Search of Optimum Gas Mixture Ratio as Gas Insulating Medium by Genetic Algorithm

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ABSTRACT

Genetic algorithm is applied to find the optimum gas mixture ratio as gas insulating medium substituting pure SF_6. Genetic Algorithm is very useful to find the optimum solution from vast searching possibilities. Testing each gas mixture by experiment requires a long time. The present method is very efficient to preselect the candidates of gas mixtures before more thorough but time-consuming investigation via experiment is carried out. The gas mixture ratio is coded as a series of bits simulating a genetic sequence of a life form. Two-term Boltzmann equation is used to calculate the effective ionization coefficient of each gas mixture that is used to evaluate the degree of adaptation of each individual representing one set of mixture ratios. Two types of degree of adaptation are used to evaluate each individual, the effective ionization coefficient at the critical ratio of the electric field to the gas density of SF_6 of 359.3×10^{21} Vm^2, and the global warming potential. Based on the degree of adaptation, better individuals can be selected as parents of the next generation, leaving their genes to future generations. After some generations, the group of individuals converges into the optimum with the best degree of adaptation.

Index Terms — **Genetic Algorithm, gas mixture, SF_6, global warming potential, Boltzmann analysis.**

1 INTRODUCTION

THE use of closed gas insulation system reduces the size of electrical power apparatus. Various gas insulated power systems, such as gas insulated switchgear (GIS) and gas insulated power transmission line (GIL), are widely used especially in urban areas, where the size reduction is necessary to keep the land cost low. SF_6 has been widely used as the gas insulating medium, because not only it has excellent insulation capability, but also it is non-toxic, chemically stable, and non-flammable. SF_6, however, has a very high global warming potential (GWP); 24000 times that of CO_2 [1]. It is anticipated that in the near future there will be an international regulation that mandates the reduction or even the complete ban on the use of SF_6. The search for an insulating gas to substitute SF_6 is going on all over the world. There are gas species exceeding the insulating capability of SF_6. If we take into account other characteristics, however, such as toxicity, chemical stability, and flammability, it is widely believed that no gas could exceed SF_6 as long as a single gas species is used [2].

It is known that by mixing multiple gas species at a certain ratio, the insulating capability dramatically increases. Each gas has different inelastic collision cross-section. If we select a mixture ratio where each gas supplements the other's deficiency, the mixture can have an insulating capability of more than the average of both species, that is, a positive synergism can be obtained. If we mix more than three gas species with the accuracy of several percents and try to find the best mixture ratio as the insulator gas, the number of combinations is enormous. If we try the search for the mixture ratio via experiment, we first have to put each gas species into a gas chamber, mix them well and carry out an experiment. Only a few combinations can be tested in one day at most, and it takes a long time to try all possible combinations. Even if we use a computer simulation, it takes a significant amount of time to test all combinations.

The purpose of the present paper is to develop a method to find the optimum mixture ratio via genetic algorithm (GA). GA is suitable to find the optimum value in the vast searching space and has been applied successfully in many areas recently. It is especially useful when although the number of parameters is small, the number of their com-

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binations is huge. GA is not a new method and there are many textbooks (see [3] for an example) describing it. In this paper we use a standard type of GA. This work is the first application of GA to find a gas mixture ratio for a gas insulator. We do not claim that the optimum mixture ratio found in the present method gives the final solution of the gas insulator substituting SF_6. But the mixture ratio derived in the present method gives a good starting point before a thorough investigation is carried out via experiments. Because we do not have to do experiment to narrow the parameter (mixture ratio) range, we can save a significant amount of time by using GA to preselect the candidate gas mixture.

In the past, there were many studies carried out to find the optimum gas mixture ratio. Most of the earlier works were experimental. Malik et al. [4] reviewed the works of 1970s. Christophorou et al. [5] attempted to identify alternative dielectric gases to pure SF_6 on the basis of published studies up to 1990s and consultation with experts in the field. There were only a few numerical or theoretical studies to find the optimum gas mixture ratio. Itoh et al. [6] carried out Boltzmann analysis to find the optimum mixture ratio of a ternary mixture composed of SF_6, c-C_4F_8, and N_2. They calculated all possible combinations of the ternary mixture by solving the three-term approximation Boltzmann equation.

The present problem of finding the optimum gas mixture is categorized as a combinatorial optimization problem. Nowadays there are many methods to solve the combinatorial optimization problems. To the authors' knowledge, there was no earlier work to search for the optimum gas mixture ratio as a combinatorial optimization problem. The work of [6] may be counted as one, though the method used is the most primitive one, searching all possible combinations. In the present problem, the system input is the gas mixture ratio and the output is either the insulating properties or GWP of the given gas mixture. The relationship between the input and output is very complicated and nonlinear. Therefore, it is very likely that the system output contains many local extremes. For such a case, conventional local search methods (for example see [7]) based on the gradient are likely to fail to find the global extremes. Recently many meta-heuristics algorithms have been proposed and applied successfully to various combinatorial optimization problems. Genetic algorithm used in this paper is one of the meta-heuristics algorithms.

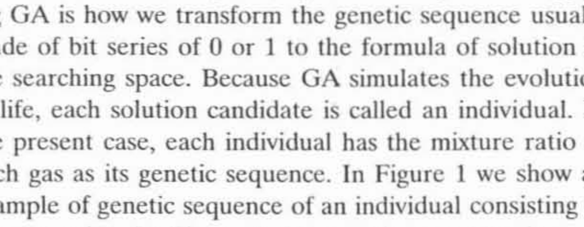
One characteristic of the present problem is that it is very time consuming. We calculate the effective ionization coefficient of a given gas mixture by solving the two-term approximation Boltzmann equation that is the fastest analytical method to calculate the effective ionization coefficient. Even for a gas mixture of six species, for example, a typical CPU time to calculate the effective ionization coefficient at a given reduced electric field is 5 s using a personal computer with a speed of 800 MHz. Therefore to try 10^4 combinations we need 14 h. If we take into account the searching space to be covered, a long time is required to do many runs to tune the parameters of the searching algorithm. To run GA, we need to define the bit size, the selection rate, the population size and the mutation rate. One advantage of GA is that it is very robust [8]. Even if we select these parameters intuitively, there is a good chance that the algorithm finds the solution anyway. Although the convergence speed might not be the fastest, it might be still faster than spending time in finding the best parameters to give the fastest convergence.

There may be other methods suitable to solve the present problem. For example, simulated annealing (SA) [9] has been applied successfully to many combinatorial optimization problems. It is said that the annealing schedule must be fine-tuned to obtain a solution within an acceptable time limit. Therefore, we might need to spend a considerable amount of computer resource in the trial to find a good annealing schedule before we even begin the actual search for the gas mixture ratio. Therefore, in the present problem we have chosen GA as the searching algorithm mainly because of its robustness.

In Section 2 of the present paper, we discuss the detail of the searching method where GA and the two-term Boltzmann analysis are combined. In Section 3, we present the computational result. In Section 4, we conclude with suggestions for future work.

2 SEARCHING METHOD

We combine GA and the two-term Boltzmann method to search for the optimum mixture ratio. In this section, we present only specific points relevant to the present problem. The most important part in each problem applying GA is how we transform the genetic sequence usually made of bit series of 0 or 1 to the formula of solution in the searching space. Because GA simulates the evolution of life, each solution candidate is called an individual. In the present case, each individual has the mixture ratio of each gas as its genetic sequence. In Figure 1 we show an example of genetic sequence of an individual consisting of three species. In Figure 1 the genetic sequence is composed of 24 bits. The first 8 bits denotes the gas species A. The second 8 bits denotes the gas species B and the third 8 bits denotes the gas species C. Each 8 bit is transformed



	Gas A	Gas B	Gas C
genetic expression	1 0 1 1 0 1 0 0	0 0 1 0 0 1 0 1	1 1 0 1 1 0 0 1
decimal numbers	180	37	217
mixture ratio	$\frac{180}{434}$	$\frac{37}{434}$	$\frac{217}{434}$

Figure 1. Example of genetic sequence of gas mixture ratio.

