago are included to illustrate how far we have come; ratios are normalized to these original CRAT-YMP running times.**

Code	Computer	Running Time (Seconds)	Ratio to TARTNP CRAY-YMP
TARTNP	**CRAY-YMP**	**5396**	**1.0**
TARTNP	**CRAY-J90**	**7727**	**1.43**
TART2022	**XPS 15 7590/64bits/Windows10**	**14**	**0.0025**
TART2016	**XPS 9100/64bits/Windows10**	**19**	**0.0035**
TART2016	**Inspiron 5759/64bits/Windows10**	**23**	**0.0043**
TART2005	AMD 3500+	47	0.0087
TART2005	AMD 3400+	48	0.0089
TART2005	IBM-PC Pentium IV/3600	58	0.0107
TART 2002	Athlon XP1800/1520	89	0.0165
TART 2002	IBM-PC Pentium IV/2000	132	0.025
TART 2002	IBM-PC Lap Top III/1200	133	0.025
TART 2002	IBM-PC Pentium III/1000	170	0.031
TART 2002	IBM-PC Pentium III/500	500	0.09
TART 2002	DEC-Alpha Model 5/625	516	0.10
TART 2002	IBM-PC Pentium II/400	579	0.11
TART 2002	PowerMAC/LapTop/500	683	0.126
TART 2002	IBM-PC Pentium II/333	697	0.13
TART 2002	DEC-Alpha Model 5/300	712	0.13
TART 2002	IBM-PC Pentium II/266	855	0.16
TART 2002	IBM-PC Pentium Pro/200	1185	0.22
TART 2002	IBM-PC Lap Top/233	1301	0.24
TART 2002	Power-MAC 7500/275	1350	0.25
TART 2002	iMAC	1664	0.31
TART 2002	HP-735/125	1834	0.34
TART 2002	SUN E3000/166	2107	0.39
TART 2002	IBM-PC LapTop/133	2990	0.58
TART 2002	CRAY-YMP	4262	0.79
TART 2002	IBM-RISC RS-6000	5739	1.06
TART 2002	CRAY-J90	6095	1.13
TART 2002	Meiko CS-2/66	6225	1.15
TART95	CRAY-YMP	4912	0.91
TART95	HP-350	4322	0.80
TART95	DEC-Alpha	6130	1.14
TART95	SUN	9673	1.79

The latest TART2022 results shown below illustrate that today my humble laptop can run the 68 criticality problems in 14 seconds; in incredible 400 times faster than TARTNP could run these same problems on a multi-million dollar CRAY-YMP. For the most up-to-date list of running times see,
http://redcullen1.net/homepage.new/speed.htm

When we compare the codes, all run on the same CRAY-YMP, we find that compared to the older TARTND code, TART95 was about 9 % faster, TART 2002 was about 21 % faster, and even though TART2005 has not been run on a CRAY-YMP its scaling on other computers indicates that it is even faster than TART 2002. So that not only has TART been extended for more general uses, but these extensions were also accomplished with no lose in running time efficiency, with each successive release of TART being even faster than the preceding version.

You should also note the advantage of today's TART over the older TARTND in terms of their ability to be used on virtually any computer. For example, a $2,000 Pentium III, 1200 MHz Laptop computer runs TART 2002 over **forty** times as fast as TARTND on a CRAY-YMP, and the Pentium-IV, 3600 MHz computer runs TART2005 over **ninety** times faster, and on an AMD 3500+ over a **hundred** times faster.

Why is Monte Carlo Used so much Today?

The last point to note from these comparisons is how far we have come in terms of available inexpensive computer power in the few years between the release of TART95 and today's TART. When TART95 was released the fastest IBM-PC then available took 18,437 seconds to run this collection of 68 problems. Even then we could foresee the potential of an inexpensive computer being able to run these problems in only about 3.4 as much time as it took on a CRAY-YMP. But I do not think anyone could foresee that just a few years later we would have available IBM-PCs that can run this collection of problems in only 14 seconds. Compared to the PCs of only a few years ago, not only does today's PC run these problems **1,320** times faster, but also it does it for a fraction of the cost.

Think about what a difference in running time of a factor of **1,320** means. **A major expense of any scientific project is your salary, so time is money, and it can be expensive** - or inexpensive, depending on how you spend it. Consider that only a few years ago if it took an entire 9 to 5, 8 hour working day (480 minutes), to run a TART problem on an IBM-PC, today it would take less than one minute (14 seconds) to run the same problem, i.e., a factor of **1,320** faster. It should be noted that this tremendous increase in available inexpensive computer power is one of the reasons that the use of Monte Carlo has expanded so much in recent years. Problems that we thought too time consuming to be practical just a few years ago, have now become routine.

This speed is even further enhanced with TART 2022; see the summary of the speed of TART at my website, http://redcullen1.net/homepage.new/speed.htm. It is also interesting to note how far Personal Computers have come in the last few years. When TART95 was released in 1996 the then fastest available 486dx2/66 PC took 18,487 seconds to run a set of benchmark problems. Today's best time of 14 seconds is an incredible 1,320 times faster - this is due to advances in computer speed, compiler design, and TART design. Think about what this means. A problem that in 1996 took an entire 9 to 5, 8 hour (480 minute) work day to complete, now takes only 14 SECONDS!!!

Why is TART so FAST?

Some users make the mistake of assuming that since TART is so much faster than other codes that perform the same types of calculations, the results based on other codes must be better than those based on TART. When you use TART, you will find that its results are just as accurate as those of other codes, and often more accurate. So why is TART so fast?

