CHAPTER IV

DEVELOPMENT OF THE COMPUTER PROGRAM

In this chapter development of the computer program for oil reserve calculation using Monte Carlo simulation technique will be discussed. This is the main purpose in this study. This developed computer program can report the probability distribution of oil reserve of a reservoir that can be used to investigate on uncertainty of calculated oil reserve due to the uncertainty of input variables. In addition, the statistical relationship between two input variables, and the statistical relationship in space of input variables, called spatial correlation, will be incorporated into the developed program. Therefore, this program can be used to investigate effect of these statistical relationships on the calculated oil reserve.

For the Monte Carlo method the random numbers is an important tool for selecting values of input variables (this random numbers is also necessary for turning bands method in generation of values of input

variable with spatial correlation). The random numbers used in the developed computer program will be obtained from random number generator subroutine. In the first section of this chapter the generated random numbers will be verified to ensure that the error causing due to an imperfection of set of random numbers can be neglected.

For spatial correlation, spectral turning bands method will be used to generate random variables in two-dimensional space. In the second section of this chapter the two important constants, harmonic number and frequency range, will be determined appropriately.

Then, the computer program for oil reserve calculation using Monte Carlo simulation will be developed. The description of this computer program development then will be described.

After the computer program has been developed the number of simulations will be determined. The number of simulations is the number of calculated oil reserve that will be used to construct probability density function of oil reserve. This number has to be large enough to calculate mean and standard deviation of calculated oil reserve with no significant error.

Random Number Generator Development and Statistical Tests of Set of Obtained Random Numbers.

In this section the random number generator subroutine used for Monte Carlo simulation and spectral turning bands method will be developed. This subroutine will be called many times during simulation process to obtain random numbers distributed evenly between 0 and 1 for selecting input variables. For spectral turning bands method the random number will be used to generate a random variable distributing according to assigned covariance function that is the random numbers will be used to obtain the random angle, ϕ_k, and frequency, δw, described in the previous chapter.

The following discussion concerning the random number is extracted from the work of Bank and Carson (1984). The widely used technique today for generating random numbers that will be used in this study is linear congruential method introduced by D.H.Lehmer in 1949. The production of a sequence of integers, Y_1, Y_2,..., between zero and m-1 is according to the following recursive relationship:

$$Y_{i+1} = (aY_i + c) \bmod m, \quad i = 0,1,2,..., \qquad (4.1)$$

where

m = the modulus; m > 0

a = the multiplier; $0 < a < m$

c = the increment; $0 < c < m$

Y_o = the starting value; $0 < Y_o < m$.

The starting value Y_o is called the seed, The selection of the values for a, c, m, and Y_o drastically affects the statistical properties and the cycle length.

Note that A = B mod M provided that (A - B) is divisible by M with no remainder. Thus, A = 502 mod 100, but 502/100 equals 5 with a remainder of 2, so that A = 2. In other words, (502-2) is evenly divisible by M = 100.

The random numbers between zero and 1 can be generated using following equation:

$$R_i = Y_i / m, \qquad i = 1,2,\ldots, \tag{4.2}$$

where m is usually 2^t for t-digit binary integers. Here Y_o, a, and c are themselves integers in the same range. Knuth(1969) summarizes the number theory needed to pick a and c;

1. Y_o can be arbitrary
2. Pick a to have three properties (for binary machines):
   a. a mod 8 = 5;

b. $m/100 < a < m - m^{1/2}$;

c. The binary digits of **a** have no obvious pattern

3. Pick **c** as an odd integer with

$c/m \approx 1/2 - 3^{1/2}/6 \approx 0.21132$.

The subroutine for generating uniform random number following the suggestions of Knuth is shown in Appendix B1 in ANSI standard Fortran (Forsythe, Malcolm, and Noler, 1977). The values of **m**, **a**, and **c** are computed automatically upon the initial entry. The main assumption here is that the machine uses binary interger number representation and multiplication is performed modulo **m**, where **m** is a power of 2. This assumption simplifies the computation. The value of **m**/2 is obtained by testing successive powers of 2 until a multiplication by 2 produces no increase in magnitude. It is also assumed that integer addition is either modulo **m** or that at least $\log_2(m)$ significant bits are returned. The values of **a** and **c** are computed following the advice of Knuth, outlined above. In the source code, **a** is called IA, and **c** is called IC. The random bit pattern of **a** is achieved by calling DATAN(1.DO), which returns the double-precision value of $\pi/4$, which, on a binary machine, is the shifted bit pattern of π. The division by 8.DO and multiplication by **m**/2 is hopefully accomplished without unduly altering this pattern. The double-precision value is finally converted to an integer, multiplied

by 8, and incremented by 5 to ensure **a** mod 8 = 5. The resulting value of **a** is roughly $(m/8)\pi \approx m/2$. This satisfies the inequality constraints. The value of **c** is $c = m\,(1/2 - 3^{1/2}/6)$.

The linear congruential method for generating random numbers is quite a good method, consisting of few calculation steps, giving broad period, and having good distribution of numbers. However, different selected seed give different set of random numbers of different quality. Therefore, to make sure that the set of generated random numbers are qualified, it is neccessary to test the set of generated random numbers using hypothesis tests of uniformity and independency.

In this investigation the statistical tests will be performed following nine tests suggested by Banks and Carson (1984). Test procedures are presented in appendix A. If the verified set of random number pass every nine tests, the verified seed will be used in this study. The nine statistical tests are listed as follows:

1. Kolmogorov-Smirnov test
2. Chi-square test
3. Runs up and runs down test
4. Runs above and below the mean
5. length of runs up and down

6. length of runs above and below the mean

7. Test for Autocorrelation

8. Gap test

9. Poker test.

In every test the number of tested random numbers is 600. Note that this number is equal to number of simulations for Monte Carlo simulation that will be determined later. Level of significance (α) used is 0.05. The test of set of random numbers can be performed as follows:

1. Set seed as an arbitrary integer,

2. Generating 600 numbers of random numbers using random number generator,

3. The set of generated random numbers will be tested using nine Fortran programs for testing shown in Appendices B2 to B10,

4. If the generated random numbers cannot pass one of the nine tests, the seed will be reassigned and again generating another set of random numbers and testing them till the set of random numbers can pass every tests.

The seed that generates random numbers that can pass every tests will be used as seed for random number generator in the computer program

for oil reserve calculation in this study.

Several seeds were used for the test, such as 50000, 50001, 50010, 50015, 54325, 65432, and so on. The set of random numbers obtained from a seed of 50015 can pass every nine tests on basis of each test and the results are shown in Appendix A. Others seed, e.g., 50000, 50001, 50010, 54325, and 65432 were used to generating random numbers, but their sets of random numbers cannot pass some tests especially test of autocorrelation.

As a result, the number 50015 is used as a seed for random number generator used in this study.

However, when perform hypothesis tests of any set of random numbers, it does not only depend on the quality of uniformity and independent of tested random numbers, but it also depends on the assigned significant index (percent of rejected area). If the significant index is assigned at small value such as 0.05 the accepted area will be large and the set of random numbers will pass the test easily. On the other hand, at large value of significant index such as 0.1 the accepted area is small causing less number of set of random numbers to pass the tests and the better set of random numbers may be achieved. But the cost would be high.

