ANT COLONY OPTIMIZATION OF SHIELDING FOR MIXED NEUTRON AND GAMMA RADIATIONS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

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JANUARY 2020

ACKNOWLEDGEMENT

Alhamdulillah. All praise to The Almighty Allah for His Guidance and Providence. Blessings to Prophet Muhammad (PBUH). May the knowledge and the experience that I have gained throughout this journey make me a better servant of Him.

I would like to express my gratitude towards my supervisors, Prof. Ir. Dr. Nahrul Khair Alang Md. Rashid, Assoc. Prof. Dr. Khaidzir Hamzah, and Assoc. Prof. Dr. Muneer Saleh for their continuous support and advice in completing this thesis. I am very honoured to have been assisted by the experts in UNIST-Core Laboratory: Prof. Deokjung Lee, Dr. Matthieu Lemaire, and Mr. Wonkyeong Kim. I am also grateful for the help extended by Nuclear Malaysia experts, namely Dr. Wan Saffiey Wan Abdullah, Dr. Faridah Idris, and Mr. Pairu Ibrahim. I highly appreciate the help provided by the SCEE Nuclear Laboratory personnel, namely Dr. Jasman Zainal, Mr. Ikhwan Samat, and Mr. Yusri Yusof. Special thanks to the Ministry of Education and Universiti Teknologi Malaysia for their financial support. Not to be forgotten, I would like to give a shout-out to my colleagues who have helped me along the way: Syahir, Husaini, Wani, Nadzmi, Laila, Aizat, Acap, Ubai, and others. Finally, I am thankful to my family, especially Mother for her endless love and encouragement. Since she has always been a strong supporter of my education, I would say that this success of mine is hers as well.

May Allah repay all of you in the goodness of this world and the hereafter.

ABSTRACT

Shielding is important in maintaining safe levels of radiation. In mixed neutrons and gamma-rays condition, more than one material are needed for shielding purposes. These materials can be arranged into a multilayer shield or they can be mixed into a composite shield. These shields have different variables and it can be increasingly complex to optimise them. In such a situation, using brute method is infeasible in terms of computation time. Recent studies have been looking into the use of metaheuristics in shield optimisation specifically the genetic algorithm (GA). This study extends the knowledge by investigating the ant colony optimisation (ACO) for shielding optimisation against mixed radiation. Three objectives were outlined: to develop an ACO-based algorithm to optimise a shield made from polyethylene (PE), boron, and tungsten, to build a GA as a comparison, and to evaluate the new shield design. MCNP5 was used for shielding calculations. There were four problem cases: a composite shield with known solution (Case 1); a composite shield with unknown solution (Case 1.2); a multilayer shield with known solution (Case 2); and a multilayer shield with unknown solution (Case 2.2). Six ACO parameters and four GA parameters were tested to observe their effects and to determine their best values for the optimisation algorithms. Four composite shields were fabricated and experimented with a ^{252}Cf mixed neutron-gamma source. It was observed that the ACO-MCNP algorithm was significantly better than the brute method. It managed to find the exact solutions for Case 1 and Case 2 while reducing the runtime of the brute method by 81.75% and 89.01% respectively. For Case 1.2 and Case 2.2, good solutions were achieved in only 2.13 hours and 1.28 hours respectively as compared to the brute method which could take almost 70 hours to complete. The results also suggest that the ACO is a good alternative to the GA for shielding optimisation. For the experimental work, it was found that the PE composite with additives of 16 wt% boron and 16 wt% tungsten had the best mixed radiation shielding performance as compared to pure polyethylene, poly-boron (25 wt%), and poly-tungsten (25 wt%).

ABSTRAK

Pemerisaian adalah penting dalam mengekalkan tahap sinaran yang selamat. Dalam keadaan wujudnya percampuran neutron dan sinaran gama, lebih dari satu bahan diperlukan bagi tujuan pemerisaian. Bahan-bahan ini boleh disusun secara berlapis atau dicampur menjadi bahan komposit. Perisai seperti ini mempunyai pelbagai pembolehubah dan usaha untuk mengoptimumkannya boleh menjadi rumit. Dalam situasi sebegini, kaedah daya kasar adalah tidak praktikal dari segi masa penyelesaian. Kajian-kajian terkini telah menguji kaedah metaheuristik untuk pengoptimuman perisaian terutamanya kaedah algoritma genetik (GA). Kajian ini melanjutkan usaha tersebut dengan menyiasat kaedah pengoptimuman koloni semut (ACO) untuk perisaian sinaran tercampur. Terdapat tiga objektif: membangunkan algoritma ACO untuk perisaian dari polietilena (PE), boron, dan tungsten; membangunkan GA sebagai perbandingan; dan menguji perisai yang baharu. MCNP5 telah digunakan untuk pengiraan pemerisaian. Terdapat empat kes masalah: perisai komposit yang berjawapan (Kes 1); perisai komposit yang tiada jawapan (Kes 1.2); perisai berlapis yang berjawapan (Kes 2); dan perisai berlapis yang tiada jawapan (Kes 2.2). Enam parameter ACO dan empat parameter GA telah diuji untuk melihat impak mereka dan untuk mengetahui nilai yang terbaik untuk algoritma pengoptimuman. Empat perisai komposit telah dihasilkan dan diuji dengan sumber sinaran tercampur ^{252}Cf. Ia didapati bahawa algorithma ACO-MCNP adalah jauh lebih baik dari kaedah daya kasar. Ia berjaya menemukan penyelesaian yang tepat bagi Kes 1 dan Kes 2 di samping mengurangkan masa penyelesaian kaedah daya kasar masing-masing sebanyak 81.75% dan 89.01%. Untuk Kes 1.2 dan Kes 2.2, algorithma tersebut menghasilkan penyelesaian yang baik masing-masing dalam jangka masa 2.13 jam dan 1.28 jam berbanding dengan kaedah daya kasar yang boleh mengambil masa hampir 70 jam untuk mendapatkan penyelesaian yang lengkap. Dapatan juga menunjukkan bahawa kaedah ACO ini merupakan satu alternatif yang baik kepada GA dalam pengoptimuman pemerisaian. Untuk kajian eksperimen, ia didapati bahawa komposit PE dengan kandungan 16 berat% boron dan 16 berat% tungsten merupakan perisai yang terbaik untuk sinaran tercampur berbanding dengan polietilena asli, poli-boron (25 berat%), dan poli-tungsten (25 berat%)