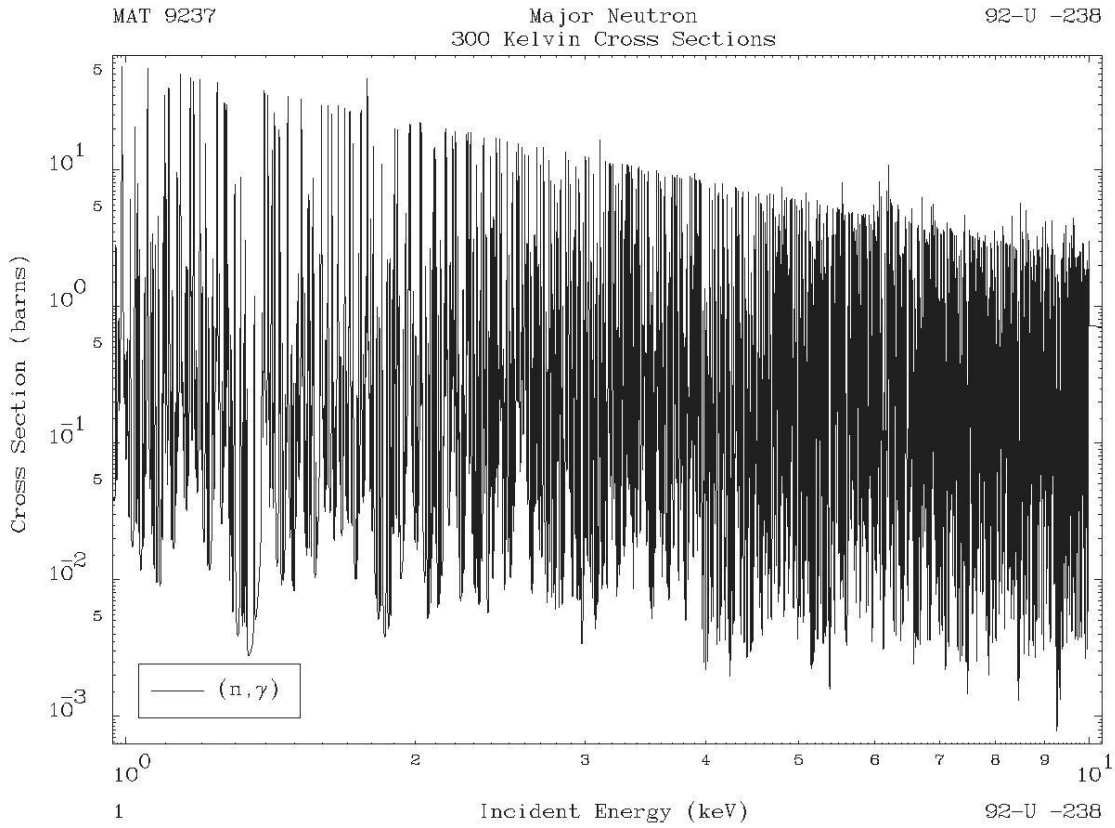
There is not any big secret to TART's speed: TART includes the three most important things necessary for generally efficient and accurate programming:

EXPERIENCE! EXPERIENCE! EXPERIENCE!

It is as simple as that. TART is based on over 50 years of continuous use and improvement. During this time over a hundred work years of physicist/programmer time, and many hundreds of work years of user experience, were incorporated into the code that we have today. To illustrate why TART is so much faster than and yet still as accurate as other codes, I will mention just a few points.

First is the use of multi-group data, including the multi-band method to account for self-shielding [12], as used by TART, compared to continuous energy cross sections used to other codes. Results using continuous energy cross sections have to be better, right? Not always! This is only true if you run a calculation for extremely long times so that you accurately sample ALL of the continuous energy cross sections. This is almost never done, and I know of no code that explicitly includes an estimate of the uncertainty in its results based on the enormous variation in continuous energy cross sections. In comparison, TART's approach is designed for the real world, and incorporates not only the best nuclear and atomic data, but also the best nuclear and atomic engineering.

There is a reason that we went to graduate school and studied nuclear engineering and physics, and all of the methods and experience gained through decades and decades of real World experience. I have tried to incorporate all of this knowledge into TART so that users can obtain the most accurate answers in the least amount of time. Sorry to say that some other similar codes have been written starting from basic principles which sounds good, but in reality, this approach can end up failing to use everything we were taught in school and costing you the code user both time and accuracy.



For example, if we look at the U-238 cross sections, in the above figure, we see capture cross sections even over a fairly small energy range of 1 to 10 keV, that vary by roughly four orders of magnitude, and we can see that it is composed of very narrow resonances with relatively large energy intervals between resonances, i.e., the ratio of resonance spacing to width is about 100 to 1. This data is VERY DIFFICULT to sample on a continuous energy basis. Indeed, if you try it you will find that in order to obtain even a fairly accurate estimate of the average cross sections and distance to collision you would have to sample billions to trillions of histories. I do not know of any code that uses continuous energy cross sections that actually does this. They simply supply you with the "best" possible cross sections and assume that this will solve your problems.

TART takes it a step further: not only does TART use the "best" cross sections, but also uses the "best" nuclear engineering. Again, consider the U-238 cross sections. Anyone who has taken a course in reactor physics knows that in this case the neutron flux will self-shield and we know the form of the self-shielding. Therefore, we do not need all of the nitty-gritty details of each and every narrow capture resonance in order to perform an accurate transport calculation. Think about it: people have been successfully designing nuclear reactors for over 70 years, and yet only fairly recently have detailed cross sections become available. So how did people design their reactors? **They did what TART now does: combine the "best" currently available nuclear data with the "best" nuclear reactor theory.** In the case of TART, the use of the multi-band method to account for resonance self-shielding [12] allows it to use multi-group, rather than continuous energy cross sections, resulting in rapid convergence of calculations,

compared to codes that use continuous energy cross sections and take forever to converge. Most important for users to understand is that this is done with virtually no lose in accuracy in the TART calculations, indeed it is fair to say that since for reasonable running times the TART results converge and those of other codes do not, from the pragmatic viewpoint of obtaining accurate answers in a reasonable amount of time, the TART results are better.

I should also mention the unresolved resonance region, where by definition we do not know the cross sections on a continuous energy basis, but it can be accurately treated by the multi-band method used by TART. **Ask yourself: what do codes that claim to use continuous energy cross sections do in the unresolved resonance region, where by the definition of "unresolved" we do not know the energy dependent cross sections?** Only a few Monte Carlo codes try to account for self-shielding in the unresolved energy region. Who knows what other codes use?

However, if you are not convinced that the multi-band method is fast and accurate for your applications, you now have the option to use continuous energy cross sections with TART; this is controlled by **sentl 20**. After implementing the continuous energy treatment in TART and evaluating it for speed and accuracy in many applications, my conclusion is that as, yet I have not found any application where the multi-band method seriously fails. Indeed, as yet the major use that I have found for the continuous energy cross section treatment is to personally verify the accuracy of the multi-band method, but only if I run using continuous energy cross sections for an exceedingly long time until it converges.