Development of the Spectral Turning Bands Method Subroutine and Determination of Involving Constants.

Turning bands method subroutine that will be developed in this study is the subprogram for simulating process (random variable) in two-dimension. The obtained random variables simulated by this subprogram will have their values distributed in space according to assigned covariance function.

Due to the complication in analytical approach to obtain uni-dimensional covariance expressed as a function of two-dimensional covariance, the spectral turning bands method for generating spatial process as described in the previous chapter will be used. The covariance function used in this study is exponential model.

The procedure used in the subroutine is expressed as a flowchart shown in Figure 4.1.

The first step is to generate 16 lines distributed evenly in a cycle having its center at the middle of interested area. The coordinate of these 16 lines will be defined by 2 elementary vectors, X and Y (SX(16,2) in Fortran program in Appendix B11), respectively.

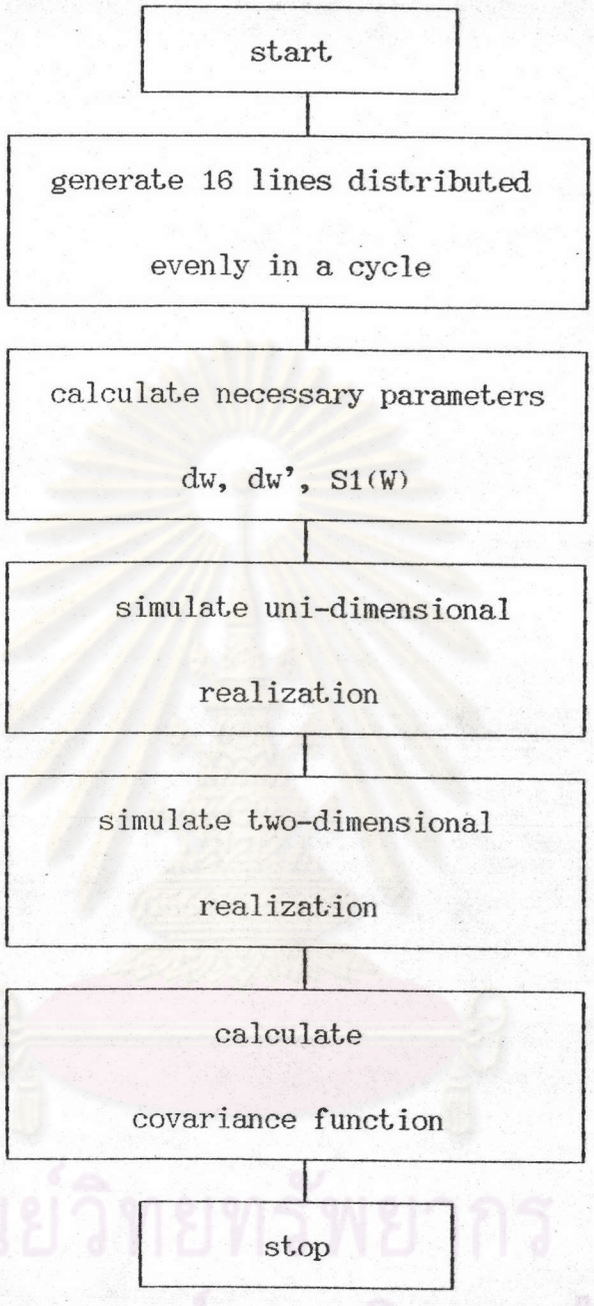

Figure 4.1. Flowchart of the two-dimensional spectral turning bands method subroutine.

Each line will be divided equally into segments (bands). The band width, UN, is calculated as a function of the width or the length of an assigned block in area (DL or DC). In this study, UN is determined to equal to half of minimum of width or length of a block, according to the suggestion of Journel and Huijbregts (1978). The length of each line must cover the interested area. The number of bands in each line, NGMAX, is equal to length of a line divided by band width. The graphically representation is shown in Figure 3.5.

After 16 lines have been already generated, then uni-dimensional realizations will be calculated and assigned to each band using spectral method as explained in the previous chapter. Then, the random variable of every blocks will be calculated using Equation (3.10). These calculated random variable will have their spatial correlation according to the assigned covariance function. The computer program for simulating random variables using spectral turning bands method is presented in Appendix B11.

In the spectral domain the value of harmonic number (M) and frequency range (Ω) used in the spectral turning bands method have to be assigned appropriately so that the error is minimum. Therefore, the value of frequency range must be ralated to correlation length (b^{-1})

(Mantoglou and Wilson, 1982) and the value of harmonic number must be large enough to reduce the error of spectral discretization. So, in order to have proper harmonic number and frequency range it is neccessary to compare covariance functions of simulated random variables obtaining at various values of harmonic numbers and frequency range to their theoretical covariance functions. The procedure of evaluation of appropriate harmonic number and frequency range is presented as follows.

1. The developed turning bands method program presented in Appendix B11 will be used to generate random variables in two-dimensional space using various value of harmonic number and frequency range shown in Table 4.1. The input variables for the calculation is set as shown in Table 4.2.

2. The random variables obtained from the calculation will be used to calculate their covariance function.

3. The covariance functions obtained from the simulation will be compared with theoretical covariance function. The proper value of harmonic number and frequency range yielding the best curve will be used in the oil reserve calculation program.

Table 4.1. Values of harmonic number (M) and frequency range (Ω) for generating random variable.

run number	harmonic number	Ω/b^*
1	20	10
2	20	20
3	20	40
4	20	60
5	50	10
6	50	20
7	50	40
8	50	60
9	100	10
10	100	20
11	100	40
12	100	60
13	150	10
14	150	20
15	150	40
16	150	60

* Remark : b^{-1} = correlation length.

Table 4.2. Parameters for finding appropriate harmonic number and frequency range.

parameter	value
correlation length for exponential covariance function, LENGTH, (foot)	600
length of a simulated block, DC, (foot)	50
width of a simulated block, DL, (foot)	50
number of blocks	70x70

The results are shown in Figures 4.2-4.5. The covariance functions of random variables simulated from the developed subroutine at various values of two constants are compared with theoretical covariance functions at correlation length equal to 600 feet. The best curve, selected because of being the nearest one from the theoretical curve, is the curve obtained by using M = 100 and $\Omega = 20b$, where b is (correlation length)$^{-1}$.