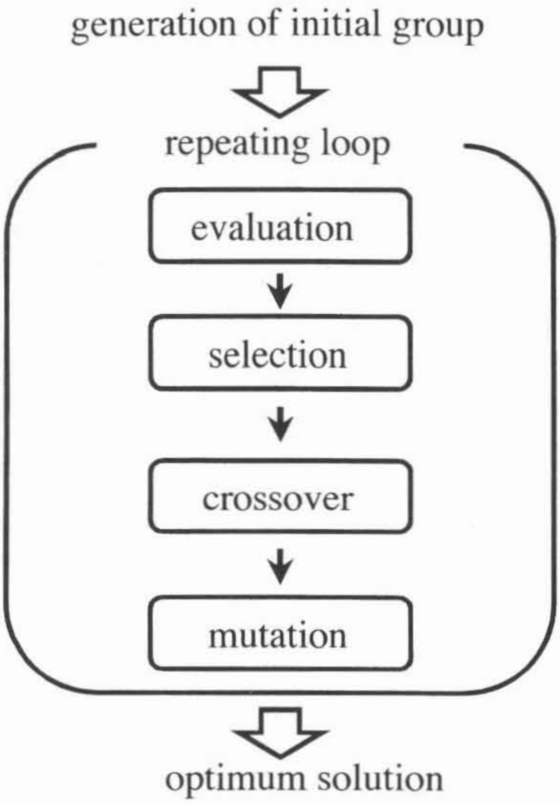


Figure 2. Flow chart of genetic algorithm.

into a number of decimal systems. In Figure 1 the 8 bits for the species A, "10110100" becomes 180. Likewise, the 8 bits for the species B and C become 37 and 217, respectively. Then, we take the sum of the three numbers, $180+37+217=434$ and divide each decimal numbers by the sum to obtain the mixture ratio of each species. The mixture ratio of species A, B, and C is 0.415, 0.085 and 0.500, respectively. With this method, each gene sequence is transformed into the mixture ratio of each species.

In Figure 2 we show the flow chart of the search method. We first generate a group of individuals of the first generation using random numbers. For each bit of gene sequence, 0 or 1 is determined by a random number. In the present paper, the number of individuals at each generation is 200 unless stated otherwise. Therefore, in the example shown in Figure 1 we use $24\times200=4800$ random numbers to generate the group of individual of the first generation.

We then evaluate each individual based on the evaluation function. The evaluation function is the analogy to measuring how easily each individual adapts to the environment to survive. In the present paper, we use two types of evaluation function. The first one is the effective ionization coefficient, i.e. $(\alpha\text{-}\eta)/N_n$ where N_n is the gas density, α is the ionization coefficient, and η is the attachment coefficient. We use the effective ionization coefficient at $E/N_n=359.3$ Td ($1\ \text{Td}=1\times10^{-21}\ \text{Vm}^2$) as the evaluation function. $E/N_n=359.3$ Td is chosen because it is the critical ratio of the electric field to the gas density of SF_6 at which $(\alpha\text{-}\eta)=0$ [10]. Therefore if the effective ionization is negative, the individual is a better gas insulator than SF_6. By limiting the evaluation function to the effective ionization coefficient at a single value of the ratio of the field to the gas density, we can minimize the computational time.

We solve the Boltzmann equation based on the steady state Townsend method with two-term approximation [11,12], because it is the fastest method to calculate the effective ionization coefficients. In the two-term Boltzmann equation, the collision term is expressed as the sum of collisions between electrons and each neutral gas species. We do not consider reactions among ions or neutrals except the case of the three-body attachment, for an example O_2. In the three-body attachment, the third body can be any neutral gas species in the mixture. The gas density is assumed to be $N_n=2.5\times10^{25}\ \text{m}^{-3}$.

The second evaluation function is GWP. The lower the GWP the better the individual is. We calculate $(E/N_n)_{cr}$, of each individual gas mixture. From this value, we calculate the gas pressure when it is used with the same insulation strength as pure 0.5 MPa SF_6. The pressure of 0.5 MPa is operational pressure of many SF_6 based gas insulated systems. For an example, if GWP of gas species A and B are 200 and 10, respectively, and the mixture ratio is 0.8 and 0.2, respectively, the GWP of the gas mixture is $0.8\times200+0.2\times10=162$. If the critical reduced ratio of the field to the gas density of the gas mixture is 250 Td, the gas pressure must be raised by a factor of $359.3/250=1.44$ to maintain the same insulation strength as for pure SF_6. Because the gas pressure must be 1.44 times that of SF_6, the GWP of the gas mixture becomes, $1.44\times162=233$ compared to 24000 of SF_6. Practically, it is difficult to raise the operational pressure beyond 1 MPa from the safety concern and we set the maximum pressure of the gas mixture to 0.9 MPa. Therefore, in order to have the same insulation strength as 0.5 MPa of SF_6 at a pressure less than 0.9 MPa, the critical ratio of the electric field to the gas density must be higher than 200 Td. When we evaluate each individual, if the critical ratio of the electric field to the gas density is less than 200 Td, the individual is automatically disqualified and prohibited to become a parent of the next generation.

The next process in GA is called "selection", similar to the natural selection in the evolution of life. Based on the evaluation function, we make ranking of all the individuals. Using the ranking, we select a pair of parents from the top portion of the ranking. There are various methods to select the parents. The selection method affects the convergence speed to reach the optimum value. In the present paper, we use the simplest method where we choose the parents from the top 80%. Alternatively described, the worst 20% of the population cannot be se-

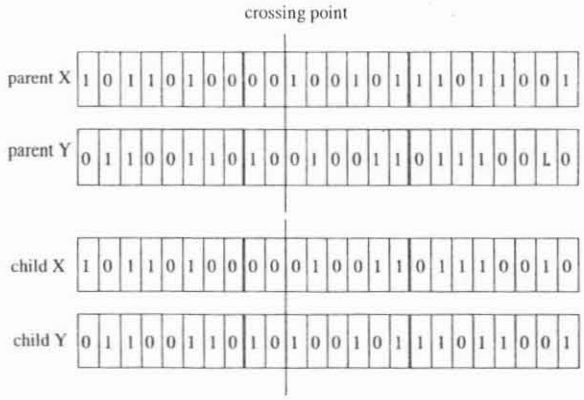


Figure 3. Schematic picture of crossover method of genetic sequences.

lected as a parent of the next generation. A random number is drawn to select a father from the top 80%. Another random number is drawn to select a mother from the top 80%. An individual can become a parent multiple times. But, it cannot be a father and a mother at the same time. If the same individual as the mother is selected as the father, we draw another random number to reselect the mother once again.

When we use GWP as the evaluation function, the disqualified individuals occupy the bottom of the ranking. But, the number of individuals with $(E/N_n)_{cr} < 200$ Td sometimes may exceed 20% of the total population. In that case, we simply select parents only from the qualified individuals, i.e., $(E/N_n)_{cr} \geq 200$ Td.

Once we select a pair of parents, we make crossover to generate two children. In Figure 3 we show an example of a crossover process. There are also various methods of crossover in GA, but we again use the simplest method. We simply cut the genetic sequence at one point and exchange each fragment. Where we cut the gene is determined by drawing a random number.

If the population consists of 200 individuals, we repeat the process of selection and crossover 100 times, because each process generates two individuals of the next generation. After we generate all the individuals of the next generation, we cause mutation. The mutation is modeled by flipping one bit from 0 to 1 or vice versa with a certain probability. The mutation rate defines the probability that any one bit flips between 0 and 1 before going to the next generation. In the present work, we use 0.001 as the mutation ratio unless stated otherwise. Then, for a mixture of three gas species (24 bits) with 200 individuals, approximately 4 or 5 individuals (4.8 to be exact) suffer mutation in one bit. After examining whether the mutation occurs or not for all the bits, we calculate the evaluation function of each individual of the next generation. Then, the processes of selection, crossover, mutation and evaluation are repeated until the results converge or the predetermined number of generations (typically 100–400 generation) is done.