I should mention here that there is not that big a difference in running time using multi-band or continuous energy cross sections (roughly a ratio of 1 to 1.6 in running time); so, there is not a big penalty in using continuous energy cross sections. But carefully check the final uncertainty on your results. **The ratio 1 to 1.6 applies to running the same number of source neutrons; you may require more source neutrons when using continuous energy cross sections, because of the additional statistical uncertainty introduced by large variations in the cross sections.**

A second example of why TART is so fast is its treatment of geometry. Compared to other codes TART uses an extremely strict geometry, which places an additional burden on the user in terms of input preparation. But the payoff is that the input is easier to check and correct (using TARTCHEK) to improve reliability, and when the code starts to run it **FLIES!!!**

For example, TART insists that the users define every space point to be within a spatial zone. Other codes do not insist on this, so why does TART? The first reason is that without insisting on this it is not possible to check the input parameters for errors; checking is now simple and straightforward using TARTCHEK, and greatly improves the reliability of the input. Next, when TART runs it greatly accelerates tracking. How can a few holes in the geometry make such an enormous difference? Consider a simple problem involving 1000 spatial zones with each zone bounded by 6 surfaces. When a particle enters a spatial region that is not defined in the problem, i.e., is a "hole" the code has to track (ray trace) to the nearest bounding surface to determine what zone it will next

enter. In this example it has to ray trace to the 6 bounding surfaces of each of the 1,000 spatial zones, to determine which of these surfaces is closest to the particle in its direction of travel, i.e., it has to ray trace to 6,000 surfaces. In contrast, with TART where a particle is always within a defined zone, in this example, neutrons are always inside one of the zones and we only have to track (ray trace) to the nearest boundary of the zone. This only involves tracking to each of the bounding surfaces of this one zone, i.e., ray trace to 6, rather than 6,000 surfaces. No wonder TART geometry is so much faster to track through. How much of an effect does this really make? TART and TARTCHEK use exactly the same geometry package. In the original method used by TARTCHEK to display 3-D objects, TARTCHEK used a general ray tracing technique that did not take advantage of TART geometry. When TARTCHEK was updated to take advantage of TART geometry the ray tracing to display 3-D objects **ran up to 200 TIMES FASTER - not 200 % - 200 TIMES (20,000%)!!!** Pictures that took hours or all night to produce could suddenly be done in minutes or seconds. The difference was dramatic. You can see for yourself; use TARTCHEK to display 3-D views of your geometry and you will be amazed at how fast it can do it - and remember in doing it, it is using EXACTLY the same routines that TART uses to track through 3-D geometry. No wonder TART is so fast.

These are but a few examples of why TART runs so much faster than other codes, with essentially no lose in accuracy. Try it for yourself and see what you think.

As related to reliability, I will also mention in passing the danger of using the default of other codes that assume that whatever volume you have not explicitly defined is vacuum that the code can freely transport through. **My experience has been that when a problem has an undefined volume in it, well over 90 % of the time it is because it is an ERROR – not really a vacuum within the problem, but rather a REAL VOLUME erroneously not correctly defined by the code user.** Other codes sweep this under the rug and make it appear that nothing is wrong, usually resulting in the wrong answer. In contrast TARTCHEK and TART will quickly find these volumes and ask you to explicitly define them – and help you do this. This approach greatly improves the reliability of the TART input.

What Code should you be using?

TART 2022 completely supersedes all older versions of TART, and it is strongly recommended that users only use the most recent version of TART 2022 and its data files. **Below I illustrate how to check the date of the code and its data files, using TART2005 as an example; you can easily do the same for TART 2022**.

How do you know if you have the most recent version of the code and its data files? As soon as the code starts to run it identifies the version you are running and the dates of its data files. Below is the beginning of the code output report. Note, the code version: **TART2022-1, January 2022**, and the date of the five data files is **22/01/19** (YY/MM/DD = 2022, August 8). Note, also the **616 groups** for the neutron data and **701 points** for the photon data. If you are using an older version of the code or its data files, it is strongly recommended that you obtain the most up-to-date code and data; see, the below section on **Availability**.

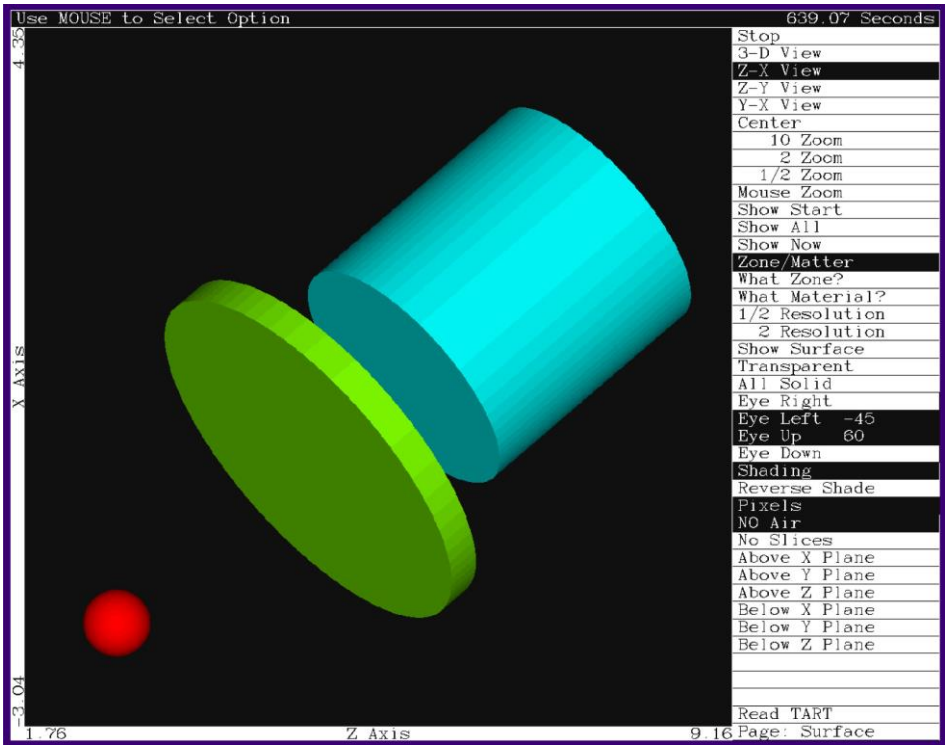
```
 TART 2022 - Neutron-Photon Monte Carlo Transport (TART2022-1, January 2022)
================================================================================
 I/O Files Opened for Entire Run
================================================================================
 Definition                                  Filename      Unit  Date
================================================================================
 TART Input Parameters...................CRIT68            2
 TART Output Listing.....................TART.OUT          3
 TART Input Scratch File.................CRIT6800.TMP     33
 Geometry Connectivity File..............GEOLINKS          15
 Neutron Interaction Data File...........TARTND             7  22/01/19
 Photon Interaction Data File............GAMDAT             8  22/01/19
 Neutron Induced Photon Production File...TARTPPD          9  22/01/19
 Multi-Band Parameter File...............NEWCROSS         10  22/01/19
 Continuous Energy Cross Section File.....NEUTRON         11  22/01/19


 Neutron Interaction Data.  616 Groups 1.0000D-11 to 2.0000D+01 MeV
 Photon Interaction Data..  701 Points 1.0000D-04 to 1.0000D+03 MeV
```