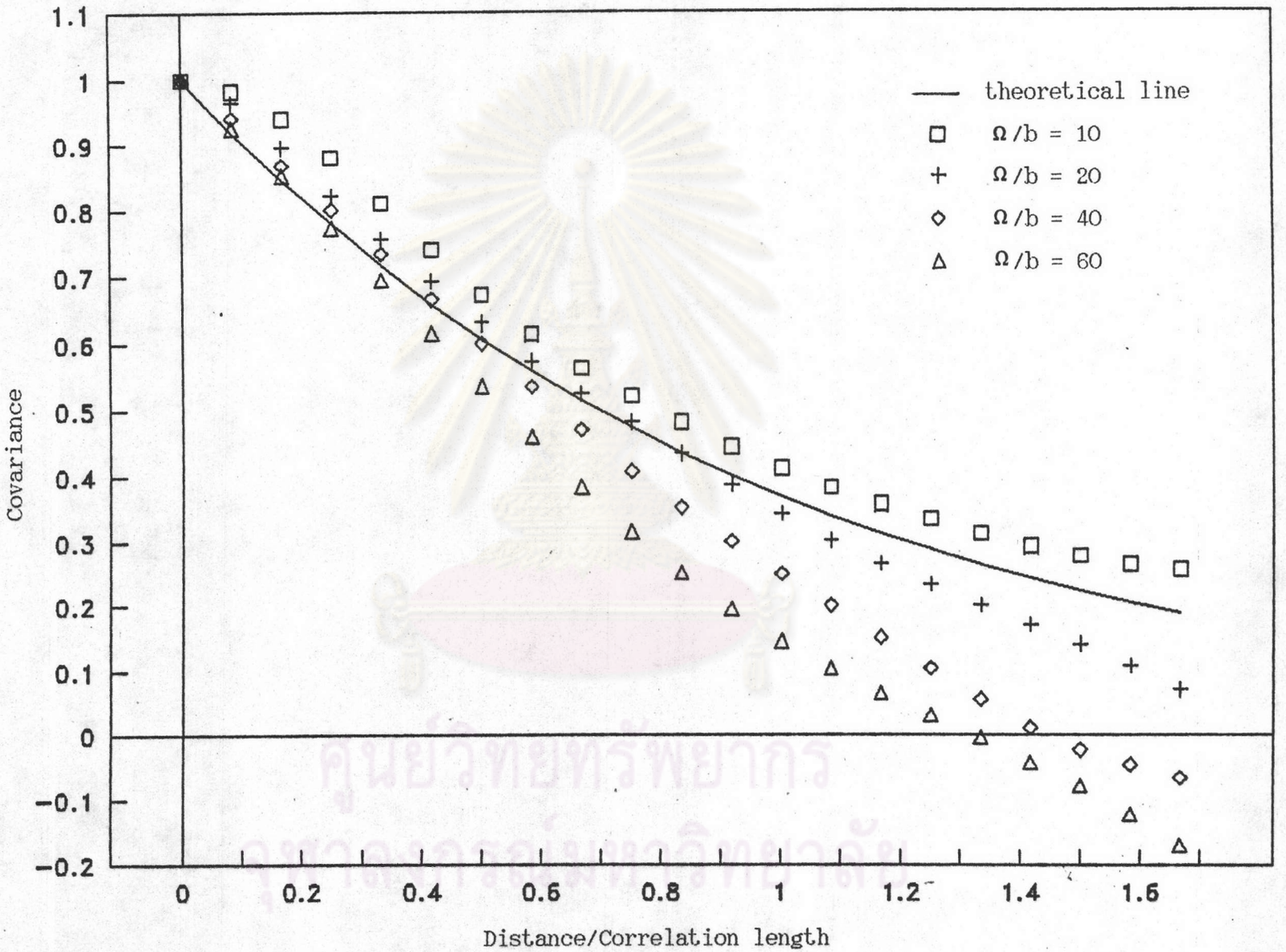

Figure 4.2. Covariance functions at harmonic number = 20 compared with theoretical curve.

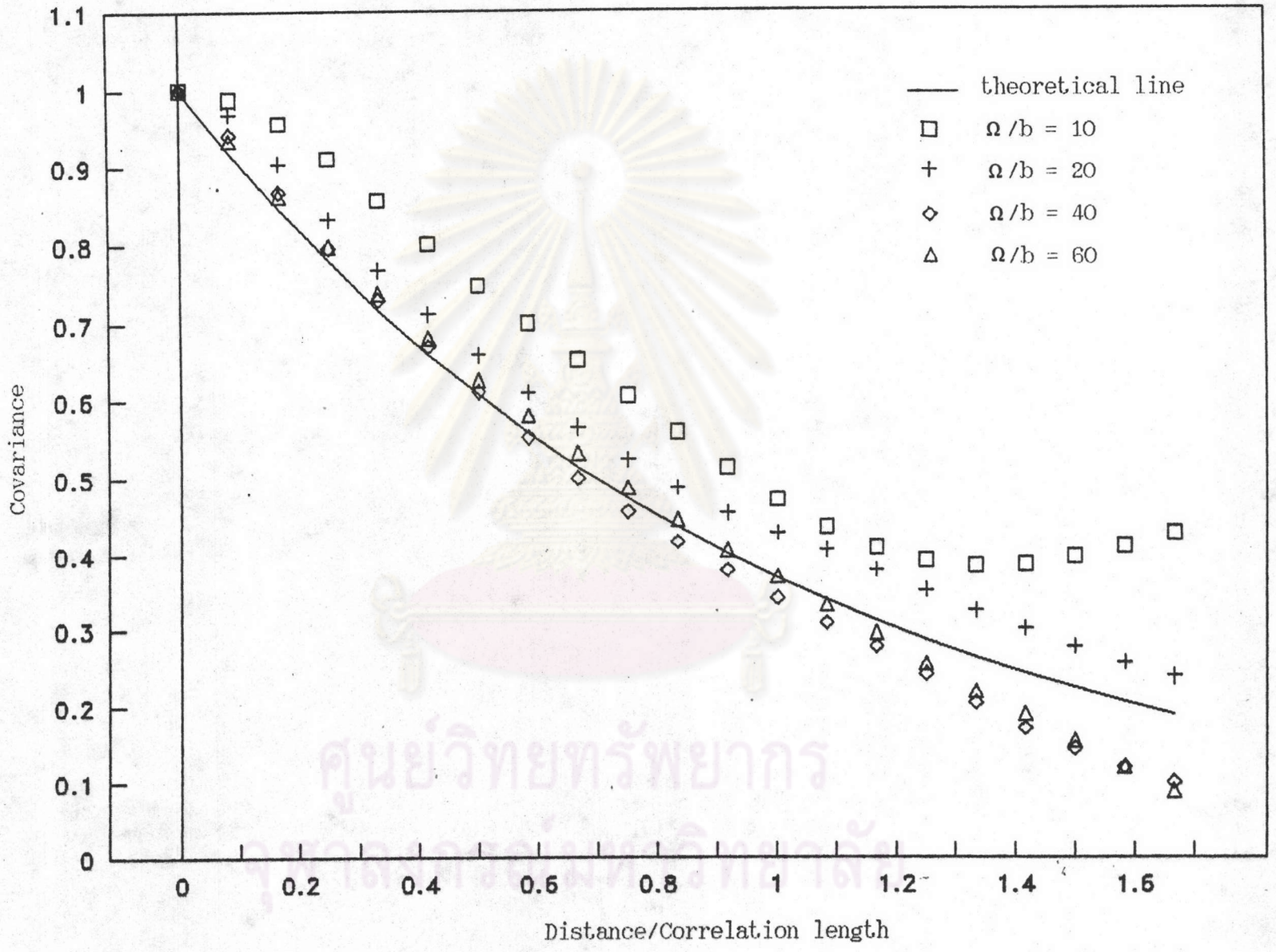

Figure 4.3. Covariance functions at harmonic number = 50 compared with theoretical curve.