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LIST OF ABBREVIATIONS

ACO – Ant colony optimization
ASP – Aligned Sendust particles
BOG – Boron oxide glass
BSF – Best-so-far
BX – Borax
COP – Combinatorial optimisation problem
CORE – Computational Reactor Physics and Experiment
EI – Epoxy ilmenite
ENDF – Evaluated Nuclear Data File
GA – Genetic Algorithm
GHz – GigaHertz
HDPE – High-density polyethylene
HVL – Half-value layer
ICRP – International Commission on Radiological Protection
KAERI – Korea Atomic Energy Research Institute
kBq – KiloBecquerel
kVp – Kilovolt-peak
LDPE – Low-density polyethylene
MCNP – Monte Carlo N-Particle
MeV – Megaelectronvolt
NEPA – National Environmental Policy Act
NPT – Non-Proliferation Treaty
OPEC – Organization of Petroleum Exporting Countries
PB – Poly-boron
PE – Polyethylene
rpm – Rotation per minute
SOM – Sub-optimisation mechanism
TSP – Travelling Salesman Problem
UNIST – Ulsan National Institute of Science and Technology
VLSI – Very-large-scale integration

LIST OF SYMBOLS

Al – Aluminium

B – Boron

Ba – Barium

Be – Beryllium

Bi – Bismuth

C – Carbon

Cf – Californium

Fe – Iron

He – Helium

n – Neutron

NaI – Sodium iodide

O – Oxygen

Pb – Lead

Pt – Platinum

Pu – Plutonium

Sb – Antimony

Sm – Samarium

W – Tungsten

wt% – Weight percentage

Xe – Xenon

Z – Proton number

γ – Gamma rays

μ/ρ – Mass attenuation coefficient

Σ_t – Total macroscopic cross-section

σ_t – Total microscopic cross-section

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The advances of nuclear technology and their widespread applications in various fields pose risks of radiation exposure to the people and the environment. There are two types of radiation: non-ionising radiation and ionising radiation. The latter is more concerned in nuclear-related activities because they can affect humans at the cellular level (Nambiar and Yeow, 2012). Examples of ionising radiation are alpha particles, beta particles, neutrons, and gamma-rays. The last two examples are the most penetrative radiations and in applications such as nuclear power reactors, they are present together. In such a situation, there is a need for different shield materials for each of them. This is due to their nature and their interaction with matter. Neutrons are neutral particles that can either be absorbed or scattered. Depending on their energy, photons are electromagnetic radiations that can mainly undergo photoelectric effect, Compton scattering, and pair production (Shultis and Faw, 2002).

To establish levels of control of exposure to the public, the International Commission of Radiation Protection (ICRP) has outlined three basic principles which are justification, optimisation, and dose limitation. The radiation dose can be reduced by: (1) maximising distance from the radiation source, (2) minimising time handling the source, and (3) positioning a shield between working personnel and the source. The first two methods can be implemented through the administration of working procedure. The third method requires more careful design and considerations as shields are generally permanent and not easily replaced.

A shield is defined as a physical material placed between an ionizing radiation source and a protected subject (often a human being) to reduce the radiation level at the subject's position (Chilton, Shultis, and Faw, 1984). Various materials have been used as shielding. Generally, hydrogenous materials such as paraffin and water are good for neutron shielding because hydrogen atoms can elastically scatter neutrons, effectively reducing their energy. Meanwhile, shields for photons such as X-rays and gamma-rays need to be made from elements of high atomic number as they have more electrons to react with the photons.

The different materials required to shield against mixed radiation can exist in the form of chemically-bonded compound material (e.g. water, polyethylene), or in the form of physically-mixed composite material (e.g. concrete, polyboron). These materials can also be stacked together into a multilayer shield. The advantage of a composite material is that the mass of a shield can be reduced by combining materials of different shielding capabilities (Nambiar et al., 2012). However, the difficulty in producing composites is in ensuring uniformity of the particles in the polymer substrate. The lack of uniformity could cause variations between simulated and experimental results (Osman et al., 2015; Waly and Bourham, 2015; Wang et al., 2015). Non-uniform composites can also result in pinholes, pure polymer areas which radiation can penetrate through (Kim, Park, and Seo, 2015). These problems are not observed in multilayer shields. While they are not as lightweight as composite shields, they can be lighter than single layer shields (McCaffrey, Mainegra-Hing, and Shen, 2009).

Different shielding applications have different design requirements. There will always be conflicting design variables. For example, a mobile system such as a surveillance robot or a spaceship favours a lighter overall mass, but usually, a good radiation shield is heavy. New, exotic materials can be used, but this results in a higher cost of development. Therefore, optimisation approaches can be utilised in resolving the conflicting requirements and in making necessary compromises. With the advent of digital computers, the solution of problems containing many variables and the creation of iterative optimisation schemes became practical. Recently, new nature-inspired metaheuristic algorithms have become popular in optimisation methods because of their simpler implementation, yet they are able to solve a diverse, often highly non-linear problems. They are also capable of finding global optimum in the case of multimodality (more than one optimum solution) (Yang, Koziel, and Leifsson, 2013). Examples are genetic algorithm, particle swarm optimisation, and ant colony optimisation. Currently, only the genetic algorithm had been used in optimising multilayer shielding against mixed radiation.