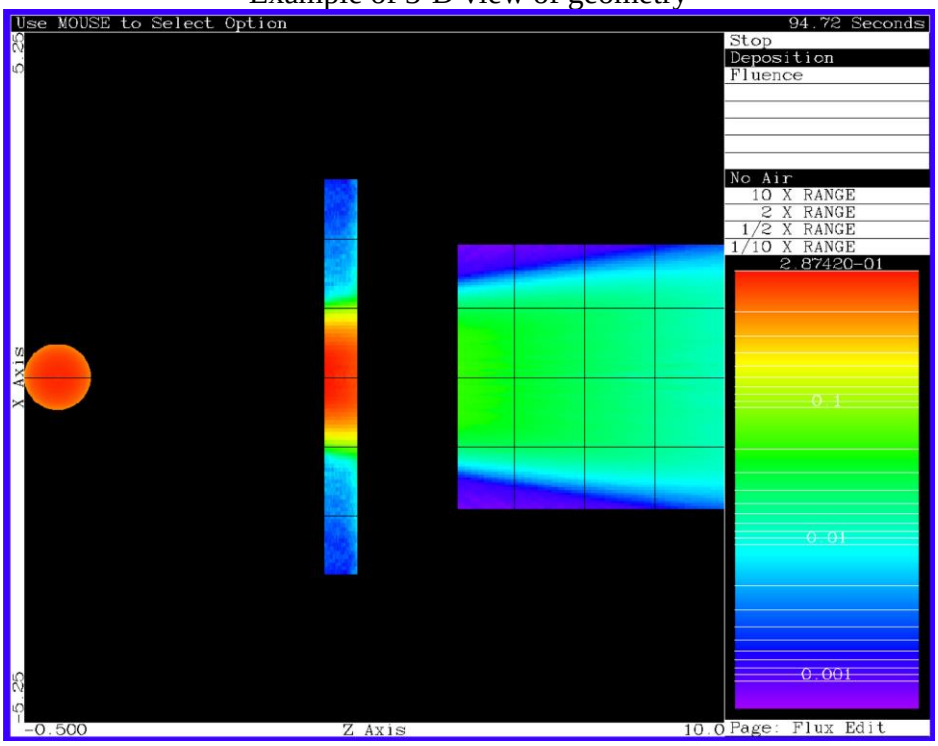
Utility Codes

In addition to the TART code, you should also be aware of the utility codes distributed with TART; of particular note are **TARTCHEK** and **TARTAID**. One of the most difficult tasks that you will face in using any 3-D combinatorial Monte Carlo code is to correctly define input parameters for the code, particularly to correctly define geometry. This is what **TARTCHEK** is designed to help you with. It is an interactive graphics code that will allow you to view and check your input parameters before you run **TART**. Even we so called "experts" on **TART** find that using **TARTCHEK** can greatly reduce the amount of time that we have to spend on input preparation, and even what is more important, greatly improve the reliability of our input parameters. In addition, the TART2022 DVD system includes **TARTAID**, which will allow you to interactively create TART input decks from scratch.

By now most, if not all, TART users are familiar with **TARTCHEK**'s ability to show you your geometry in 2-D, and to quickly assess for error in your TART input parameters. But many users are still not familiar with two additional capabilities of TARTCHEK as shown below: first its ability to **show you geometry in 3-D**, and second its ability to **overlay results of a TART calculation on your geometry**. Particularly the latter is an extremely powerful tool to help you "see" the big picture, as far as global variations of energy deposition or flux. Instead of spending days or weeks wading your way through a thick output listing trying to understand the results, using **TARTCHEK** a few minutes after you finish a TART calculation you can "see" the results overlaid on your geometry. Not only will this save you time, but it can also improve your overall understanding of the results, by showing you the "big picture" of how flux, deposition. etc., in each zone is related to that in all other zones. This is something that is exceedingly difficult to "see" regardless of how long you stare at an output listing. If you are not using **TARTCHEK** you are only making your job more difficult, and you do not know what you are missing.



Example of 3-D view of geometry



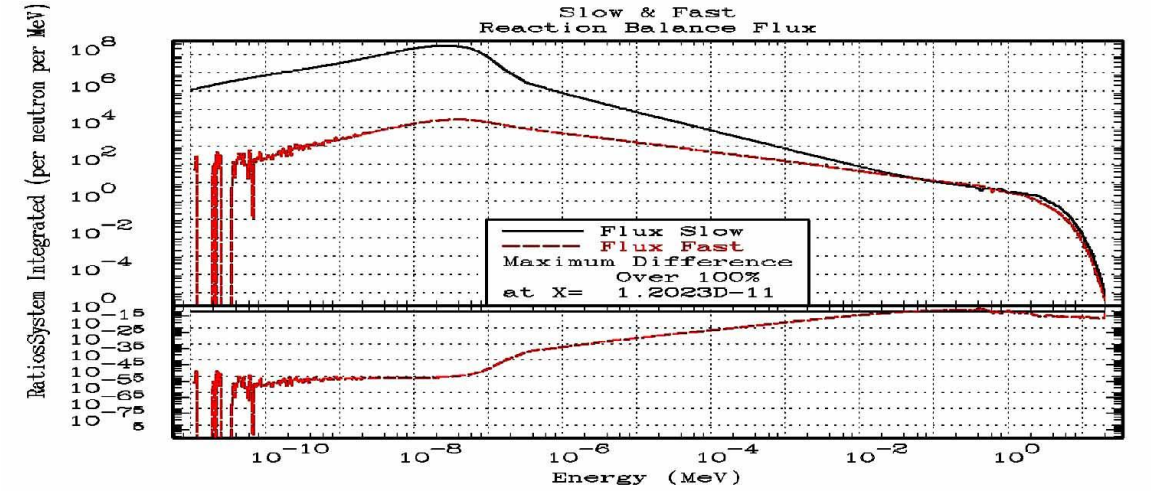
Example of energy deposit overlaid on geometry

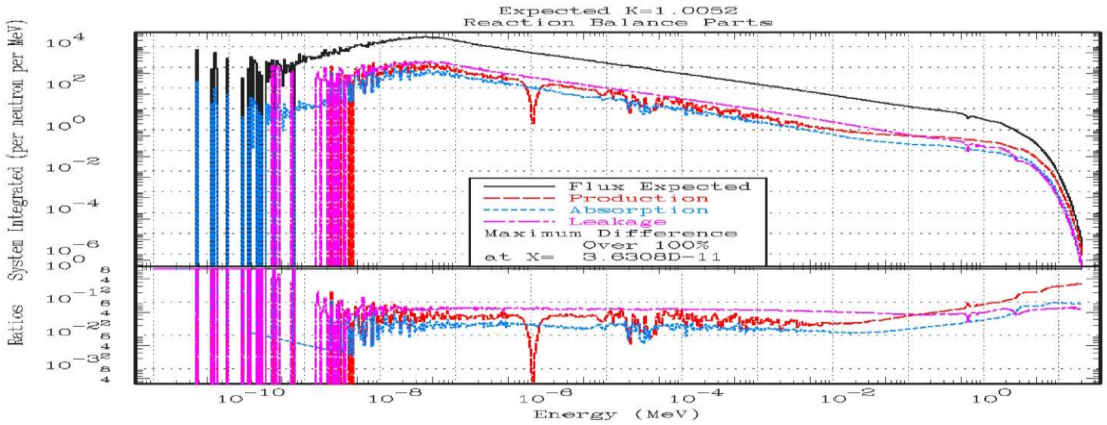
TARTAID is another code you should be aware of. In addition to **TARTCHEK**, which can be used to check existing TART input, and display TART results, the TART2022