Table 2 GWP of gas species used in the search [1]. GWP of the gases not listed in this Table is assumed to be 0.

Species	GWP
SF_6	23900
C_3F_8	7000
C_2F_6	9200
CF_4	6500
CO_2	1

Before we began the search of gas mixture ratio, we compiled sets of electron-neutral collision cross-section data of the following 14 species: SF_6, CF_4, C_2F_6, C_3F_8, N_2, O_2, CO_2, CO, H_2, H_2O, He, Ne, Ar and Xe. The collision cross-section data have been taken from many literature sources. The data sets taken from the literature have been modified so that the effective ionization coefficients calculated by the two-term Boltzmann equation match with the data of literature between 200 Td and 500 Td. Another GA makes the modification. In the Appendix, we discuss the detail and show the graphs of collision cross-section. Among the fourteen gases, perfluorocarbon gases have been chosen because they are known to be electro-negative gases and regarded as possible substitutes to SF_6 [13]. Other molecular gases have been chosen because they are abundant in the atmosphere and relatively harmless to the environment and humans. Rare gases have been chosen for the same reasons. These fourteen species are not the only species that should be looked at. There could be other species that are abundant and harmless. Once we obtain a reliable collision cross-section data, we can easily expand the number of gas species to be included in the search for an optimum mixture ratio. In Table 1 we list the parameters used for each case of the search. In Table 2 we list GWP of the fourteen gas species used in this paper [1].

Table 1 List of gas species used in the search and the evaluation function.

No.	Evaluation function	Number of gas species	Gas species
1	$(\alpha-\eta)/N_n$ at 359.3Td	6	CO, CO_2, N_2, C_2F_6, C_3F_8, CF_4
2	$(\alpha-\eta)/N_n$ at 359.3Td	14	SF_6,CO,CO_2,N_2,C_2F_6,C_3F_8,CF_4,H_2O, H_2,O_2,Ne,He,Ar,Xe
3	$(\alpha-\eta)/N_n$ at 359.3Td	13	CO,CO_2,N_2,C_2F_6,C_3F_8,CF_4,H_2O,H_2, O_2,Ne,He,Ar,Xe
4	$(\alpha-\eta)/N_n$ at 359.3Td	10	CO,CO_2,N_2,H_2O,H_2,O_2,Ne,He,Ar,Xe
5	GWP	7	SF_6,CO,CO_2,N_2,C_2F_6,C_3F_8,CF_4

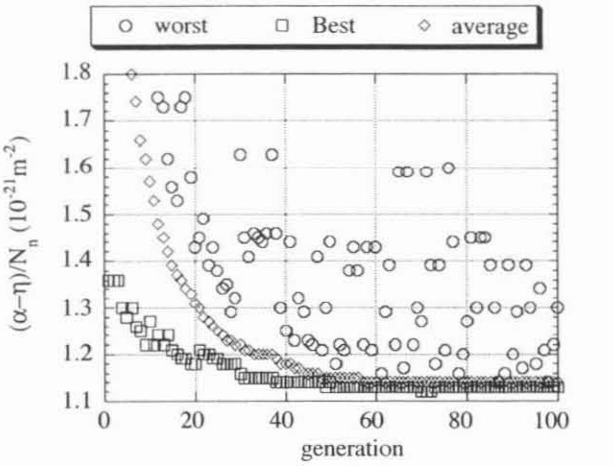


Figure 4. The best, average, and worst values of the evaluation function at each generation for the case 1.

3 SEARCH RESULT AND DISCUSSION

In Figure 4 we show how the computation converges. In the figure, we plot the best, average, and worst values of the effective ionization coefficients among 200 individuals at each generation for case 1. In this example we have tested a gas mixture composed of 6 species. The six species have been chosen to manifest that the present problem has many local extremes and we have to tune the parameters of GA. The average and best values show sharp decreases as the generation proceeds and become steady at approximately 90th generation. The worst value tends to decrease initially but increases soon and scatters widely afterward. In this example the mutation rate is 0.001.

In Figure 5 we show how the number of individuals affects the result. In the figure we plot the evaluation function of the best individual during 100 generations for different numbers of individuals. All the parameters except the number of individuals are kept the same among the five cases plotted in Figure 5. The mutation rate is 0.001. As the number of individual becomes too small, the solution tends to converge to a local extreme. From this result, we need at least 40 or 50 individuals to obtain the optimum solution. The minimum number should increase as the number of gas species increases and the searching space expands. To make sure that we obtain the optimum solution even for a large number of gas species (the maximum is 14 species for case 2), we set the number of individuals to 200.

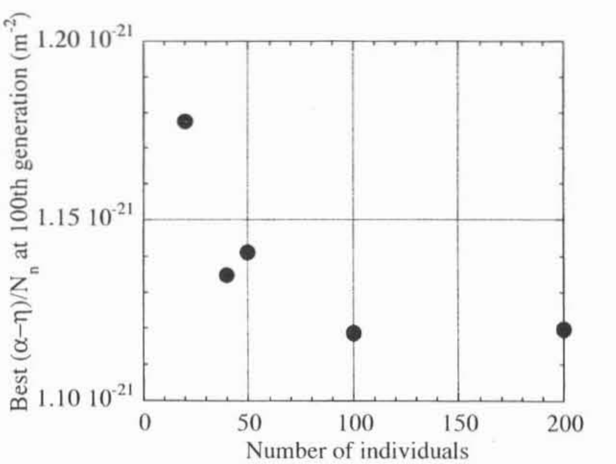


Figure 5. The effective ionization coefficient of the best individual during 100 generations with different numbers of individuals for case 1.

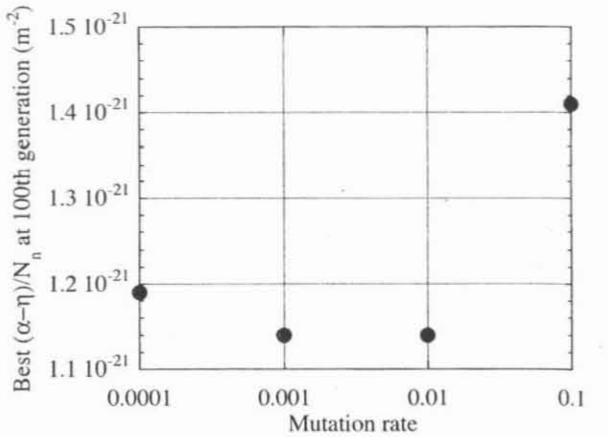


Figure 6. The effective ionization coefficient of the best individual during 100 generations with different mutation rates for case 1.

In Figure 6 we show how the mutation rate affects the result. In the figure we plot the evaluation function of the best individual after 100 generations for different mutation rates. All the parameters except the mutation rate are kept the same among the four cases plotted in Figure 5. The number of individuals is 50. Figure 6 indicates that there is an optimum value as the mutation rate. If the mutation rate is too large, the evolutionary process is destroyed by frequent mutations. If the mutation rate is too small, there is a risk of falling into a local extreme. From this result, we have chosen 0.001 as the mutation rate for the rest of study.

In Figure 7 we show the result of case 2 where we have tested a gas mixture composed of 14 species. The average and best values show sharp decreases as the generation proceeds and become steady at approximately 300th generation. The worst value decreases initially but increases soon and stays relatively steady afterward. In Figure 8 we show how the mixture ratio of the best individual changes as the generation proceeds. Initially, there are many species involved in the best individual, but those who have low insulation strength are dismissed quickly. The dominant species at the initial stage of the evolution are SF_6, CO, N_2, C_2F_6, and C_3F_8. They have large attachment collision cross-sections or large vibrational excitation cross-sections. After 100th generation, the best individual becomes the gas mixture of mostly PFC gases, i.e. SF_6, C_2F_6

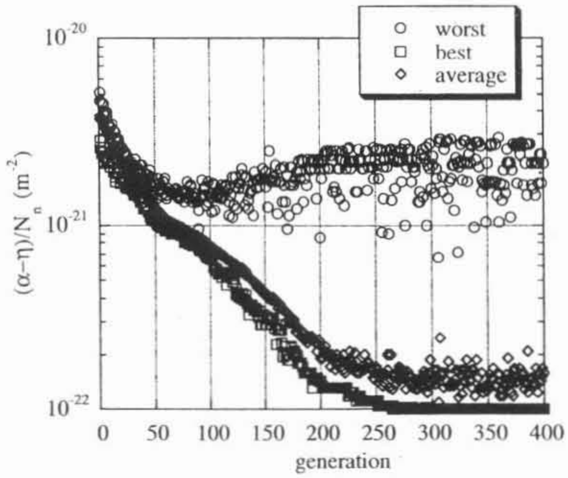


Figure 7. The best, average, and worst values of the evaluation function at each generation for the case 2.