1.2 Problem Statement

In a shielding optimisation process, there can be many goals and constraints. For a multilayer shield, the variables are the arrangement of the layers and the thickness of each layer. For a composite shield, the composition of elements and the thickness of the shield are considered. The variables can be increasingly complex when other application-related requirements are included. When this happens, determining the exact solution using brute method is not feasible in terms of computation cost and computing time. Therefore, researchers have been investigating the use of metaheuristics (a class of approximate optimisation algorithms) in shield optimisation. Previous studies only focused on the genetic algorithm (GA) (Hu et al., 2008; Kim and Moon, 2010; Cai et al., 2018). There seems to be a lack of researches on the use of other metaheuristics. Therefore, a study on the application of ant colony optimisation (ACO) to shielding design was proposed. Depending on the problem, the ACO algorithm was found to have some advantages over the GA. The former has higher computational efficiency, is less affected by poor initial solutions, and is able to maintain collective information from all iterations (Maier et al., 2003; Camp and Bichon, 2004; Aydoğdu and Saka, 2012). The performance and behaviour of the ACO for shield optimisation problem are still undetermined because there is no investigation on this matter so far. It is also unknown if the metaheuristic has any advantage over the GA for this problem. In addition, a novel composite shield design made up of polyethylene, boron, and tungsten can be investigated using the optimisation algorithms and experiments.

1.3 Objectives of the Study

Based on the problem statement, the main objective of this study is to determine the performance of ACO algorithm in shielding optimisation. It is separated into three specific objectives:

1. To develop an ACO algorithm for optimising a novel shield consisting of polyethylene, boron, and tungsten against neutrons and gamma-rays.
2. To develop a genetic algorithm for comparison with the ACO algorithm.
3. To evaluate the shielding effectiveness of the new shield design.

1.4 Scope of the Study

There were two cases for the shields: multilayer (three layers) and composite. The multilayer shield was optimised in terms of thickness and arrangement, while the composite shield was optimised in terms of its elemental weight percentages and thickness. The shielding materials were polyethylene, boron, and tungsten. This was due to the ability of the polyethylene to moderate fast neutrons from the source, the ability of the boron to absorb the moderated neutrons, and the ability of the tungsten to absorb gamma-rays from the source and also secondary photons from neutron interactions with the shielding material.

Three types of optimisation algorithms were developed. The first algorithm was a brute method (trial-and-error) algorithm which the exact solution to the shielding problem was identified by evaluating every possible combination of the shielding variables. The last two algorithms were based on the Ant Colony Optimisation method and Genetic Algorithm method. Testing was done for six ACO parameters and four GA parameters to determine the most suitable settings for the shielding optimisation problem. The ACO parameters were the number of iterations, the number of ants, the pheromone relative coefficient, the heuristic information relative coefficient, the pheromone addition constant, and the evaporation coefficient. On the other hand, the

GA parameters were the number of generations, the number of individuals, the parent-to-population ratio, and the mutation rate. The performances of ACO and GA were assessed based on their running times and the quality of the generated results (i.e. how close they were from the exact solutions).

The shields were evaluated using MCNP5 simulations and experimental work. In the MCNP5 calculations, the radiation source was made to release monoenergetic 700-keV neutrons and 200-keV photons to simulate the most probable energy of the radiations emitted by a mixed neutron-gamma source (Hadad et al., 2016; Boulogne and Evans, 1968). The desired output was the dose rates in the detector volume. For the experiment, the source used is ^{252}Cf. The shield performance was gauged based on the comparison between the unshielded dose rates with the transmitted dose rates.

1.5 Significance of the Study

This research extends the research on the use of metaheuristics for radiation shielding optimisation, specifically the ACO method. Its advantage over the brute method and the GA method can be determined through the comparison between their optimisation performance. The resulting algorithm can be used to optimise a shielding made up of any material available to the designer. Besides, due to the flexibility of the metaheuristic, the ACO can be utilised for other shielding applications such as mobile nuclear devices and spacecraft. This can be done by changing the optimisation goals and constraints. The success of the implementation of ACO in shielding optimisation means that other metaheuristics can also be explored in order to develop better tools for shielding designers. The outcome of the experiment also reveals the potential of a new shield design made up of polyethylene, boron, and tungsten in a mixed neutron-gamma condition.

1.6 Organisation of Chapters

Chapter 1 introduces the background, the problem statement, objectives, scopes, and significance of the research. **Chapter 2** discusses a literature review of radiation shielding, metaheuristics, ant colony optimisation, and previous related studies of other authors. **Chapter 3** describes the methodology of simulations and experiments that were used in this research. **Chapter 4** includes the discussion of results. **Chapter 5** concludes the thesis with a summary of the findings and recommendations for future work.