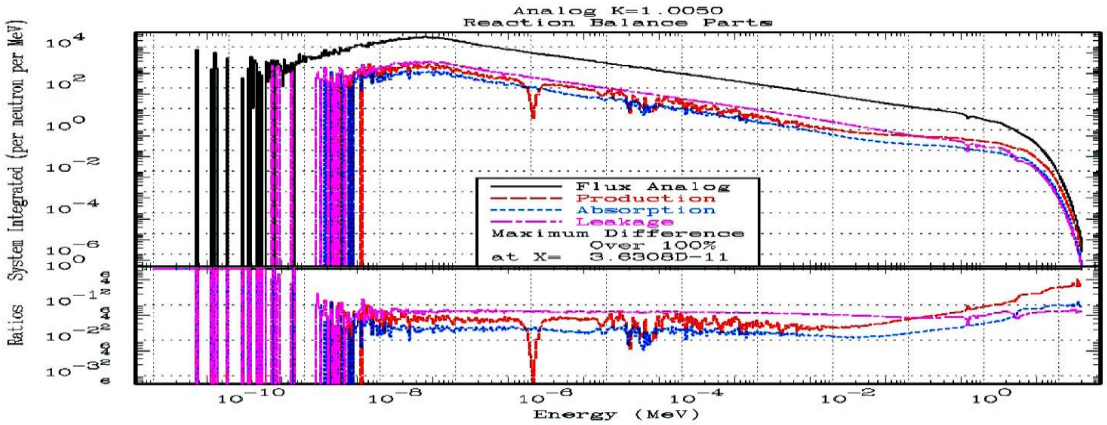
DVD system also includes **TARTAID**. This code is designed to help you create TART input from scratch. It is particularly helping to define very detailed geometry, involving many spatial zones. For example, to create a TART input deck involving 10,000 or even 100,000 spatial zones, takes only minutes using **TARTAID**.

You should also be away of the utility codes **MULTIPRO** and **TARTSUM**, which will allow you to easily run many TART problems simultaneously, and then add together results from any number of TART problems and produce a combined output file in **EXACTLY** the same format as any other single TART problem output file. Our computers are getting faster and faster, but we are running into the speed of light problem, where we can only get so much work done using a single processor. TART's approach to multiprocessing allows us to avoid this limit, in the sense that we can now compress the work that used to take many days, into a single day. This is true on either multiprocessing computers or a group of single processors computers. Just run your problems on ANY computer(s), using as many processors as you have access to, and **TARTSUM** will combine the results for you. Note, since the combined output file produced by **TARTSUM** is in **EXACTLY** the same format as any other single TART problem output file, if you are one of the many TART users who have utility codes to further process TART output results - not to worry - your utility codes will work on the combined file, exactly the same way they work on the results of a single TART run.

I will again mention the **KeffPLOT** code which is new for TART2022. The results from criticality calculations were included in tabulated form for earlier versions of TART, but KeffPLOT allows you to "see" and compare EXPECTED and ANALOG results, and the effect of changing TART input options, e.g., thermal scattering ON/OFF. Below are two examples of KeffPLOT results: In the first case comparing the flux in a slow (thermal) system to that in a fast system, followed by a comparison EXPECTED and ANALOG results for a same fast critical system.







Documentation

Although **TART 2022**, supersedes all earlier versions of TART, the most complete documentation for TART is still,

TART95: A Coupled Neutron-Photon Monte Carlo Transport Code, Lawrence Livermore National Laboratory, UCRL-MA-121319, July 4, 1995, by D. E. Cullen, A.L. Edwards, and E.F. Plechaty

For later changes see also,

TART96: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Monte Carlo Transport Code", Lawrence Livermore National Laboratory, UCRL-ID-126455, November 1996. Available online: **https://e-reports-ext.llnl.gov/pdf/230699.pdf**

TART2005: A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-SM-218009, November 22, 2005; Available on-line: **https://e-reports-ext.llnl.gov/pdf/329012.pdf**

TART2012: A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, LLNL-TR-577352, July 22, 2012; Available on-line: **https://e-reports-ext.llnl.gov/pdf/630173.pdf**

TART2016: A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, LLNL-SM-704560, Code Release: LLNL-CODE-708759, September 2016, by D.E. Cullen. Available on-line: 837508.pdf (exlibrisgroup.com)

These documents, as well as all other TART documentation, is now available on the TART 2022 DVD.

Availability

In the past I personally distributed TART within LLNL. Currently since I am retired and no longer located on site, I can no longer offer this service to provide TART to users at LLNL, but Dave Heinrichs has kindly agreed to distribute TART 2022 within LLNL.

At Livermore, for copies of the system, contact **Dave Heinrichs, X-45679**.

Outside of Livermore, within the United States, contact the Radiation Safety Information Computational Center (RSICC), Oak Ridge National Laboratory (e. mail: pdc@ornl.gov),

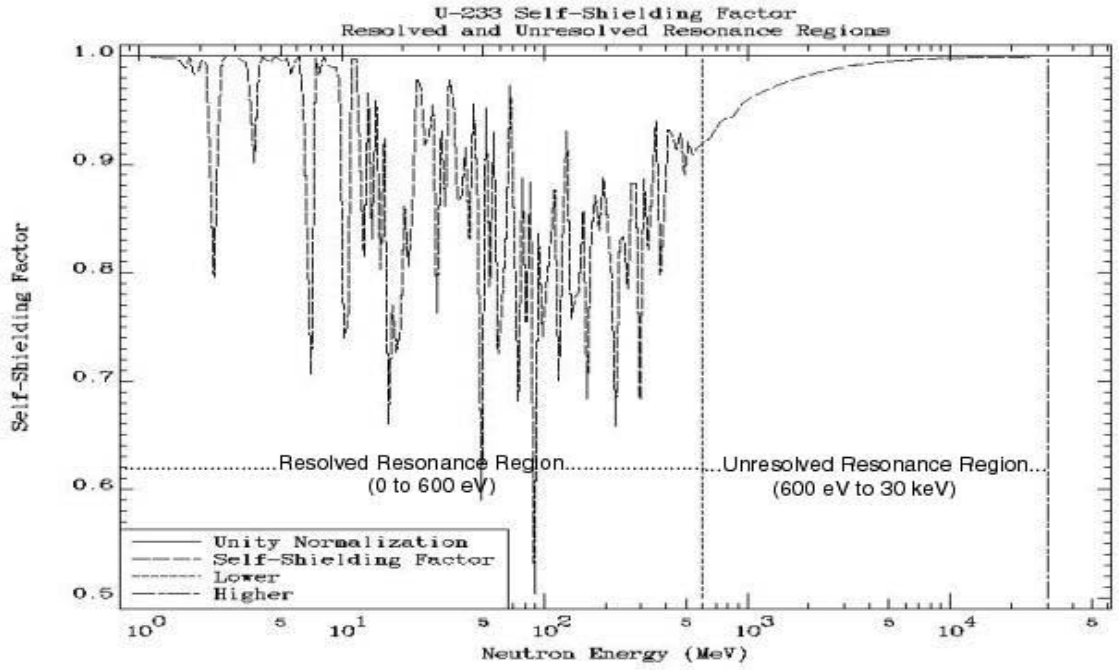
Outside of the United States, contact the OECD Nuclear Energy Agency/Data Bank (NEA/DB), Paris, France (e. mail: programs@nea.fr).