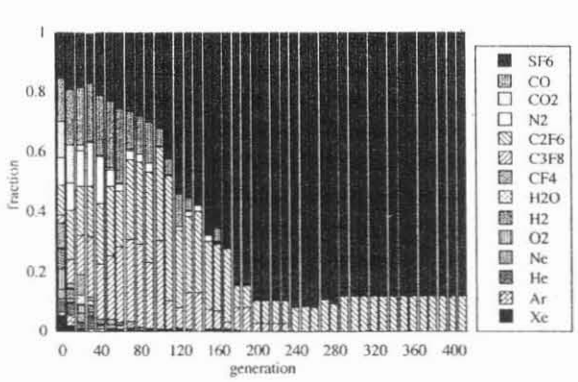


Figure 8. Evolution of the best gas mixture among 14 species over generations. The result of case 2 search is shown.

and C_3F_8. After 300th generation, the mixture ratio of the best individual stays the same and most of the individuals have more or less similar genetic sequences. Therefore, the crossover rarely produces new genes. Once such a state is reached, only the mutation can change the course of evolution. In this case, however, the mutation does not work. We have waited for 100 generations from 300th generation to 400th generation for the mutation to affect the evolution. But the result shown in Figure 8 indicates that the evolution is almost finished.

In case 2, the best individual has the mixture ratio of $SF_6/C_2F_6 = 0.881/0.119$ and the effective ionization coefficient is 1.01×10^{-22} m^2. Pure SF_6 has 1.5×10^{-22} m^2 at 359.3 Td for the collision cross-section data used in this paper, although the literature value gives 0 at this ratio of the electric field to the gas density. The critical ratio of the electric field to the gas density of SF_6 with the present collision cross-section data is 354 Td. In order to confirm that the binary mixture ratio is the optimum value, we have calculated the effective ionization coefficient of the binary mixture at every 1% of the mixture ratio between 0 and 100%. The result shows the mixture ratio of $SF_6/C_2F_6 = 0.881/0.119$ indeed gives the lowest effective ionization coefficient. With the help of genetic algorithm, we can find the best mixture ratio exceeding the insulation capability of pure SF_6. The difference from pure SF_6, however, is very little. The slight improvement of the insulation capability probably will not justify the replacement of pure SF_6 by the binary mixture of $SF_6/C_2F_6 = 0.881/0.119$, considering the additional cost associated with handling two gas species instead of one. The result of case 2 confirms that SF_6 has the insulation strength far better than the other 13 species. As long as SF_6 is included in the calculation, the result does not differ much from pure SF_6.

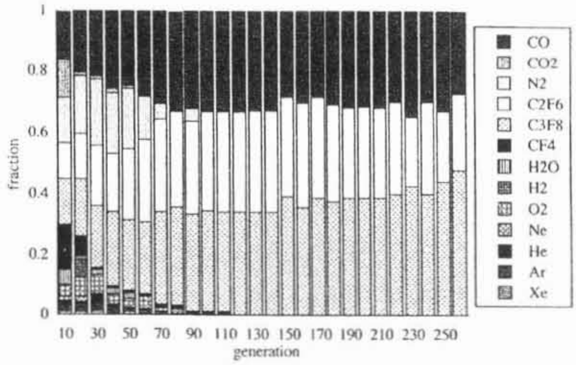


Figure 9. Evolution of the best gas mixture among 13 species over generations. The result of case 3 search is shown.

In order to avoid the strong influence of SF_6, we intentionally remove SF_6 from the list of gas species. In case 3, we search the best mixture ratio among 13 species excluding SF_6. Figure 9 shows the evolution of the best individual. The best mixture ratio is $CO/C_2F_6/C_3F_8 = 0.27/0.25/0.48$ and the effective ionization coefficient is 1.12×10^{-21} m^2. This value is higher than the effective ionization coefficient of any single species among 13 species and agrees with the best value found in case 1 where all the three species, CO, C_2F_6, and C_3F_8 are included. In Figure 10 we show the effective ionization coefficients of major gas species used in this study. At 359.3 Td, the effective ionization coefficient of CO is already lower than that of C_2F_6. At $E/N_n > 400$ Td, it becomes lower than even that of C_3F_8. Carbon monoxide (CO) has large vibrational excitation cross-sections near 2 eV and also the ionization cross-section is small compared to C_2F_6 or C_3F_8. The addition of CO to C_3F_8 gives the positive synergism due to CO. Further addition of C_2F_6 supplements the excitation cross-section of C_3F_8 and lowers the effective ionization coefficient further. In order to confirm that the ternary mixture ratio is not the local minimum, we have calculated all possible binary combinations among C_3F_8, CO, and C_2F_6. None of the binary mixture has an effective ionization coefficient lower than 1.12×10^{-21} m^2 given by the ternary mixture.

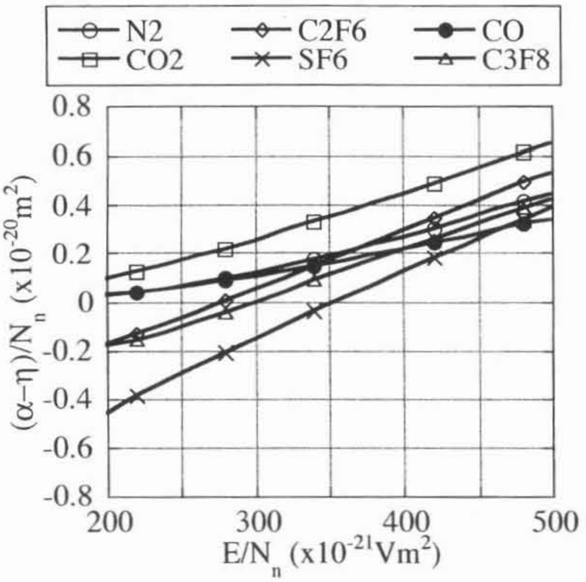


Figure 10. Effective ionization coefficients of gas species with high insulation capability among 14 gas species investigated.

The result of case 3 shows the dominant characteristic of PFC gas even if SF_6 is excluded. As long as we use PFC gas, the GWP of the gas mixture can be very high. In case 4, we search the gas mixtures composed of non-PFC gases only and show the result in Figure 11. The search converges to pure CO and the effective ionization coefficient is 1.69×10^{-21} m^2. Therefore, if we use non-PFC gas, the best solution is to use pure CO.

So far the effective ionization coefficient has been used as the evaluation function. The final purpose of this study, however, is to find gas insulation media to replace SF_6 from the environmental point of view. Even if the effective ionization coefficient is lower than that of SF_6, we can still use that gas by raising the operational pressure. There is a practical limit on the operational pressure from the safety point of view. If the pressure were too high, the cost to implement the safety mechanism to the gas container would be unacceptable. In the present study, we set the limit to 0.9 MPa, because above 1 MPa Japanese law requires additional safety protection for the gas container. We have selected 0.9 MPa to have a margin of 0.1 MPa to the limit of 1 MPa. Because the standard pressure of gas insulated system used is typically 0.5 MPa, we tolerate the gas mixture with the critical ratio of the electric field to gas density, $(E/N_n)_{cr}$, up to $360 \times 0.5/0.9 = 200$ Td.