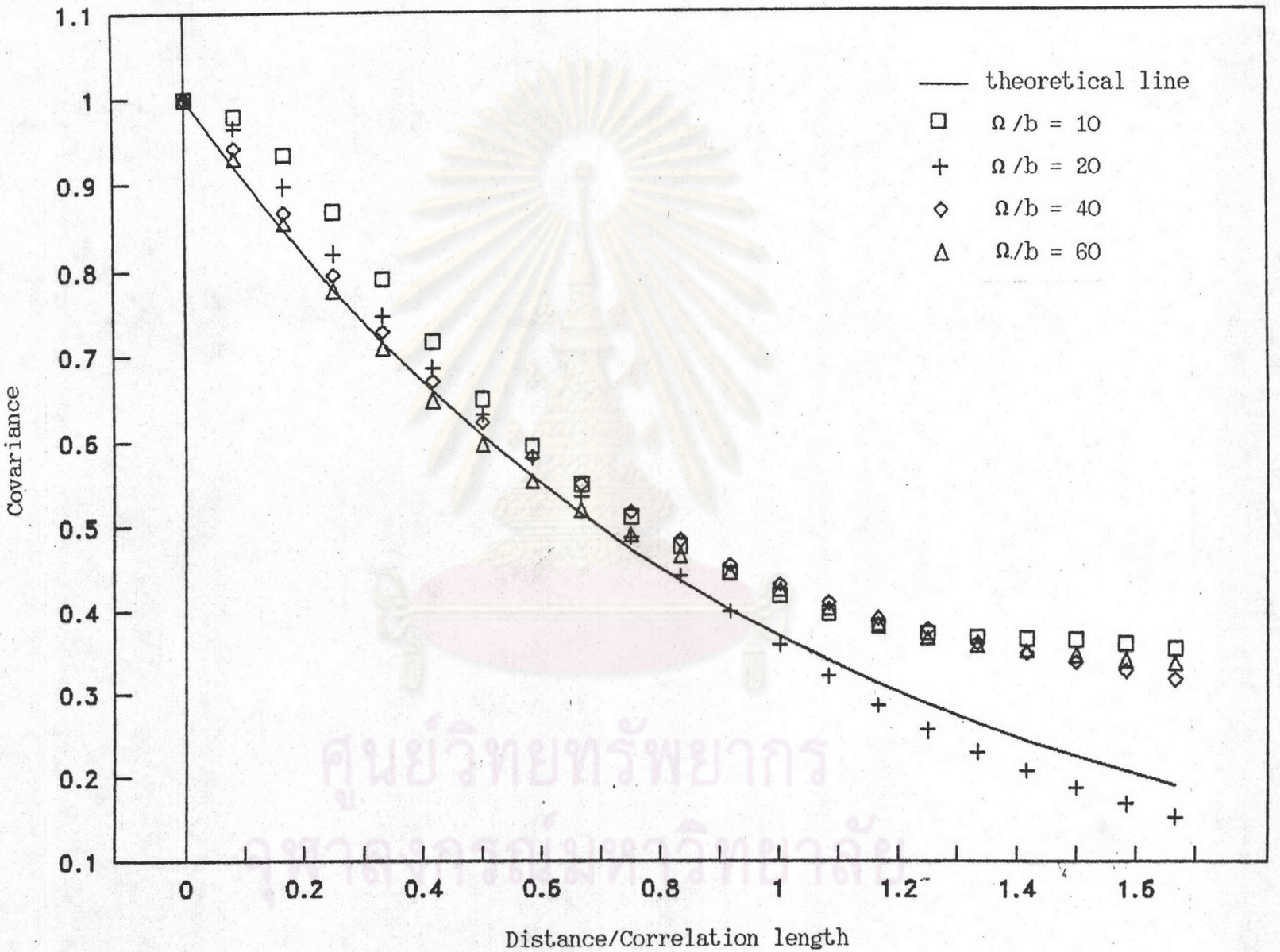

Figure 4.4. Covariance functions at harmonic number = 100 compared with theoretical curve.