Code Installation

The code is distributed with detailed instructions concerning installation and testing of the code. These instructions are periodically updated for distribution with the code, to ensure that the instructions are as up-to-date as possible, and exactly correspond to the version of the code that you will be implementing and using. As such, installation instructions will not be included here, **i.e., see the TART 2022 DVD that you receive for the most up-to-date instructions.**

Appendix A: Illustration of Resonance Region Self-Shielding

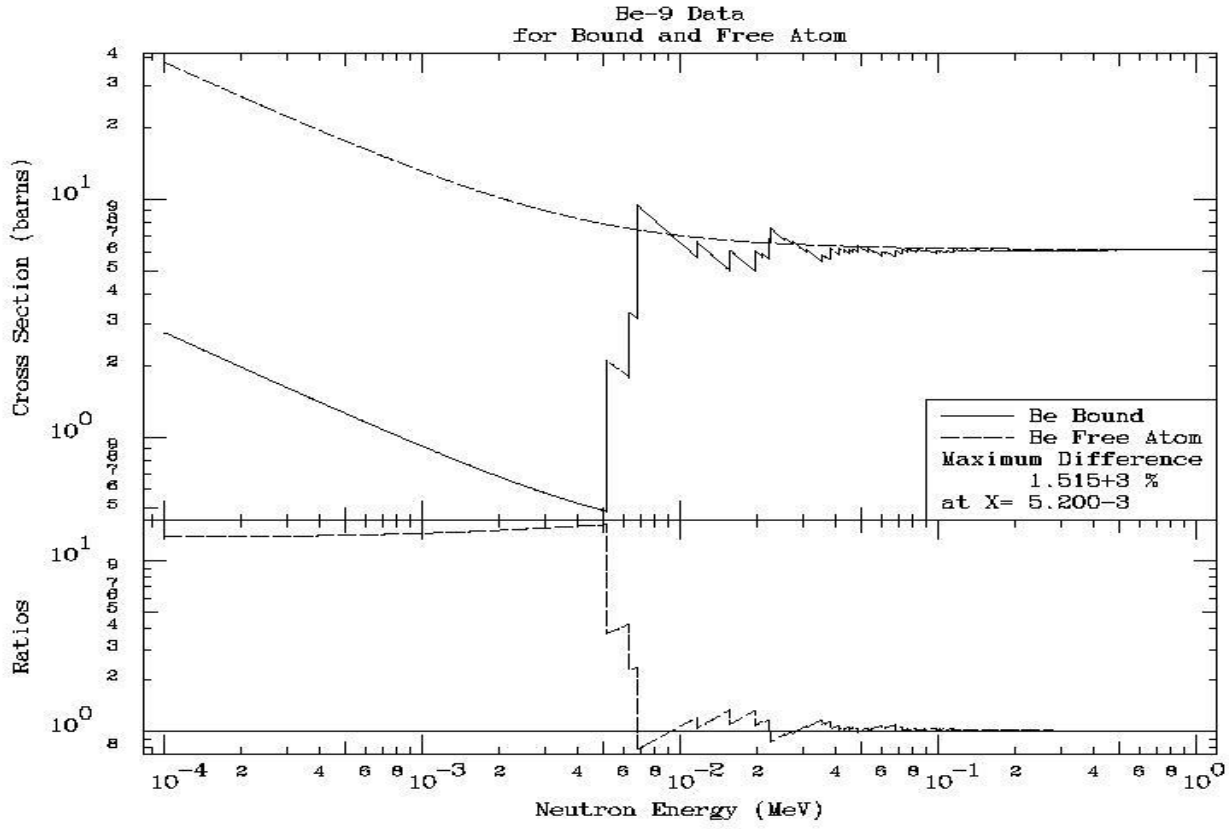
The below figure illustrates the effect of resonance self-shielding on the 700 group U-233 cross sections used by TART. 700 groups may seem like a lot, and you might think that there would be little or no resonance self-shielding. If this were the case the self-shielding factors, which are defined as the ratio of self-shielded to unshielded cross section, would be unity in all groups. The below figure illustrates that this is not the case, because the 700 groups are not nearly enough to accurately represent the energy dependent shape of the many narrow resonances in U-233. In the case of U-233 the resolved resonance region extends up to 600 eV, and the unresolved resonance region extends from 600 eV up to 30 keV (indicated by the two vertical lines on the below figure). Note, that the current TART data includes self-shielding in both the resolved and unresolved resonance regions. **Note, we are not talking about minor differences here; as we can see from the below figure many of the self-shielded group averages are 20 to 30% less than the unshielded values, and in one case only half (50%).**



Example of self-shielding in U233

Appendix B: Comparison of Bound and Free Atom Be-9 Data

The below figure illustrates the effect of molecular binding on the total cross section of Be-9. At higher energies, above the eV energy range, the effects of binding are negligible, and the cross sections are identical. At lower energies note the discontinuities in the bound cross at Bragg edges, and **below about 5 milli-eV the bounding cross section deceases by over an order of magnitude.**



Appendix C: The Effect on Reactivity using Total versus Prompt Nu-bar

The below table illustrates the difference in reactivity (K-effective) of the 68 criticality problems distributed with TART using either total (prompt and delayed) or only prompt number of neutrons per fission (nu-bar). Note that the difference depends on the type of fissile material used, where the delayed fraction is small for Pu-239, intermediate for U-233, and larger for U-235, which can be seen by the magnitude of the differences in K-effective for these three dissimilar materials in a variety of systems.

Averaged over all 68 criticality problems the K-effective using only prompt neutrons is over 0.5% lower than when the total (prompt plus delayed) neutrons per fission (nu-bar) is used; prompt = 0.994163, total = 0.999340 (see, the end of the below table). From the below table we can clearly see the difference in the delayed fraction for Pu239 ~ 0.2%, U233 ~ 0.4%, U235 ~ 0.6%.