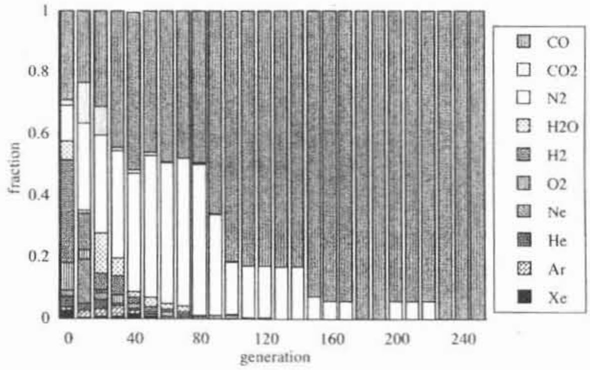


Figure 11. Evolution of the best gas mixture among 10 species over generations. The result of case 4 search is shown.

In the search, we first calculate $(E/N_n)_{cr}$, of each individual. We calculate $(\alpha\text{-}\eta)/N_n$ at $E/N_n = 200$ Td. If it is positive, we disqualify the individual automatically. If it is negative, we calculate $(E/N_n)_{cr}$ with a precision of ± 0.3 Td. Then we calculate GWP

$$GWP = \frac{359.3}{(E/N_n)_{cr}} \sum_{i=1}^{N_s} G_i X_i \qquad (1)$$

where G_i is the GWP of each gas species listed in Table 2 and X_i is the mixture ratio of each gas species. Because we have to calculate $(E/N_n)_{cr}$, it requires much longer CPU time than the searches in cases 1–4 where a single value of $(\alpha\text{-}\eta)/N_n$ at 359.3 Td has been used as the evaluation function. Therefore, in case 5, we limit the gas species to major gas species that have shown strong influence over the other species. We select the seven species based on the result of case 2 shown in Figure 8, where these gas species stay relatively longer without being removed by the selection processes in evolution.

Table 3 lists the results of case 5. The critical reduced electric field of this gas mixture is 200 Td, exactly the lowest limit allowable for the use at 0.9 MPa. Replacing the small amount of C_2F_6 and CF_4 by C_3F_8 does not make much difference. The mixture ratio of 0.5% of SF_6, however, makes a large difference in the result. Therefore, the gas mixture can be made of SF_6, CO, CO_2, N_2, and C_3F_8. Because C_3F_8 has a relatively low GWP compared to the other PFC gases, the gas becomes electronegative by having C_3F_8 while keeping low GWP. To supplement the insulating capability at low E/N_n, N_2, CO, and CO_2 are needed. At low E/N_n, these gas species show more or less the same effective ionization coefficient as shown in Figure 10.

It is difficult to consider the result of case 5. The global warming potential is certainly reduced to approximately one-eighth of pure SF_6. But, it is still 3200, which is even higher than the GWP of many hydrofluorocarbons (HFCs) that are also the target of possible regulation as global warming gases. For example, the GWP of HFC-125 (CHF_2CF_3) is 2800 [1]. Therefore, probably replacement

Table 3 The best gas mixture ratio found in the search of case 5 and its global warming potential.

Case No	GWP	Mixture ratio						
		SF_6	CO	CO_2	N_2	C_2F_6	C_3F_8	CF_4
5	3211.3	0.005	0.324	0.102	0.330	0.001	0.236	0.001

of SF_6 by the gas mixture listed in Table 3 will not be justified from the viewpoint of environmental protection.

In the present paper, we have looked for the optimum gas mixture ratio mainly from the viewpoint of environmental protection. The present method, however, can be used to look for the optimum mixture ratio from different perspective, such as cost. The cost is especially important when we consider a large amount of SF_6 gas used in GIL. To find the cheapest gas mixture ratio while maintaining sufficient insulation strength, the method used for case 5 can be directly applied. The total cost of a given gas mixture can be calculated by replacing G_i of equation (1) by the cost of each gas species. Other properties, such as toxicity, chemical stability, liquefaction temperature, etc., can be also incorporated in the same manner once we have a certain numerical index of each property for each gas species.

4 CONCLUSION

A NEW method to find the optimum gas mixture ratio as gas insulating media has been proposed. Genetic algorithm (GA) is used with the two-term Boltzmann equation to find the combination of gas species that can possibly replace SF_6 with higher insulation capability and lower global warming potential (GWP). This method can save a significant amount of time by preselecting possible candidates before they are thoroughly investigated by experiment or more detailed analysis.

We have searched for the optimum combination of gas mixture from 14 gas species; SF_6, CF_4, C_2F_6, C_3F_8, N_2, O_2, CO_2, CO, H_2, H_2O, He, Ne, Ar and Xe. The insulation capability of each gas mixture is evaluated by the effective ionization coefficient at 359.3 Td that is the critical ratio of the field to the gas density of SF_6 [10]. The binary mixture of SF_6 and C_2F_6 improves the insulation capability of pure SF_6. But the improvement is not large enough to justify the replacement of pure SF_6 by the binary mixture. Without SF_6, no combination of the other 13 gas species has exceeded the insulation capability of pure SF_6. The best gas mixture second to pure SF_6 is the ternary mixture of $CO/C_2F_6/C_3F_8 = 0.27/0.25/0.48$. Although this gas mixture is better than any single species or any binary mixture among 13 gas species, it is still has a very high GWP. The search for the optimum gas among the 10 no-PFC gas species (N_2, O_2, CO_2, CO, H_2, H_2O, He, Ne, Ar, Xe) has resulted in pure CO.

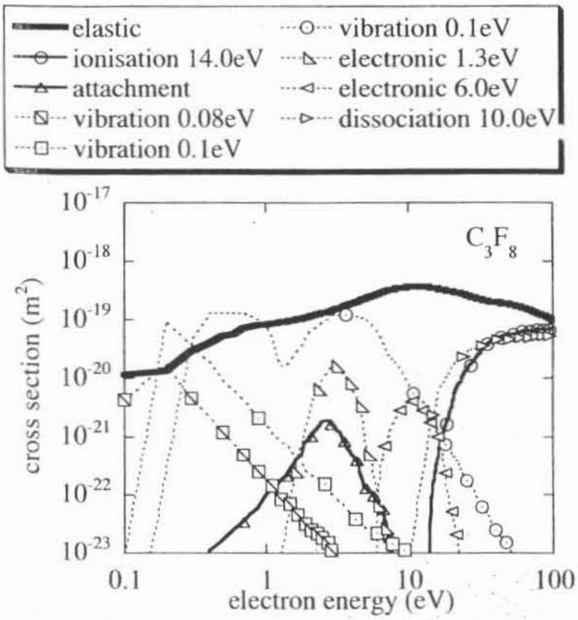


Figure 12. Collision cross-section data of C_3F_8 before modification. This data set is based on [14]. Threshold energies are also listed.

Assuming that the increase of gas pressure up to 1.4 times of pure SF_6 (0.9 MPa compared to 0.5 Mpa of pure SF_6) is tolerated, the gas mixture with the lowest GWP while maintaining the gas insulation strength has been carried out. The search has resulted in the gas mixture of SF_6, CO, CO_2, N_2, and C_3F_8. But GWP of the optimum gas mixture is still higher than 3200, which is not low enough to replace the pure SF_6 by this gas mixture.