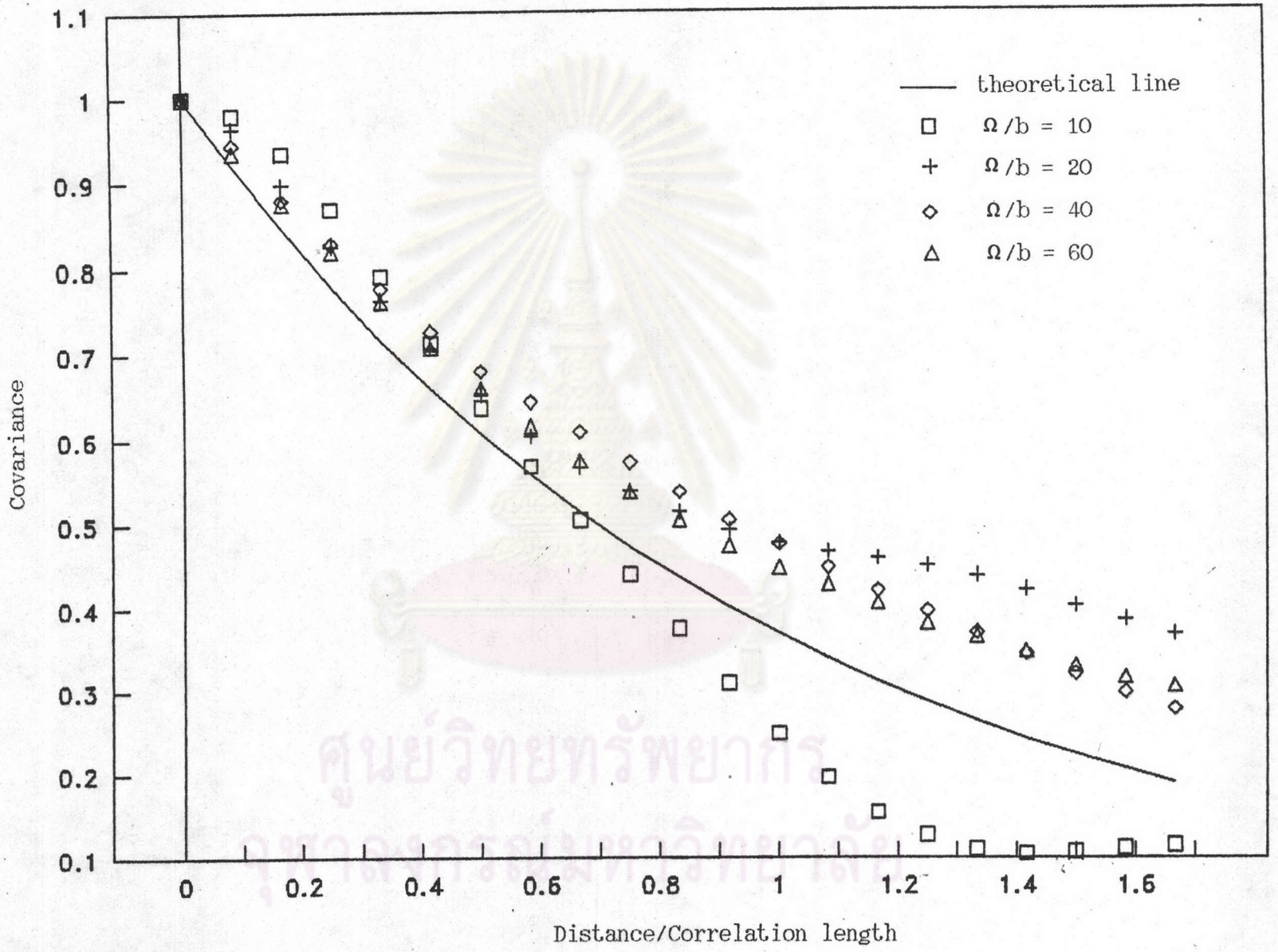

Figure 4.5. Covariance functions at harmonic number = 150 compared with theoretical curve.

In addition, the appropriated value of harmonic number and frequency range also were further tested at different correlation length, 400 and 800 feet. The results show that the simulated covariance functions are close to their theoretical covariance function.

From the test the spectral turning bands method used in the Monte Carlo simulation in this study will have values of harmonic number and frequency range being 100 and 20b, respectively.

The Computer Program Development for Oil Reserve Calculation Using Monte Carlo Simulation.

A computer program for oil reserve calculation using Monte Carlo simulation to be developed in this study is the program that can report uncertainty of oil reserve due to uncertainty of input variables. The method of calculation of oil reserve is volumetric method using Equation (3.2).

As already known, most reservoirs consist of thin layer of formation which usually cover a large area. With this reason it is decided that a reservoir will be treated as a two-dimensional system for reserve calculation purpose.

In developing the computer program, two options concerning

division of the reservoir have been offered. For the first option a reservoir will be treated as a single block while for the second option, the reservoir will be divided into many small blocks with uniform properties along the vertical direction (thickness). In the second option all available information can be optimally used.

The input variables involving in reserve calculation are as follows:

1. area (acre)
2. recovery factor
3. gloss thickness (foot)
4. net to gloss thickness ratio
5. oil sand to net sand ratio
6. initial oil formation volumn factor
7. porosity
8. water saturation.

For the case that there is a statistical relationship between porosity and water saturation, the value of water saturation will be determined using the assigned statistical relationship.

For the case that an input variable has spatial correlation, its realization will be generated using spectral turning bands method. In

this study the random variable having spatial correlation is assumed to be second-order stationary and statistically isotropic in two-dimensional space.

The steps of calculation within the developed program are as follows.

1. In the first part of the program, input data involved in oil reserve calculation will be read from data input file. These data are:

- Number of simulations or realizations, NOLOOP
- Number of blocks in X-axis and Y-axis, NCO and NLI
- Parameters involved distribution of input variables.
- Correlation length.

2. Generation of area of a reservoir will be performed. Then, area, width and length of each block will be calculated (in case when a reservoir is divided into blocks).

3. Values of input variables are assigned to every blocks using random numbers.

4. For the case that an input variable having spatial correlation, its values are simulated using spectral turning bands method subroutine. The distribution of values of an input variable obtained from this subroutine is normal distribution with zero mean. Therefore, if the distribution of that input variable is not normal, the

transformation from normal distribution to any desired distribtuion is required. Equation (4.3) to (4.5) (Abramowitz and Stegun, 1964) can be used to calculate cumulative probability for normal distribution. Then using these cumulative probability with the specified distribution of the desired random variable, the values of the desired random variable can be obtained.

$$P(X) = 0.5 + 0.5[1 - \exp(-2X^2/\pi) - 2(\pi - 3) X^4 \exp(-X^2/2)/(3\pi^2)]^{1/2}, \quad X > 0 \qquad (4.3)$$

$$P(X) = 1 - 0.5[(4 + X^2)^{1/2} - X] (2\pi)^{-1/2} \exp(-X^2/2), \quad X > 1.4 \qquad (4.4)$$

$$P(X) = 1 - (2\pi)^{-1/2} \exp(-X^2/2) / X, \quad X > 2.2 \qquad (4.5)$$

where X = normal distributed variable

$P(X)$ = cumulative probability.

In Figure 4.6, the transformation of a normal distributed variable to a desired distribution is shown graphically.

5. In case of having statistical relationship between porosity and water saturation, its statistical relationship will be expressed as in Equation (3.3).

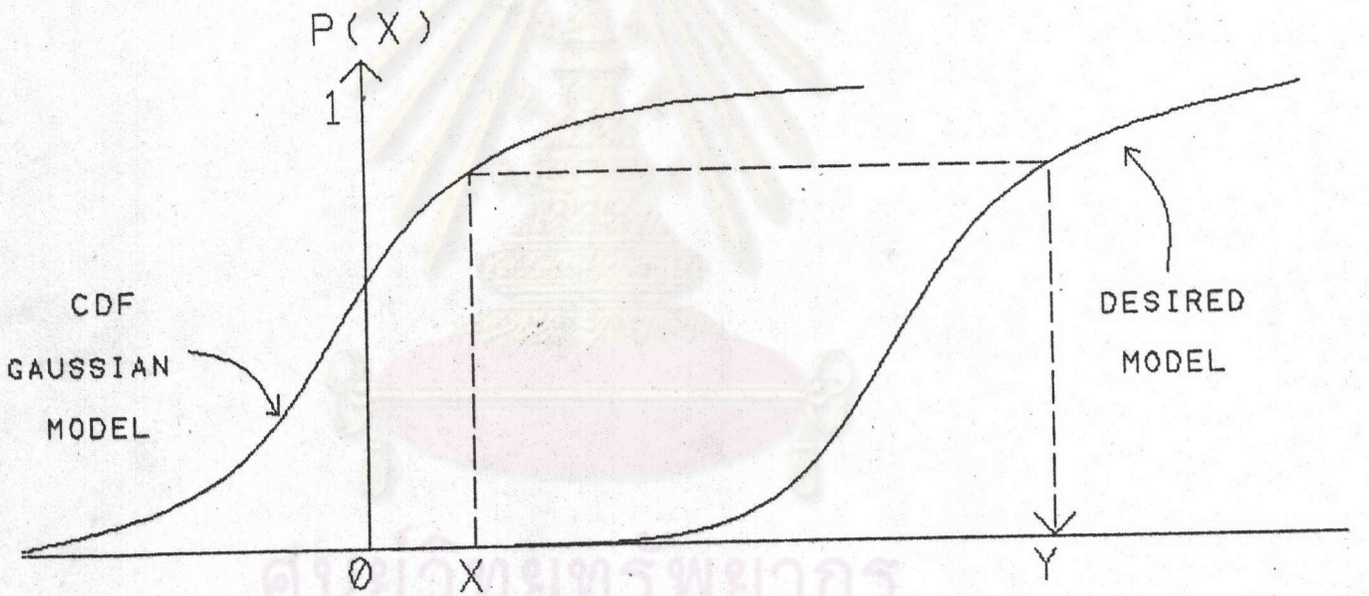

Figure 4.6. Tranformation from normal distributed variable to desired distribution.