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APPENDIX A List of Publications

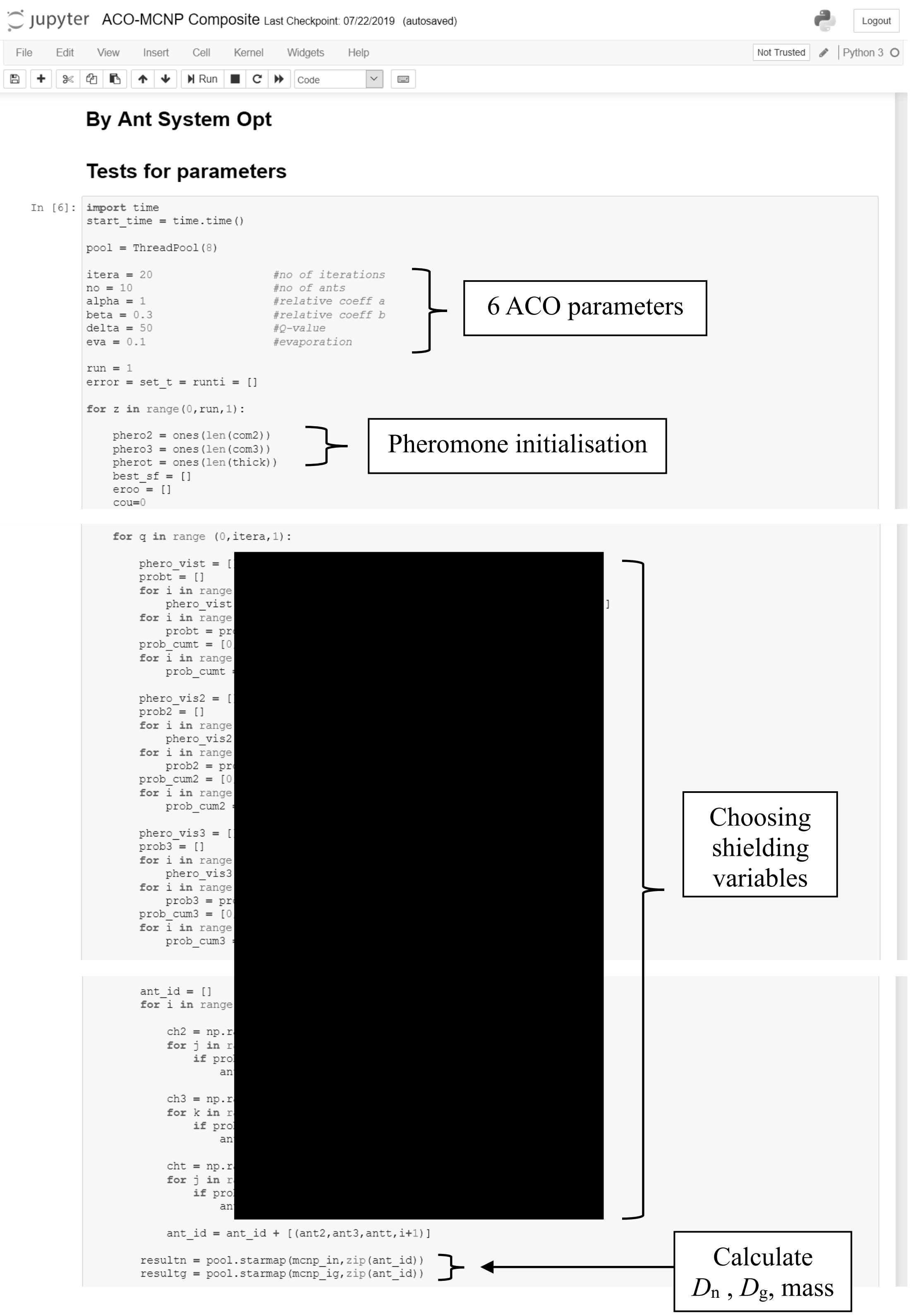
Indexed Conference Proceedings

1. **Sazali, M. A. B.**, Rashid, N. K. A. M., & Hamzah, K. (2017, July). Ant Colony Optimization of Multilayer Shielding for Mixed Neutron and Gamma Radiations: A Preliminary Study. In *2017 25th International Conference on Nuclear Engineering* (pp. V009T15A058-V009T15A058). American Society of Mechanical Engineers. **(Indexed by SCOPUS)**

2. **Sazali, M. A.**, Rashid, N. K. A. M., & Hamzah, K. (2018, January). A preliminary study to metaheuristic approach in multilayer radiation shielding optimization. In *IOP Conference Series: Materials Science and Engineering* (Vol. 298, No. 1, p. 012042). IOP Publishing. **(Indexed by SCOPUS)**

3. Sazali, M. A., Rashid, N. K. A. M., & Hamzah, K. (2019, June). A review on multilayer radiation shielding. In *IOP Conference Series: Materials Science and Engineering* (Vol. 555, No. 1, p. 012008). IOP Publishing. **(Indexed by SCOPUS)**

APPENDIX B ACO-MCNP Python Script



By Ant System Opt

Tests for parameters

```
In [6]: import time
        start_time = time.time()

        pool = ThreadPool(8)

        itera = 20                  #no of iterations
        no = 10                     #no of ants
        alpha = 1                   #relative coeff a
        beta = 0.3                  #relative coeff b
        delta = 50                  #Q-value
        eva = 0.1                   #evaporation

        run = 1
        error = set_t = runti = []

        for z in range(0,run,1):

            phero2 = ones(len(com2))
            phero3 = ones(len(com3))
            pherot = ones(len(thick))
            best_sf = []
            eroo = []
            cou=0
```