Although the searching method has been proven useful and quick to test many possible combinations of gas species, the search results have been a little disappointing. The search result has indeed confirmed the excellence of SF_6 as the gas insulation medium. The advantage of the present method, however, is that it is very easy to expand if we want to add another gas species as a possible constituent of gas mixture as long as a reliable set of electron-neutral collision cross-section is available. For the moment, we have formulated the collision cross-section data sets for 14 gas species. But there are still many other gas species that are abundant and environmentally acceptable. Addition of such untested gas species might produce

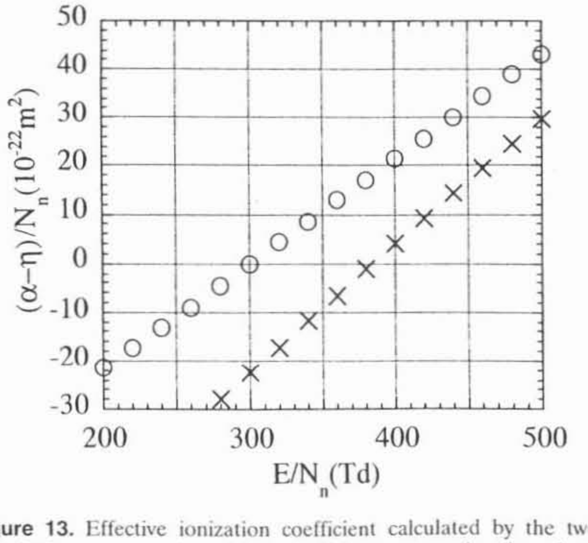


Figure 13. Effective ionization coefficient calculated by the two-term Boltzmann equation with the collision cross-section data shown in Figure 12. The circle denotes experimental values taken from [15].

eventually a new gas insulating media replacing SF_6 gas. This method would be useful to judge whether the new gas mixture is worth investigating thoroughly by far more expensive and time-consuming experiment. The search for the optimum gas mixture alternative to SF_6 from a comprehensive point of view, including the aspects of environment, cost, liquefaction temperature, toxicity and others, is also another interesting future subject.

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5 APPENDIX

Here we explain the formulation of the sets of collision cross-section data. The data on the electron-neutral collision cross-section are published in the literature. The data are based on measurement, Monte-Carlo simulation, or Boltzmann analysis. There are also many published data on the effective ionization coefficient and other electron swarm parameters based on measurement, Monte-Carlo simulation and Boltzmann analysis. In the present paper, we use the two-term Boltzmann equation to calculate the effective ionization coefficient. This is the fastest method to calculate, but at the same time employs the crudest approximation. Therefore, for an example, if we calculate the effective ionization coefficient with the collision cross-section data determined by experimental measurement or Monte-Carlo simulation, the results are often different from the effective ionization coefficient measured by the experiment. Also, the experimental measurement of the collision cross-section data always contains a certain degree of uncertainty.

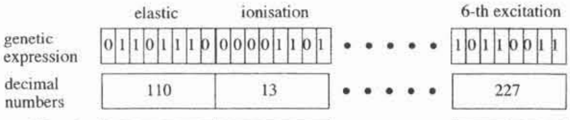

Figure 14. Genetic sequence used in genetic algorithm to find the optimum data set of collision cross-section for the two-term Boltzmann analysis.

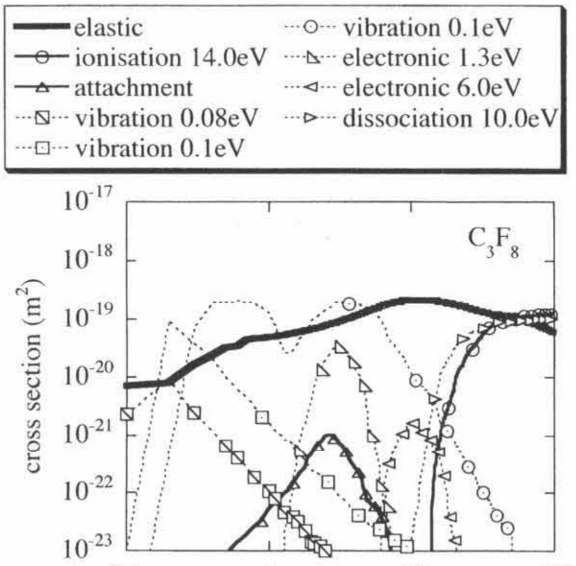

Figure 15. Collision cross-section data of C_3F_8 after modification. Threshold energies are also listed.

In the present paper, before we began the search for the gas mixture, we needed to determine the electron-

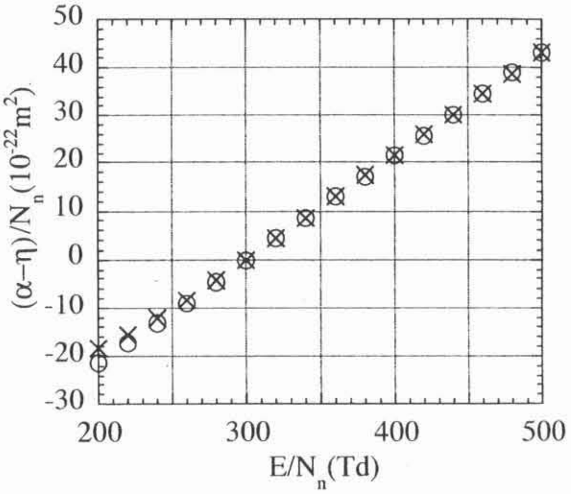

Figure 16. Effective ionization coefficient calculated by the two-term Boltzmann equation with the collision cross-section data shown in Figure 15. The circle denotes experimental values taken from [15].

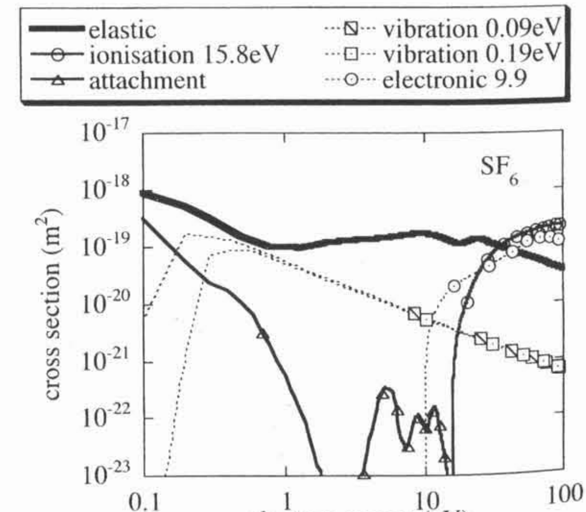

Figure 17. Collision cross-section data of SF_6 after modification. Threshold energies are also listed.

neutral collision cross-section data for each gas species. We looked for sets of cross-section data in the literature but the data were not always in suitable format for the two-term Boltzmann analysis. Therefore, we have decided to modify each collision cross-section data so that the macroscopic value, such as the effective ionization coefficient, calculated by the two-term Boltzmann equation matches with the experimentally measured value.

In order to modify the collision cross-section data, we have used another GA. For example we show a set of collision cross-section data of C_3F_8 in Figure 12. These data are taken from [14]. When we use these collision cross-section data for the two-term Boltzmann equation, we obtain the effective ionization coefficients as shown in Figure 13. The experimental data in this figure are taken from [15]. In order to have the appropriate cross-section data that match with the experimental values in Figure 13 we modify the cross-section data shown in Figure 12. There are several ways to modify the collision cross-section data. One is to multiply each collision cross-section by a certain factor and the other is to modify the shape of curve in Figure 12. Adding new excitation cross-sections is also of-

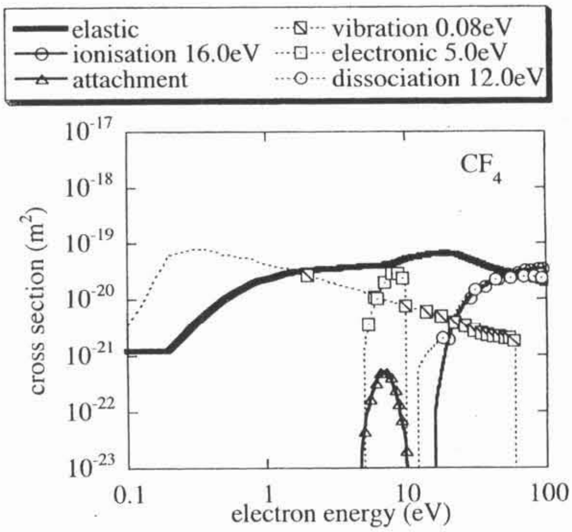

Figure 18. Collision cross-section data of CF_4 after modification. Threshold energies are also listed.