Problem	Fuel	Reflector		Total	Prompt	Difference
c10100	pu-a	be	5.222	1.000290	0.997982	-0.231 %
c20100	pu-a	be	8.170	1.002780	1.000700	-0.208 %
c30100	pu-a	be	13.000	1.004140	1.002190	-0.195 %
c40100	pu-d			0.997953	0.995940	-0.202 %
c50100	pu-d	be	3.690	0.998140	0.996117	-0.203 %
c60100	pu-d	be	5.250	0.999445	0.997735	-0.171 %
c70100	pu-d	c	3.830	0.998298	0.996177	-0.213 %
c80100	pu-d	ti	8.000	0.986907	0.984861	-0.208 %
c90100	pu-d	w	4.700	0.992985	0.991153	-0.185 %
c10010	pu-d	u-235	0.660	0.999219	0.996183	-0.305 %
c11010	pu-d	u-238	1.930	0.992996	0.990539	-0.248 %
c12010	pu-d	u-238	6.740	0.997434	0.994696	-0.275 %
c13010	pu-d	u	4.130	1.000410	0.997680	-0.274 %
c14010	pu-d	u	19.600	0.998271	0.994706	-0.358 %
c10100	u-233			0.996675	0.993851	-0.284 %
c20100	u-233	be	2.050	1.000000	0.996944	-0.307 %
c30100	u-233	be	4.200	1.002300	0.999646	-0.265 %
c40100	u-233	w	2.440	0.998245	0.995478	-0.278 %
c50100	u-233	w	5.790	0.997022	0.994353	-0.268 %
c60100	u-233	u-235	1.210	1.001660	0.998594	-0.307 %
c70100	u-233	u-235	1.980	1.005640	1.001760	-0.387 %
c80100	u-233	u-235	4.820	1.009170	1.003760	-0.539 %
c90100	u-233	u	2.300	1.002160	0.998909	-0.325 %
c10010	u-233	u	5.310	1.004550	1.001070	-0.348 %
c11010	u-233	u	19.910	1.002520	0.998268	-0.426 %
c001	u-235	be	1.27	0.991333	0.984829	-0.660 %
c002	u-235	be	2.54	0.993284	0.986833	-0.654 %
c003	u-235	c	1.27	1.002000	0.995486	-0.654 %
c004	u-235	c	2.54	1.003290	0.996490	-0.682 %
c005	u-235	mg	1.27	0.991813	0.985385	-0.652 %
c006	u-235	mg	2.54	0.994947	0.988433	-0.659 %
c007	u-235	al	1.27	0.989334	0.982866	-0.658 %
c008	u-235	al	2.54	0.988649	0.982307	-0.646 %
c009	u-235	ti	1.27	0.994135	0.987767	-0.645 %
c010	u-235	ti	2.54	0.996451	0.989906	-0.661 %
c011	u-235	fe	1.27	0.998081	0.991672	-0.646 %
c012	u-235	fe	2.54	0.990955	0.984332	-0.673 %
c013	u-235	ni	1.27	0.990904	0.984588	-0.641 %
c014	u-235	ni	2.54	0.994334	0.987967	-0.644 %
c015	u-235	cu	1.27	0.991635	0.985316	-0.641 %
c016	u-235	cu	2.54	0.998562	0.992127	-0.649 %
c017	u-235	mo	1.27	1.003360	0.996582	-0.680 %
c018	u-235	mo	2.54	1.013120	1.006210	-0.687 %
c019	u-235	mo-allo		1.003810	0.997282	-0.655 %
c020	u-235	w	1.27	0.987416	0.980685	-0.686 %
c021	u-235	w	2.54	0.987675	0.981390	-0.640 %
c10100	u-235			0.998285	0.992167	-0.617 %

c20100	u-235			1.004730	0.997933	-0.681 %
c30100	u-235			1.001100	0.994867	-0.627 %
c40100	u-235	be	2.222	0.998019	0.991442	-0.663 %
c50100	u-235	be	3.260	0.999108	0.992707	-0.645 %
c60100	u-235	be	4.710	1.002990	0.996677	-0.633 %
c70100	u-235	be	5.440	1.000370	0.993858	-0.655 %
c80100	u-235	be	9.270	1.001940	0.995947	-0.602 %
c90100	u-235	be	11.790	1.001540	0.995308	-0.626 %
c10010	u-235	c	10.160	0.997750	0.991028	-0.678 %
c11010	u-235	c	15.240	0.993739	0.987280	-0.654 %
c12010	u-235	ni	4.940	0.997086	0.990638	-0.651 %
c13010	u-235	cu	5.030	1.003730	0.997110	-0.664 %
c14010	u-235	cu	10.560	1.009160	1.002330	-0.681 %
c15010	u-235	w	5.080	1.000260	0.993600	-0.670 %
c16010	u-235	w	10.160	1.001170	0.994547	-0.666 %
c17010	u-235	pb	8.990	1.020890	1.014200	-0.660 %
c18010	u-235	pb	17.220	1.020590	1.013680	-0.682 %
c19010	u-235	u	1.760	1.001340	0.994603	-0.677 %
c20010	u-235	u	4.470	1.005410	0.998442	-0.698 %
c21010	u-235	u	9.960	1.002660	0.995373	-0.732 %
c22010	u-235	u	18.010	0.998976	0.991576	-0.746 %
			Averages	**0.999340**	**0.994163**	**-0.521 %**

Appendix D: Summary of New Conventions and Options

These are NEW for TART2005; there are no changes for TART 2016 or 2022

To help explain and illustrate the use of the new options the TART2022 DVD distribution includes example input decks. I encourage you to use TARTCHEK to look at these examples - particularly using 3-D views, so you can see them better.

See chapter 2, on Input Parameters for details. Here I only briefly list the new input options and conventions.

Cubic surface

xcubic nb x0 y0 z0 d c b a
ycubic nb x0 y0 z0 d c b a
zcubic nb x0 y0 z0 d c b a

Torus

xtorus nb x0 y0 z0 a b c
ytorus nb x0 y0 z0 a b c
ztorus nb x0 y0 z0 a b c

Macro surfaces: boxes, cylinders, and cones with finite limits

xyzbox nb dx dy dz [x0 y0 z0]
xyzbox2 nb x1 x2 y1 y2 z1 z2
xcan nb rad dx [x0 y0 z0]
ycan nb rad dy [y0 x0 z0]
zcan nb rad dz [z0 x0 y0]
xconic nb rad1 x1 rad2 x2 [y0 z0]
yconic nb rad1 y1 rad2 y2 [x0 z0]
zconic nb rad1 z1 rad2 z2 [x0 y0]

Macro volumes: simplified input for complicated surfaces

xsurf nz ns x1 ri1 ro1 &
x2 ri2 ro2 &
x3 ri3 ro3 &
(continued for more points)

ysurf nz ns y1 ri1 ro1 &
y2 ri2 ro2 &
y3 ri3 ro3 &
(Continued for more points)

zsurf nz ns z1 ri1 ro1 &
z2 ri2 ro2 &

z3 ri3 ro3 &
(Continued for more points)

Rotation about the X, Y or Z axis

xrotate ang is1 thru is2
xrotate ang is1 is2 is3.....
yrotate ang is1 thru is2
yrotate ang is1 is2 is3.....
zrotate ang is1 thru is2
zrotate ang is1 is2 is3.....