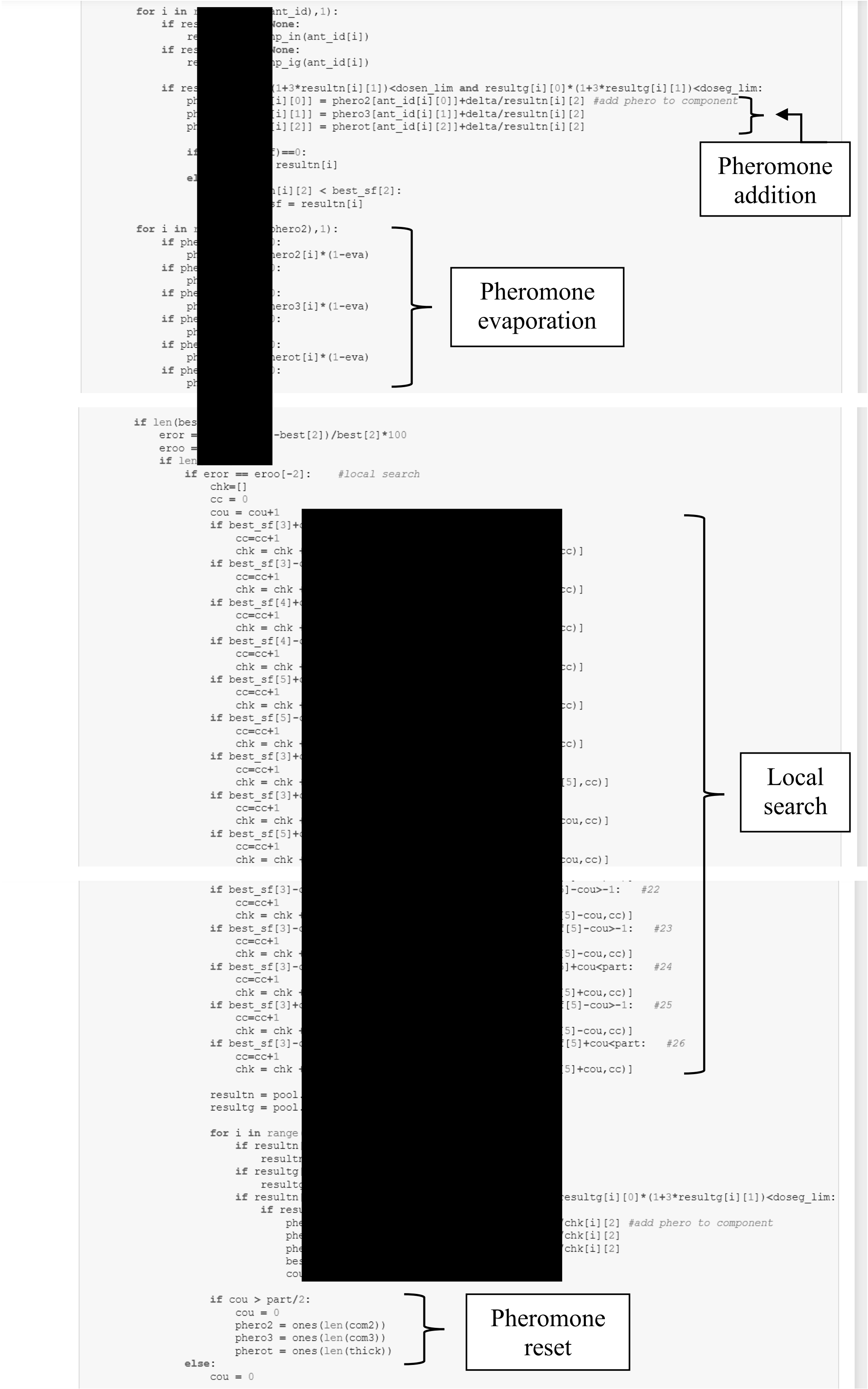
6 ACO parameters

Pheromone initialisation

```
    for q in range (0,itera,1):

        phero_vist = [ [redacted]
        probt = []
        for i in range
            phero_vist                                                ]
        for i in range
            probt = pr
        prob_cumt = [0
        for i in range
            prob_cumt

        phero_vis2 = [
        prob2 = []
        for i in range
            phero_vis2
        for i in range
            prob2 = pr
        prob_cum2 = [0
        for i in range
            prob_cum2

        phero_vis3 = [
        prob3 = []
        for i in range
            phero_vis3
        for i in range
            prob3 = pr
        prob_cum3 = [0
        for i in range
            prob_cum3


        ant_id = []
        for i in range

            ch2 = np.r
            for j in r
                if pro
                    an

            ch3 = np.r
            for k in r
                if pro
                    an

            cht = np.r
            for j in r
                if pro
                    an

            ant_id = ant_id + [(ant2,ant3,antt,i+1)]

        resultn = pool.starmap(mcnp_in,zip(ant_id))
        resultg = pool.starmap(mcnp_ig,zip(ant_id))
```