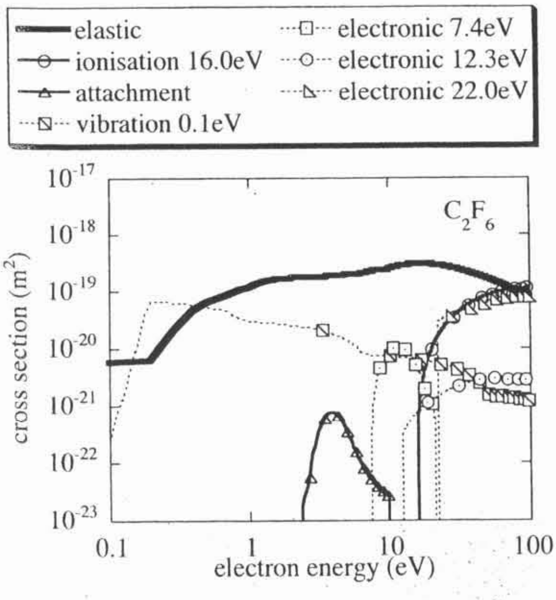

Figure 19. Collision cross-section data of C_2F_6 after modification. Threshold energies are also listed.

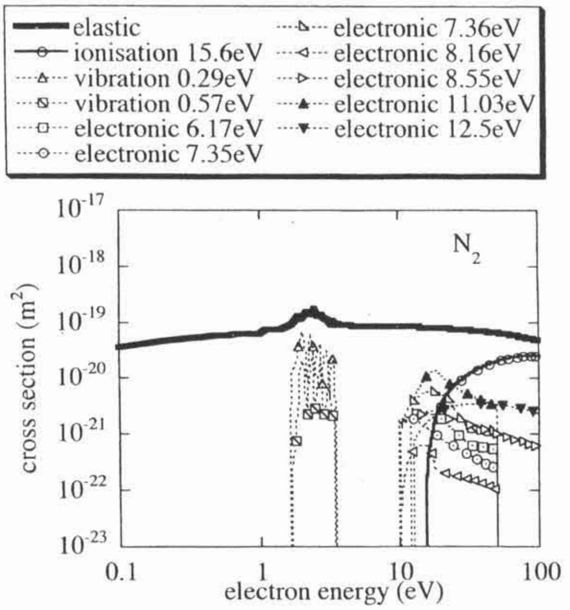

Figure 20. Collision cross-section data of N_2 after modification. Threshold energies are also listed.

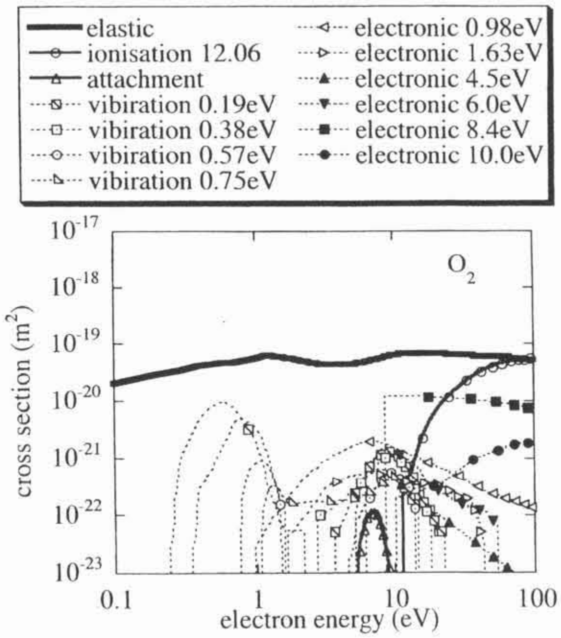

Figure 21. Collision cross-section data of O_2 after modification. Threshold energies are also listed.

ten done to adjust the electron swarm parameters. In this paper, we multiply each collision cross-section data by a certain factor and the multiplication factor is determined by GA.

The cross-section data in Figure 12 has nine types of cross-sections, i.e., elastic, ionization, attachment and six excitations. Each cross-section is multiplied by a modification factor. We assume that this factor ranges between 1/3 and 3. In Figure 14, we show an example of genetic sequence. Each individual consists of $8\times9=72$ bits for the case of nine types of cross-sections. Each cross-section has a modification factor given by 8 bits. The 8 bits number is transformed into a decimal number, j, and the modification factor is given by $3^{(j-128)/128}$. In the example shown in Figure 14, the elastic cross-section data in Figure 12 are multiplied by 0.857 over all the electron energies, the ionization data is multiplied by 0.373, and so on. In this way, each individual has a new set of cross-section data and the effective ionization coefficients are calculated at every 20 Td from 200 Td to 500 Td.

The difference from the values taken from literature is used to evaluate the degree of adaptation of each individ-

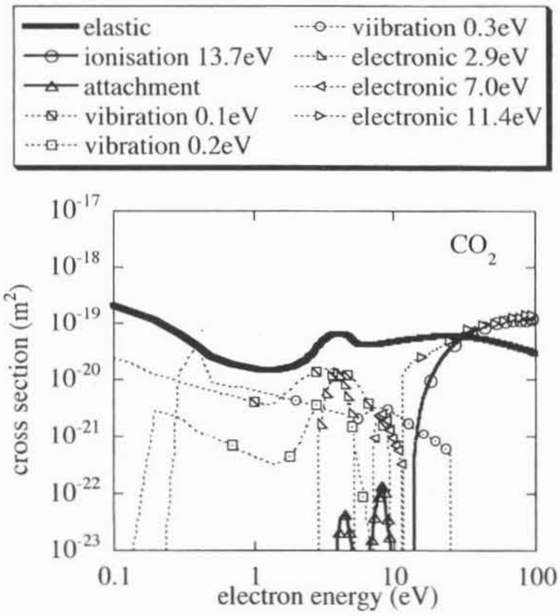

Figure 22. Collision cross-section data of CO_2 after modification. Threshold energies are also listed.

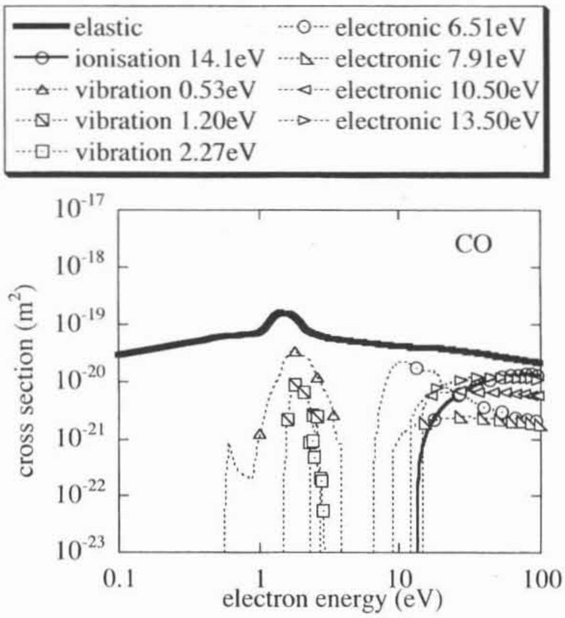

Figure 23. Collision cross-section data of CO after modification. Threshold energies are also listed.

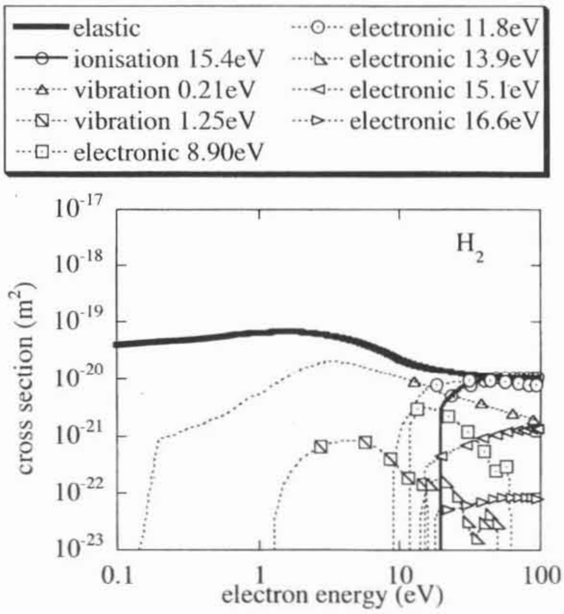

Figure 24. Collision cross-section data of H_2 after modification. Threshold energies are also listed.