Translation of Spatial Coordinates

addxyz xadd yadd zadd is1 thru is2
addxyz xadd yadd zadd is1 is2 is3.....

Cloning (Duplicating) Surfaces

clones ns is1 thru is2
clones ns is1 is2 is3.....

Reduced, Reflecting Geometry

xabove x0
yabove y0
zabove z0

xbelow x0
ybelow y0
zbelow z0

New Sources

source19 (spherical shell), **source 20** (cylindrical shell), and **source21** (a rectangular box) allow you to sample from irregularly shaped zones,

source19 nz1 thru nz2 ri ro [x0 y0 z0]
s19 nz1 thru nz2 ri ro [x0 y0 z0]
s19g nz1 thru nz2 ri ro [x0 y0 z0]

source20 nz1 thru nz2 z1 z2 ri r0 [x0 y0]
s20 nz1 thru nz2 z1 z2 ri r0 [x0 y0]
s20g nz1 thru nz2 z1 z2 ri r0 [x0 y0]

source21 nz1 thru nz2 x1 x2 y1 y2 z1 z2
s21 nz1 thru nz2 x1 x2 y1 y2 z1 z2
s21g nz1 thru nz2 x1 x2 y1 y2 z1 z2

Defining Zone Volume by User Input

volume nz1 vz1 nz2 vz2 nz3 vz3…..

Changes in sentinels

"BEST" Options, now set for you

ALL sentinels now have a default value that I consider giving you the **BEST** physics. Therefore, I strongly suggest that you NOT DEFINE MOST sentinels as TART input; in which case the default value will be used. I say MOST because there are a few sentinels you will want to define, such as sentl 2 and 3, that define the number of neutron or photon samples to run; these are strongly problem dependent, e.g., any given problem can require thousands to trillions of neutron and/or photon samples.

Sentinels 20 (self-shielding), 25 (fluorescence) and 39 (thermal scattering) are now all initialized as ON. You should NEVER use/change these unless you really do want to turn off this physics. Starting with TART2005, if a continuous energy cross section file (named NEUTRON) is present Sentinel 20 defaults to 2, to use this data; for compatibility with older TART data libraries, which do not include continuous energy cross sections, if file NEUTRON is not present sentinel 20 defaults to 1, to use multi-band parameters.

Sentinels 8, 9, 13, 14, 15 and 16, limit the energy range for tracking and tallying neutrons and photons. These are now automatically set for you, and you should NEVER use these unless you really do want to limit these ranges.

New Sentinels, 54 through 57

54 - definition of the number of neutrons per fission; use either $<\nu>$, or sample the probability distribution of ν.

55 - define a correlated spontaneous fission source.

56 - what to tally with tally types 11 and 12: neutrons entering a zone, absorption, capture, fission….

57 - use either total or prompt $<\nu>$. Starting with TART2005, this option is also used to control the energy and time dependence of delayed neutrons; it now defaults to 2, for static criticality, to use the delayed neutron energy spectra, but all neutrons are produced promptly (immediately); for time dependence problems 3 is used for this option to include a delayed in time of delayed neutron emission.

References

[1] **TART2016:** A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, LLNL-SM-704560, Code Release: LLNL-CODE-708759, September 2016, by D.E. Cullen. Available on-line:
PDFfiller - Report_ LLNL-SM-704560.pdf (uslegalforms.com)

[2] **TART2012:** A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, LLNL-TR-577352, July 22, 2012, by D.E. Cullen. Available online: Tart2012 (osti.gov)

[3] **TART2005:** A Coupled Neutron-Photon 3-D, Time Dependent, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-SM-218009, November 22, 2005, by D.E. Cullen.

[4] "**TART95**: A Coupled Neutron-Photon Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-MA-121319, July 1995, by D.E. Cullen, A.L. Edwards, and E.F. Plechaty

[5] "**TART96**: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-ID-126455, November 1996, by D.E. Cullen:

[6] "**TART97**: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-ID-126455, Rev. 1, November 1997, by D.E. Cullen

[7] "**TART98**: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Time Dependent Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-ID-126455, Rev. 2, November 1998, by D.E. Cullen

[8] "**TART2000**: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Time Dependent Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-ID-126455, Rev. 3, November 2000, by D.E. Cullen

[9] "**TART2002**: A Coupled Neutron-Photon 3-D, Combinatorial Geometry Time Dependent Monte Carlo Transport Code," Lawrence Livermore National Laboratory, UCRL-ID-126455, Rev. 4, June 2003, by D.E. Cullen

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[11] Private Communication, (circa 1975), by R.J. Howerton

[12] **"Nuclear Data Preparation"**, pp. 279-425, Vol. 1, in "The Handbook of Nuclear Engineering", Springer Publishing, NY, NY (2010), by D.E. Cullen. See also, "**URR-Pack:** Calculating Self-Shielding in the Unresolved Resonance Energy Range," INDC(NDS)-0711, Rev. 1, by D.E. Cullen and Andrej Trkov, Nuclear Data Section, IAEA, Vienna, July 2016.

[13] "**THERMAL**: A Routine Designed to Calculate Neutron Thermal Scattering," Lawrence Livermore National Laboratory, UCRL-ID-120560-Rev-1, Sept. 1995, by D.E. Cullen.

[14] "New Thermal Neutron Scattering Files for ENDF/B-VI Release 2", Los Alamos National Laboratory (March 1994), by R.E. MacFarlane.

[15] "**POINT2021**: ENDF/B-VIII.0 Temperature Dependent Cross Section Library", IAEA-NDS-0237, Nuclear Data Section (NDS), IAEA, Vienna, Austria, May 2021. .

[16] "**EPDL97**: the Evaluated Photon Data Library, '97 Version," Lawrence Livermore National Laboratory, UCRL--50400, Vol. 6, Rev. 5, by D.E. Cullen; this is now the official ENDF/B-VI photon interaction data library.

Now replaced by ,"**EPICS2017**: Electron Photon Interaction Cross Sections", IAEA-NDS-225, Rev. 1,February 2018, by D.E. Cullen, Nuclear Data Section, IAEA, Vienna, Austria, September 2014

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