Choosing shielding variables

Calculate D_n , D_g, mass

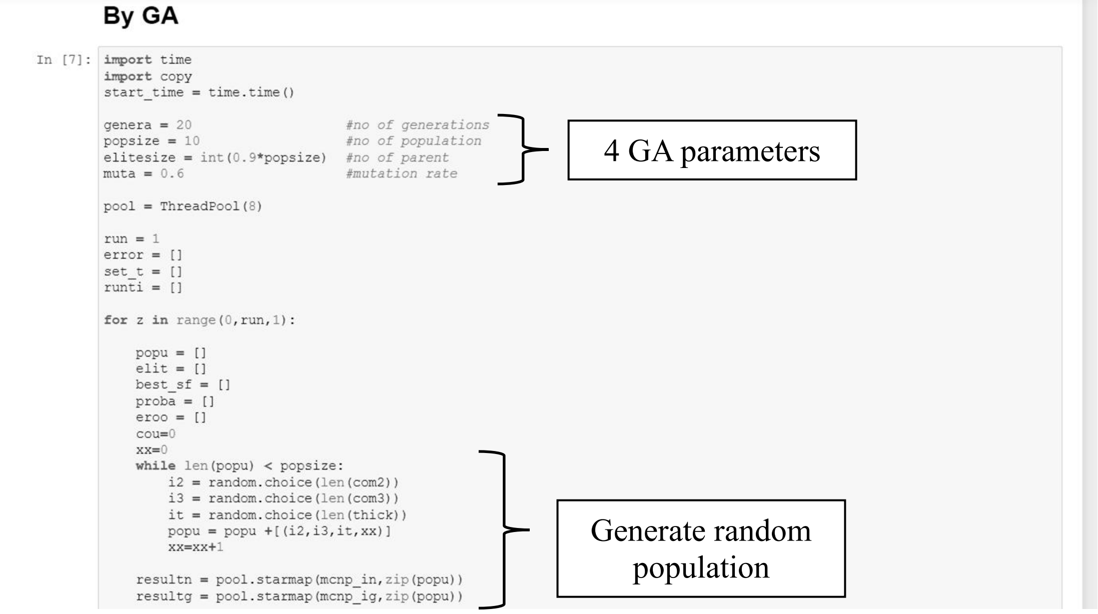


```
for i in r [redacted] ant_id),1):
    if res None:
        re np_in(ant_id[i])
    if res None:
        re np_ig(ant_id[i])

    if res (1+3*resultn[i][1])<dosen_lim and resultg[i][0]*(1+3*resultg[i][1])<doseg_lim:
        ph [i][0]] = phero2[ant_id[i][0]]+delta/resultn[i][2] #add phero to component
        ph [i][1]] = phero3[ant_id[i][1]]+delta/resultn[i][2]
        ph [i][2]] = pherot[ant_id[i][2]]+delta/resultn[i][2]

        if f)==0:
            resultn[i]

        el
            n[i][2] < best_sf[2]:
                sf = resultn[i]

for i in r phero2),1):
    if phe 0:
        ph hero2[i]*(1-eva)
    if phe 0:
        ph
    if phe 0:
        ph hero3[i]*(1-eva)
    if phe 0:
        ph
    if phe 0:
        ph herot[i]*(1-eva)
    if phe 0:
        ph
```

```
if len(bes
    eror = -best[2])/best[2]*100
    eroo =
    if len
        if eror == eroo[-2]:    #local search
            chk=[]
            cc = 0
            cou = cou+1
            if best_sf[3]+c [redacted]
                cc=cc+1
                chk = chk cc)]
            if best_sf[3]-c
                cc=cc+1
                chk = chk cc)]
            if best_sf[4]+c
                cc=cc+1
                chk = chk cc)]
            if best_sf[4]-c
                cc=cc+1
                chk = chk cc)]
            if best_sf[5]+c
                cc=cc+1
                chk = chk cc)]
            if best_sf[5]-c
                cc=cc+1
                chk = chk cc)]
            if best_sf[3]+c
                cc=cc+1
                chk = chk [5],cc)]
            if best_sf[3]+c
                cc=cc+1
                chk = chk cou,cc)]
            if best_sf[5]+c
                cc=cc+1
                chk = chk cou,cc)]
```

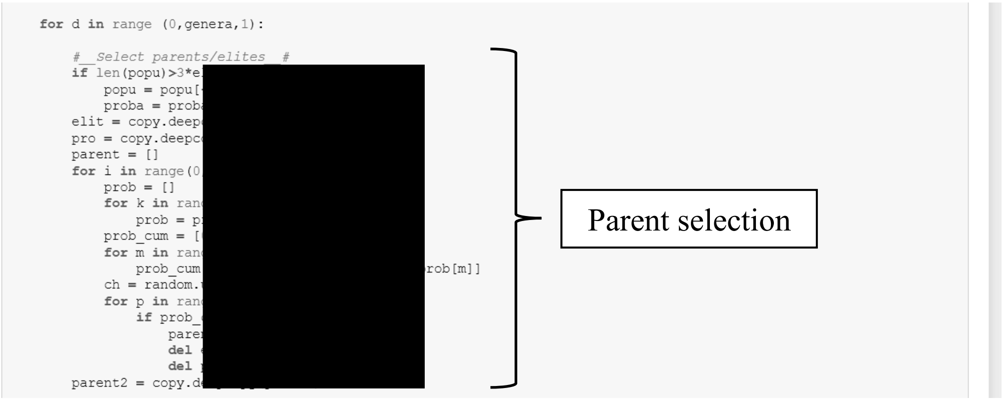
```
            if best_sf[3]-c ]-cou>-1:   #22
                cc=cc+1
                chk = chk [5]-cou,cc)]
            if best_sf[3]-c f[5]-cou>-1:   #23
                cc=cc+1
                chk = chk [5]-cou,cc)]
            if best_sf[3]-c ]+cou<part:   #24
                cc=cc+1
                chk = chk [5]+cou,cc)]
            if best_sf[3]+c f[5]-cou>-1:   #25
                cc=cc+1
                chk = chk [5]-cou,cc)]
            if best_sf[3]-c f[5]+cou<part:   #26
                cc=cc+1
                chk = chk [5]+cou,cc)]

            resultn = pool.
            resultg = pool.

            for i in range
                if resultn
                    resultn
                if resultg
                    resultg
                if resultn esultg[i][0]*(1+3*resultg[i][1])<doseg_lim:
                    if resu
                        phe chk[i][2] #add phero to component
                        phe chk[i][2]
                        phe chk[i][2]
                        bes
                        cou

            if cou > part/2:
                cou = 0
                phero2 = ones(len(com2))
                phero3 = ones(len(com3))
                pherot = ones(len(thick))
        else:
            cou = 0
```