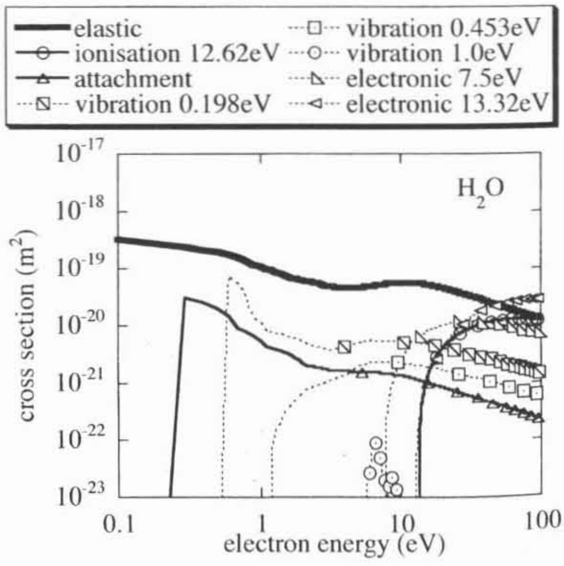

Figure 25. Collision cross-section data of H_2O after modification. Threshold energies are also listed.

ual. The evaluation function is defined by

$$\epsilon = \sum_{i=1}^{i=16} |(\alpha - \eta)_i^* - (\alpha - \eta)_{ref}| \qquad (2)$$

where $(\alpha - \eta)_i^*$ is the effective ionization coefficient calculated for each individual. The subscript i denotes the ith value of the reduced electric field between 200 Td and 500 Td. We take the sum of 16 points. In equation (2), $(\alpha - \eta)_{ref}$ is the reference value, that is, the experimentally measured value taken from the literatures. The smaller is the value of ϵ, the better the individual is. In this way, we select good individuals at each generation. The rest of GA is similar to the one carried out for the search of gas mixture ratio. Regarding the literature data of the effective ionization coefficient to be compared with, we have used only the data from experimental measurements.

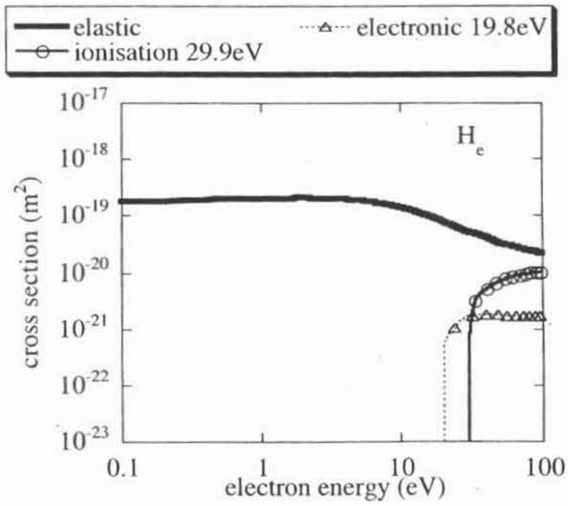

Figure 26. Collision cross-section data of He after modification. Threshold energies are also listed.

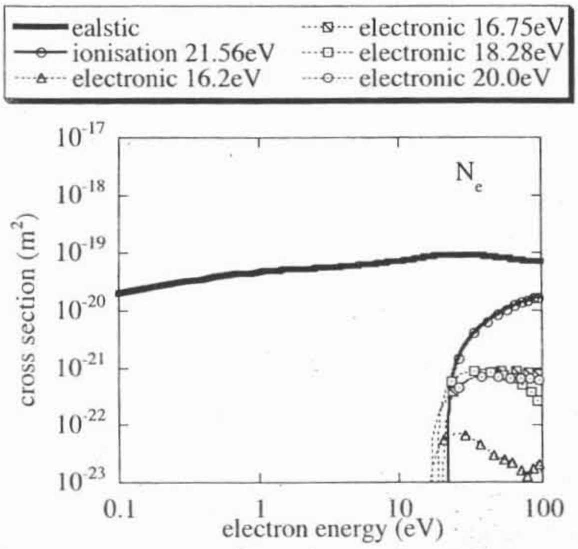

Figure 27. Collision cross-section data of Ne after modification. Threshold energies are also listed.

In the case of C_3F_8, GA has found the optimum individual with the modification factors of 0.603, 0.544, 1.839, 2.147, 0.392, 1.953, 0.548, 1.035 and 1.590 for elastic, ionization, attachment and six excitations, respectively. In Figure 15 we show the collision cross-section data of C_3F_8 that has been modified by these factors. The effective ionization coefficient calculated by the modified collision cross-section data shows a very good agreement with the experimental value, as shown in Figure 16. The value of ϵ for this case is 0.757×10^{-21} m^2. We use this collision cross-section data in the search of gas mixtures. For the other 13 gas species used in the search of gas mixtures, the same method has been applied to modify the collision cross-section data. In Figures 17 to 29, we show the modified collision cross-section data used for the search of gas mixtures. In Table 4 we list the values of ϵ for each set of

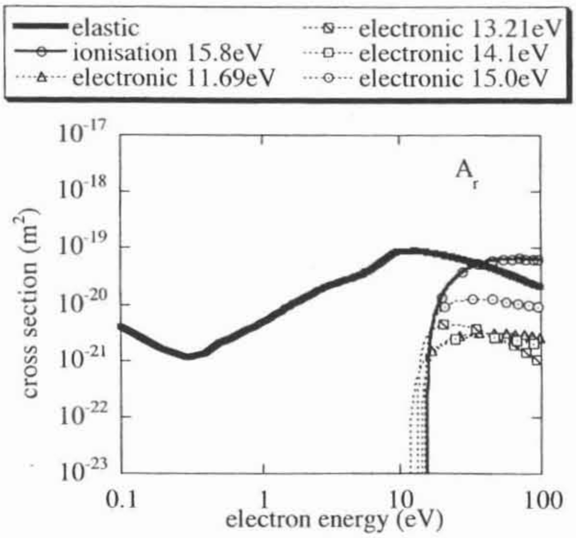

Figure 28. Collision cross-section data of Ar after modification. Threshold energies are also listed.

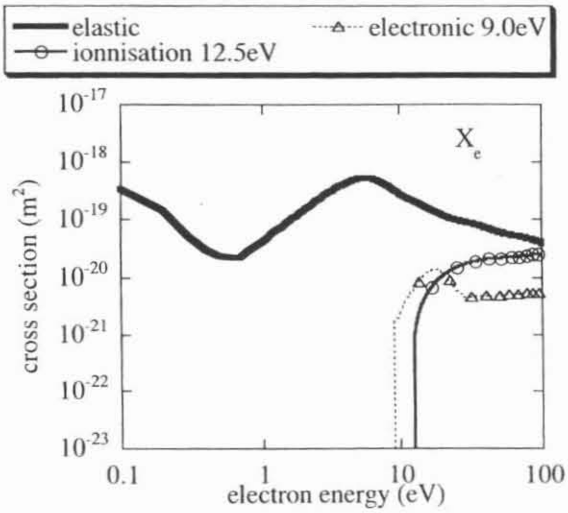

Figure 29. Collision cross-section data of Xe after modification. Threshold energies are also listed.

Table 4 The difference of effective ionization coefficients between the experimental values taken from the references and the values calculated by the modified set of collision cross-section data. See Eq. 2 for the definition of ε.

Gas	$\epsilon(10^{-21}\mathrm{Vm}^2)$	Reference data
SF_6	1.67	[15]
CF_4	0.713	[15]
C_2F_6	0.277	[15]
C_3F_8	0.757	[15]
N_2	0.613	[16]
O_2	1.31	[15]
CO_2	4.86	[15]
CO	0.485	[17]
H_2	0.628	[18]
H_2O	3.28	[15]
He	2.97	[19]
Ne	1.31	[18]
Ar	1.05	[20]
Xe	0.671	[20]

collision cross-section data along with the literature used as the reference.

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