6. The value of oil in place of each block is obtained by using equation (3.1) and the oil reserve is multiplication product of summation of the oil in place in each block and recovery factor.

7. The oil reserve calculation will be performed repeatedly from step 2 to 6. Probability density function and cumulative distribution function of calculated oil reserve will, then, be estimated.

The developed program for oil reserve using Monte Carlo simulation is presented in appendix B12.

Validation of the Developed Computer Program.

The developed program has to be validated before being used. The primary checks are as follows:

1. checking data transfer between main program and subroutines,
2. checking results obtained from every calculation steps.

In addition, the validation by checking correction of calculated oil reserve can be done by assigning distribution of independent input variables as normal distribution. If the program is valid, expectation of calculated oil reserve should be

$$E[N_R] = 7758\ E[A]\ E[h_g]\ E[R_1]\ E[R_2]\ E[\phi]\ E[1-S_w]\ E[E_R]\ E[1/B_{o1}] \quad (4.6)$$

Note that, this equation can be used when there is no statistical relationship between any input variables.

With the validation mentioned above, it is believed that the developed computer program can give correct results.

Description of the Developed Program.

Description of the developed program will be presented here in order to guide readers for use and further modification.

The first part of the program is input data section. Data input file presented in Appendix B13 is designed for easy use. Number of simulations (NOLOOP), number of blocks in X- and Y-axes (NCO and NLI), and ratio of length to width of a block (RATIO) will be entered firstly. The number of simulations should be large enough so that probability density function of calculated oil reserve has no significant error. Number of blocks should correspond to availability of information. The ratio of length to width of a block will infer shape of assigned block, e.g., a block will be square if the ratio is 1.

Then, descriptions of input variables will be read into the simulation as follows:

1. Name of input variables (NAME),

2. Type of distribution (TYPE). In this program, the available types of distribution of input variables are uniform distribution (UNIF), triangular distribution (TRIA), normal distribution (NORM), and Log-normal distribution (LOGN). The input variables can also be treated as deterministic values (DETM),

3. Parameters for the distribution (DETEM, MAX, MIN, MODE, MEAN, STDDEV). These parameters essentially for each type of distribution are presented in appendex A,

4. Correlation length in case of having spatial correlation (LENGTH). The exponential covariance function is only used in this simulation,

5. Parematers of relationship between porosity and water saturation (AMU1, AMU2, AMU3) including standard deviation of random part used in the following equation:

$$S_w = AMU1\ \phi^2 + AMU2\ \phi + AMU3 + \text{Random part.} \qquad (4.7)$$

After these informations has been already entered into the simulation, area of the reservoir will be determined. If area is not assigned as deterministic value, area will be determined using parameters of distribution and a random number. Then, length and width of a block (DC,DL) will be calculated using number of blocks and ratio

of length to width of a block.

In the next step, values of other input variables of Equation (3.1) will be generated for each block. In case that an input variable is not treated as a deterministic variable, the value of that input variable will be determined using parameters of its distribution and a random number. In case that an input variable has spatial correlation, its realization will be obtained using spectral turning bands method subroutine. In case of having statistical relationship between porosity and water saturation, realization of water saturation will be obtained using value of porosity and parameters representing the statistical relationship.

Value of oil in place in each block will be determined using Equation (3.1). Total oil in place of a reservoir is summation of oil in place of every block. Note that, in case that an input variable is treated as a deterministic variable, its value will be not assigned to each block but will be multiplied by total multiplication product of all other variables. Oil reserve, then, will be obtained by multiplying oil in place with recovery factor. Note that, the recovery factor can be treated as deterministic value or random variable.

There are many subroutine used in the Monte Carlo simulation as

follows:

1. Random number generator subroutine. The method used in this subroutine is Linear Congruential method. The appropriate seed assigned for this subroutine was determined in the previous section.

2. Subroutines for generating uniform, triangular, and normal distributed variate. For the uniform and triangular distributions, geometrical method is used to determined random variate. In case of generating normal variate, numerical method of Bell (Forsythe et al., 1977) is used. In case that type of distribution is Log-normal distribution, parameters have to be read into the simulation in Log-term.

3. Subroutine for turning bands method for generating random variable having assigned spatial correlation. Input data for this subroutine are correlation length (LENGTH) and dimension of a block (DC,DL). Output data is set of random variates that is distributed in space according to assigned covariance function.

The first step of this subroutine is to compute rotation matrix of the 16 lines. These lines will be distributed exactly and uniformly in a cycle and having two unit vectors, SX(IT,1) and SX(IT,2), where IT is line number (1-16) to characterize their distribution.

The next step, parameters concerning spectral turning bands method of Equation (3.21) are calculated. Required constants, harmonic number and frequency range were determined in the previous section as 100 and 20/(correlation length), respectively. Value of Δw (DW) is equal to (frequency range)/(harmonic number). $\Delta w'$ (DWP) is equal to DW/20 following Tompson et al.'s (1989) recommendation.

Uni-dimensional realization is then generated using Equation (3.21). Band width is set as 0.5 of length or width of a block. Number of bands is equal to length of diagonal divided by band width plus 4 in order to cover the whole area of interest.

The last step, two-dimensional realization is generated using Equation (3.10).

4. Subroutine for constructing probability density function and cumulative distribution function of oil reserve.

Information transfered to the subroutine for constructing probability density function and cumulative distribution function of oil reserve is set of oil reserves and number of simulations. In addition, this subroutine will also calculate minimum, maximum, median, mode, mean, and standard deviation of calculated oil reserves.

Determination of Appropriate Number of Simulations for Calculation of Oil Reserve.

Before the analyses of effect of various variables on calculated oil reserve are performed, number of simulations has to be determined. The number of simulations is the number of calculated oil reserve to be obtained in each Monte Carlo run. The number of simulations can be decided by observing mean and standard deviation of calculated oil reserves at various number of simulations used. The appropriate number of simulations is the number that mean and standard deviation of calculated oil reserves do not significant change when the number of simulations is further increased.

To determine the number of simulations, the Monte Carlo run using developed program will be performed many times with same data but varying number of simulations (NOLOOP in Fortran program in Appendix B12) as shown in Table 4.3. The results, shape of curve, mean, and standard deviation of every Monte Carlo run are compared.

The number of simulations will be determined using 3 cases of calculations, with a simple data (no spatial correlation) and two more complicated ones (with spatial correlation). The number of simulations that satisfies the set criterion are choosed and will be used in all

later Monte Carlo run.

Table 4.3. Number of oil reserve in each Monte Carlo run to determine the appropriate number of simulations.

case number	number of simulations
1	50
2	100
3	200
4	400
5	600
6	800
7	1,000

Input data, type of distribution, and value characterizing probability distribution of every input variable for determining the appropriate number of simulations in every cases is shown in Table 4.4.