APPENDIX C GA-MCNP Python Script

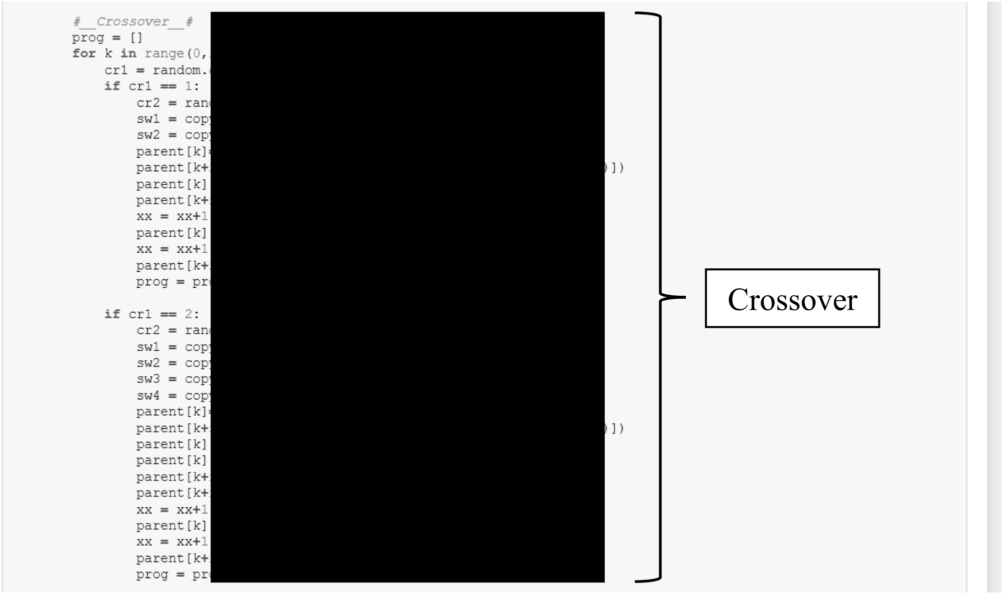


By GA

```
In [7]: import time
        import copy
        start_time = time.time()

        genera = 20                     #no of generations
        popsize = 10                    #no of population
        elitesize = int(0.9*popsize)    #no of parent
        muta = 0.6                      #mutation rate

        pool = ThreadPool(8)

        run = 1
        error = []
        set_t = []
        runti = []

        for z in range(0,run,1):

            popu = []
            elit = []
            best_sf = []
            proba = []
            eroo = []
            cou=0
            xx=0
            while len(popu) < popsize:
                i2 = random.choice(len(com2))
                i3 = random.choice(len(com3))
                it = random.choice(len(thick))
                popu = popu +[(i2,i3,it,xx)]
                xx=xx+1

            resultn = pool.starmap(mcnp_in,zip(popu))
            resultg = pool.starmap(mcnp_ig,zip(popu))
```



```
    for d in range (0,genera,1):

        #__Select parents/elites__#
        if len(popu)>3*e[redacted]
            popu = popu[
            proba = proba
        elit = copy.deep
        pro = copy.deepc
        parent = []
        for i in range(0
            prob = []
            for k in ran
                prob = p
            prob_cum = [
            for m in ran
                prob_cum
            ch = random.
            for p in ran
                if prob_
                    pare
                    del
                    del
        parent2 = copy.d
```