Number of blocks assigned in each Monte Carlo run in case of no spatial correlation is 1x1. The area is set as deterministic value at 1.7424×10^{8} $foot^{2}$ (4,000 acres) and the simulated area is square. Therefore, the width and length of the simulated block will be 13,200 feet.

Table 4.4. Data for determination of appropriate number of simulations.

Variables and their parameters
1. Area type of distribution: deterministic value value = 4,000 acres
2. Recovery factor type of distribution: deterministic value value = 0.12
3. Gross thickness type of distribution: normal distribution mean = 200 feet standard deviation = 10 feet
4. Net to gloss ratio type of distribution: deterministic value value = 0.6
5. Oil sand to net sand ratio type of distribution: deterministic value value = 0.7

Table 4.4 (continued). Data for determination of appropriate number of simulations.

Variables and their parameters
6. Initial oil formation volume factor type of distribution: deterministic value value = 1.2
7. Porosity type of distribution: normal distribution mean = 0.22 standard deviation = 0.03
8. Water saturation type of distribution: triangular distribution maximum = 0.45 minimum = 0.15 mode = 0.25

In case of the two complicated systems having spatial correlation of an input variable, data in Table 4.4 will also be used for determination of number of simulations and the spatial correlation of porosity will be incorporated in the calculation. Number of blocks determined are 25 and 625. Therefore, the width and length of a block

will be 2,640 and 528 feet for the 25- and 625-block systems, respectively. The assigned correlation length is 5,280 feet. So, ratio of correlation length to width of a block are 2 and 10 for the 25-block and 625-block system, respectively.

For the first case (no spatial correlation), the probability density functions of calculated oil reserve at various number of simulations; 50, 100, 200, 400, 600, 800, and 1,000 are shown in Figures 4.7 to 4.13, respectively. The values of mean and standard deviation of calculated oil reserve using various number of simulations are shown graphically in Figures 4.14 and 4.15, respectively.

From the results it can be noticed that when the number of simulations was set at small value such as 50 and 100, the obtained oil reserve probability density function curves are not smooth. When the number of simulations was increased, e.g., 600, 800, and 1,000, the obtained probability density function curve will be smoother and have rather similar shape.

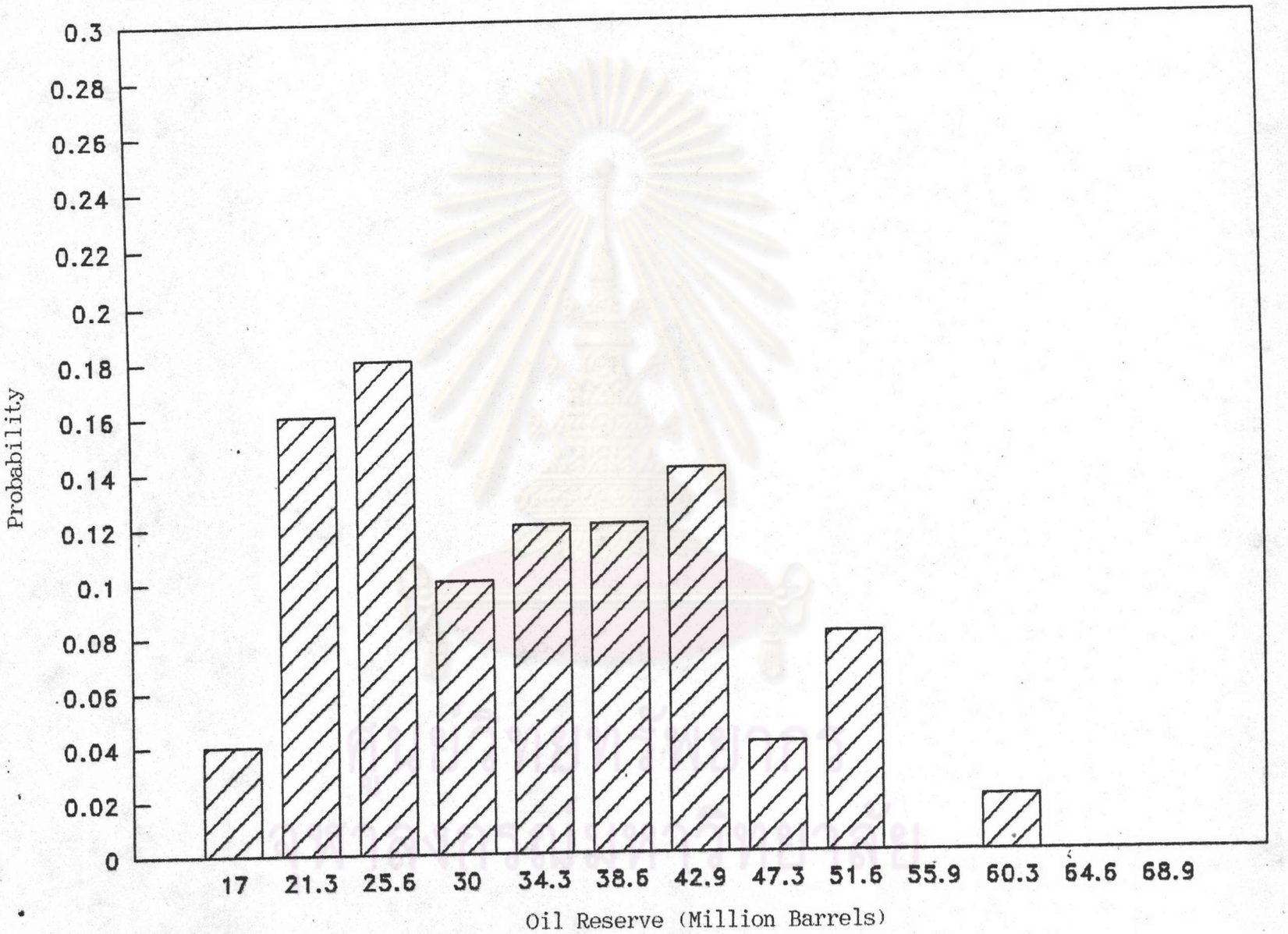

Figure 4.7. Probability density function of oil reserve at number of simulations = 50, without spatial correlation.