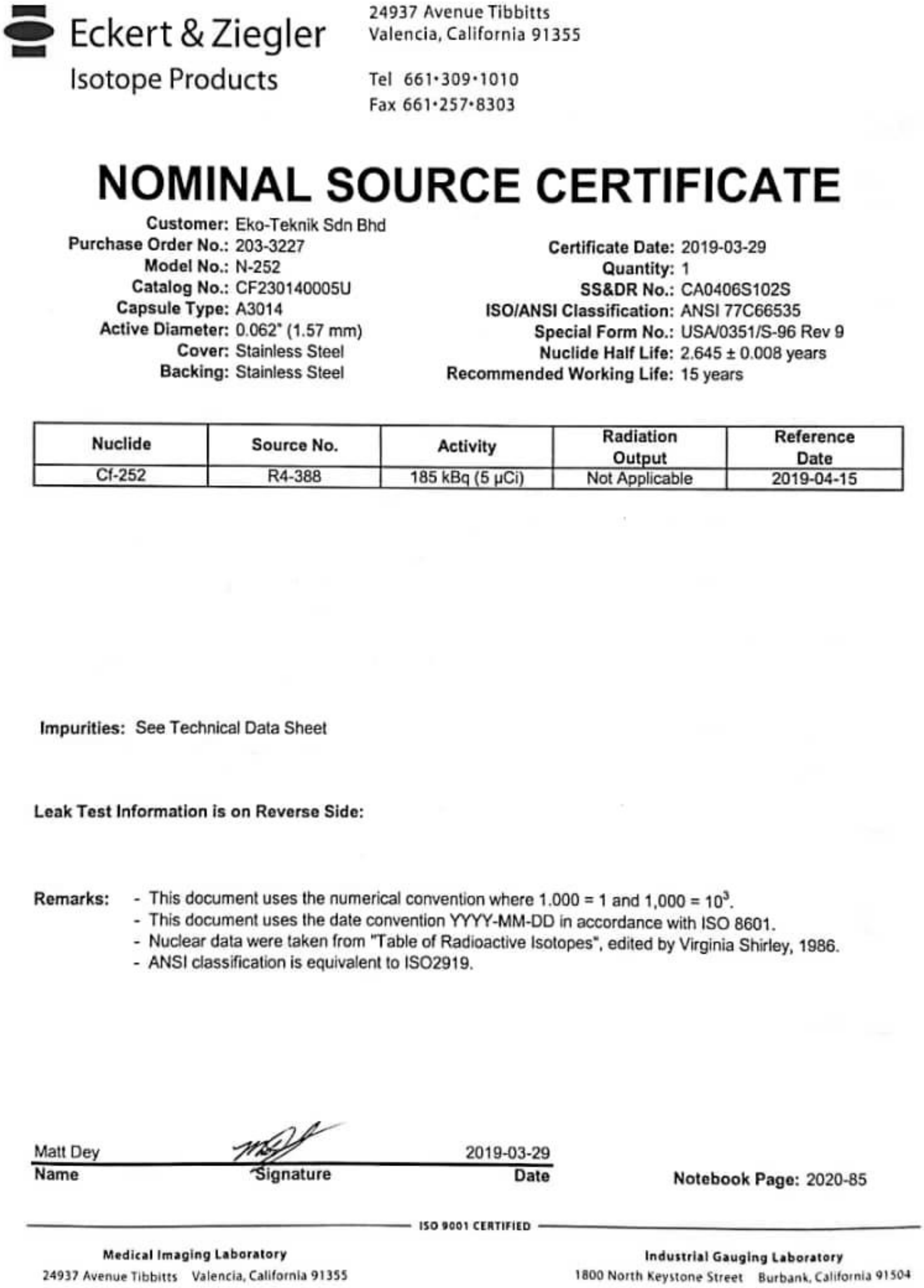
```
        #__Crossover__#
        prog = []
        for k in range(0,[redacted]
            cr1 = random.
            if cr1 == 1:
                cr2 = ran
                sw1 = cop
                sw2 = cop
                parent[k]
                parent[k+
                parent[k]
                parent[k+
                xx = xx+1
                parent[k]
                xx = xx+1
                parent[k+
                prog = pr

            if cr1 == 2:
                cr2 = ran
                sw1 = cop
                sw2 = cop
                sw3 = cop
                sw4 = cop
                parent[k]
                parent[k+
                parent[k]
                parent[k]
                parent[k+
                parent[k+
                xx = xx+1
                parent[k]
                xx = xx+1
                parent[k+
                prog = pr
```

```
#__Mutation__#
for i in range(0,len(pro[redacted]
    mut = random.uniform
    if 0 < mut < muta:
        cr1 = random.cho
        if cr1 == 1:
            cr2 = random
            prog[i][cr2]
        if cr1 == 2:
            cr2 = random
            prog[i][cr2]
            prog[i][cr2+
        if cr1 == 3:
            prog[i][0] =
            prog[i][1] =
            prog[i][2] =

#__Select next gen__#
resultn = pool.starmap(m
resultg = pool.starmap(m

next1 = []
next2 = []
for a in range(0,len(res
    if resultn[a] is Non
        resultn[a]=mcnp_
    if resultg[a] is Non
        resultg[a]=mcnp_
    next1 = next1 + [pro
    next2 = next2 + [1/r
    if resultn[a][0]*(1+                             nd resultg[a][0]*(1+3*resultg[a][1]) < doseg_lim:
        if len(best_sf)=
            best_sf = re
        else:
            if resultn[a
                best_sf

popu = popu + next1
proba = proba + next2
```

```
if len(best_sf) > 0:[redacted]
    eror = (best_sf[2
    eroo = eroo + [er
    if len(eroo)>1:
        if eror == er
            chk=[]
            cc = 0
            cou = cou
            if best_s
                cc=cc
                chk =                                          ],cc)]
            if best_s
                cc=cc
                chk =                                          ],cc)]
            if best_s
                cc=cc
                chk =                                          ],cc)]
            if best_s
                cc=cc
                chk =                                          ],cc)]
            if best_s
                cc=cc
                chk =                                          u,cc)]
            if best_s
                cc=cc
                chk =                                          u,cc)]
            if best_s
                cc=cc
                chk =                                          _sf[5],cc)]
            if best_s
                cc=cc
                chk =                                          ]+cou,cc)]
            if best_s
                cc=cc
                chk =                                          ]+cou,cc)]
            if best_s
                cc=cc
                chk =                                          _sf[5],cc)]
```

```
            resultn = p[redacted]_in,zip(chk))
            resultg = p               _ig,zip(chk))

            for i in ra               :
                if resu
                    res               hk[i])
                if resu
                    res               hk[i])
                if resu               esultn[i][1])<dosen_lim and resultg[i][0]*(1+3*resultg[i][1])<doseg_lim:
                    if                st_sf[2]:
                                      ] = phero2[chk[i][0]]+delta/chk[i][2] #add phero to component
                                      ] = phero3[chk[i][1]]+delta/chk[i][2]
                                      ] = pherot[chk[i][2]]+delta/chk[i][2]
                                      [i]


            if cou > 4:
                cou = 
                c = lis               ))
                random.
                popu, p
                popu=li
                proba=l
        else:
            cou = 0
```

APPENDIX D Neutron Source Specifications



Eckert & Ziegler
Isotope Products

24937 Avenue Tibbitts
Valencia, California 91355

Tel 661•309•1010
Fax 661•257•8303

NOMINAL SOURCE CERTIFICATE

Customer: Eko-Teknik Sdn Bhd
Purchase Order No.: 203-3227
Model No.: N-252
Catalog No.: CF230140005U
Capsule Type: A3014
Active Diameter: 0.062" (1.57 mm)
Cover: Stainless Steel
Backing: Stainless Steel

Certificate Date: 2019-03-29
Quantity: 1
SS&DR No.: CA0406S102S
ISO/ANSI Classification: ANSI 77C66535
Special Form No.: USA/0351/S-96 Rev 9
Nuclide Half Life: 2.645 ± 0.008 years
Recommended Working Life: 15 years

Nuclide	Source No.	Activity	Radiation Output	Reference Date
Cf-252	R4-388	185 kBq (5 μCi)	Not Applicable	2019-04-15

Impurities: See Technical Data Sheet

Leak Test Information is on Reverse Side:

Remarks:
- This document uses the numerical convention where 1.000 = 1 and 1,000 = 10^3.
- This document uses the date convention YYYY-MM-DD in accordance with ISO 8601.
- Nuclear data were taken from "Table of Radioactive Isotopes", edited by Virginia Shirley, 1986.
- ANSI classification is equivalent to ISO2919.

Matt Dey
Name

Signature

2019-03-29
Date

Notebook Page: 2020-85

ISO 9001 CERTIFIED

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