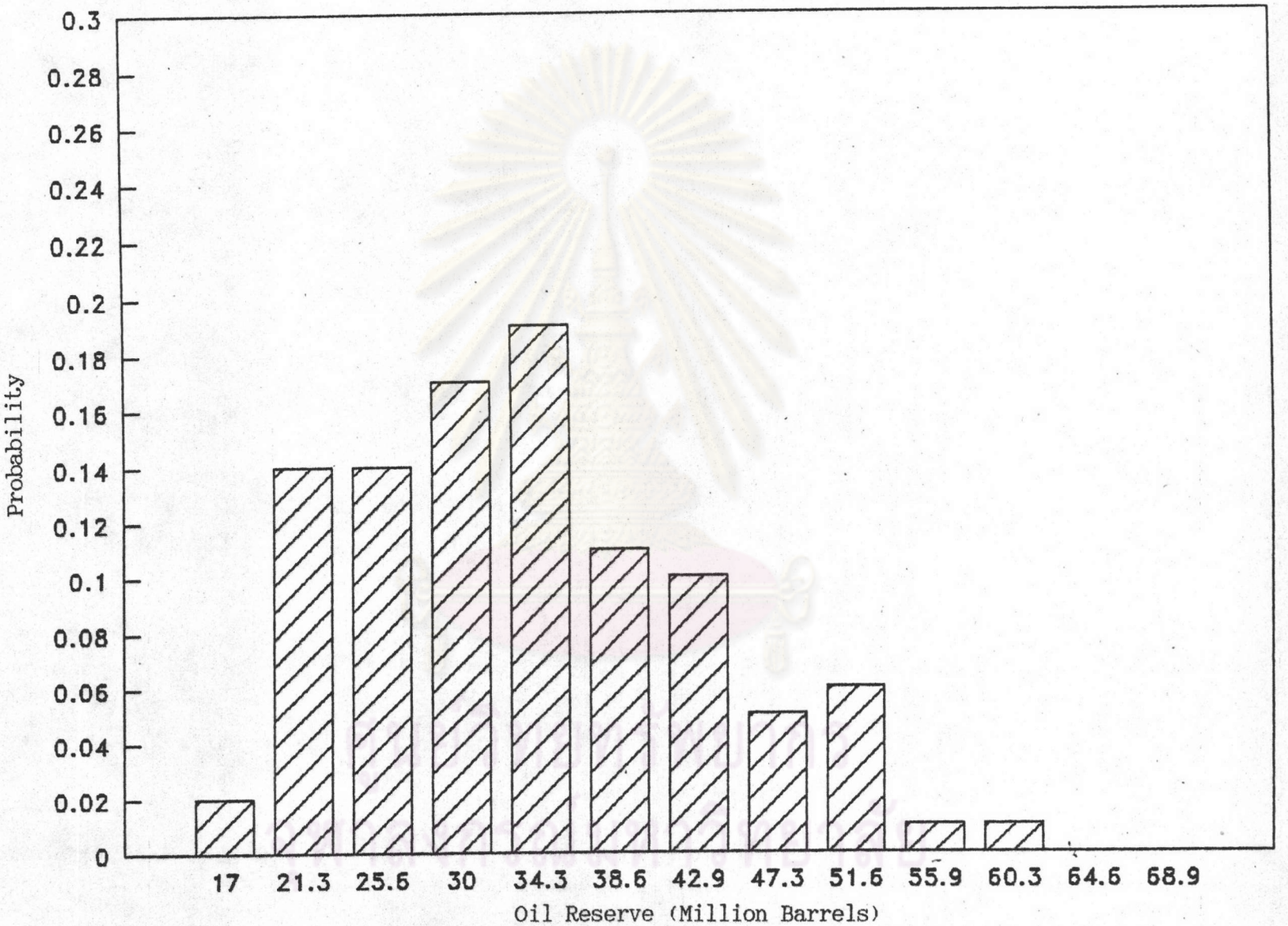

Figure 4.8. Probability density function of oil reserve at number of simulations = 100, without spatial correlation.

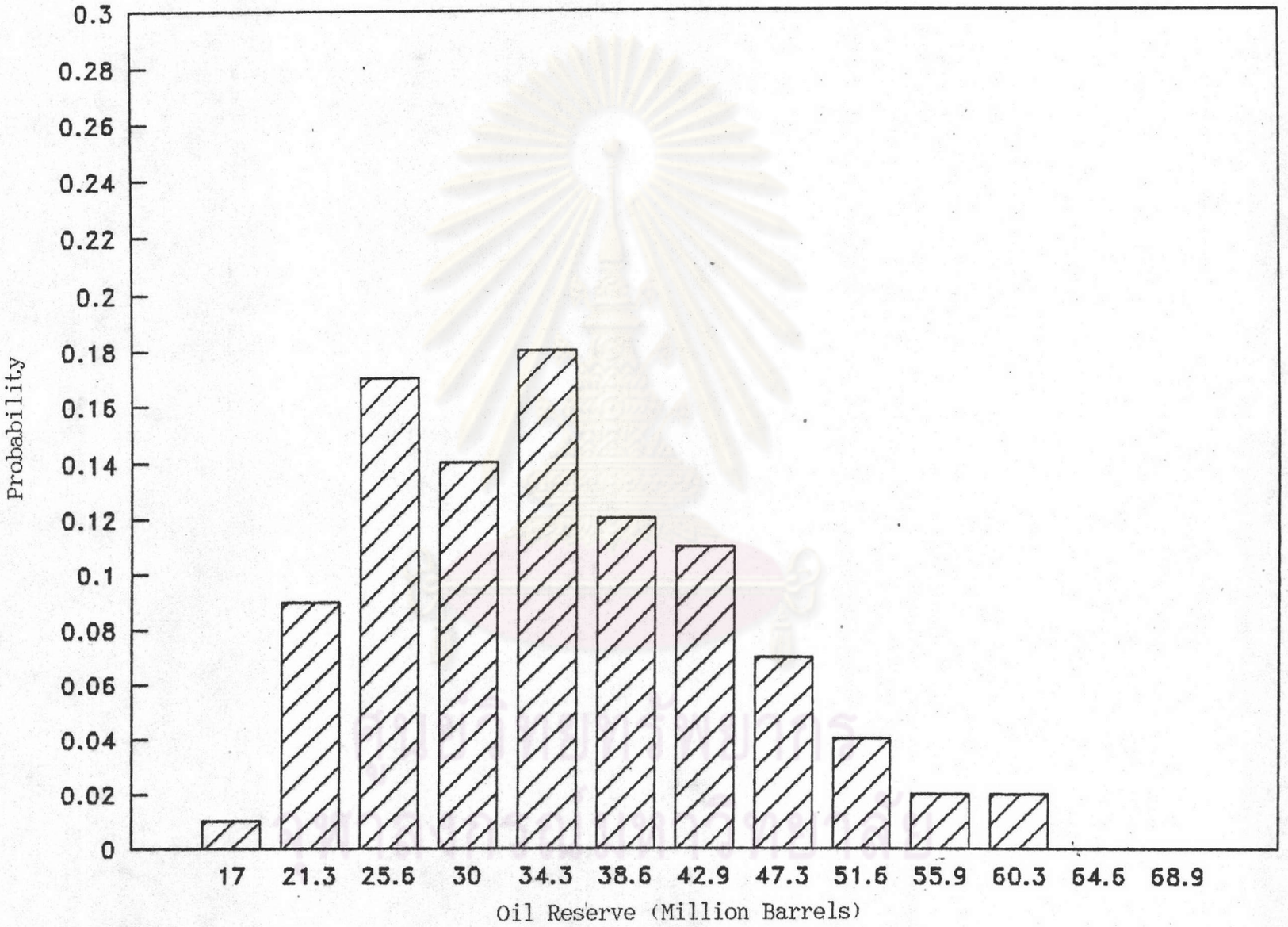

Figure 4.9. Probability density function of oil reserve at number of simulations = 200, without spatial correlation.

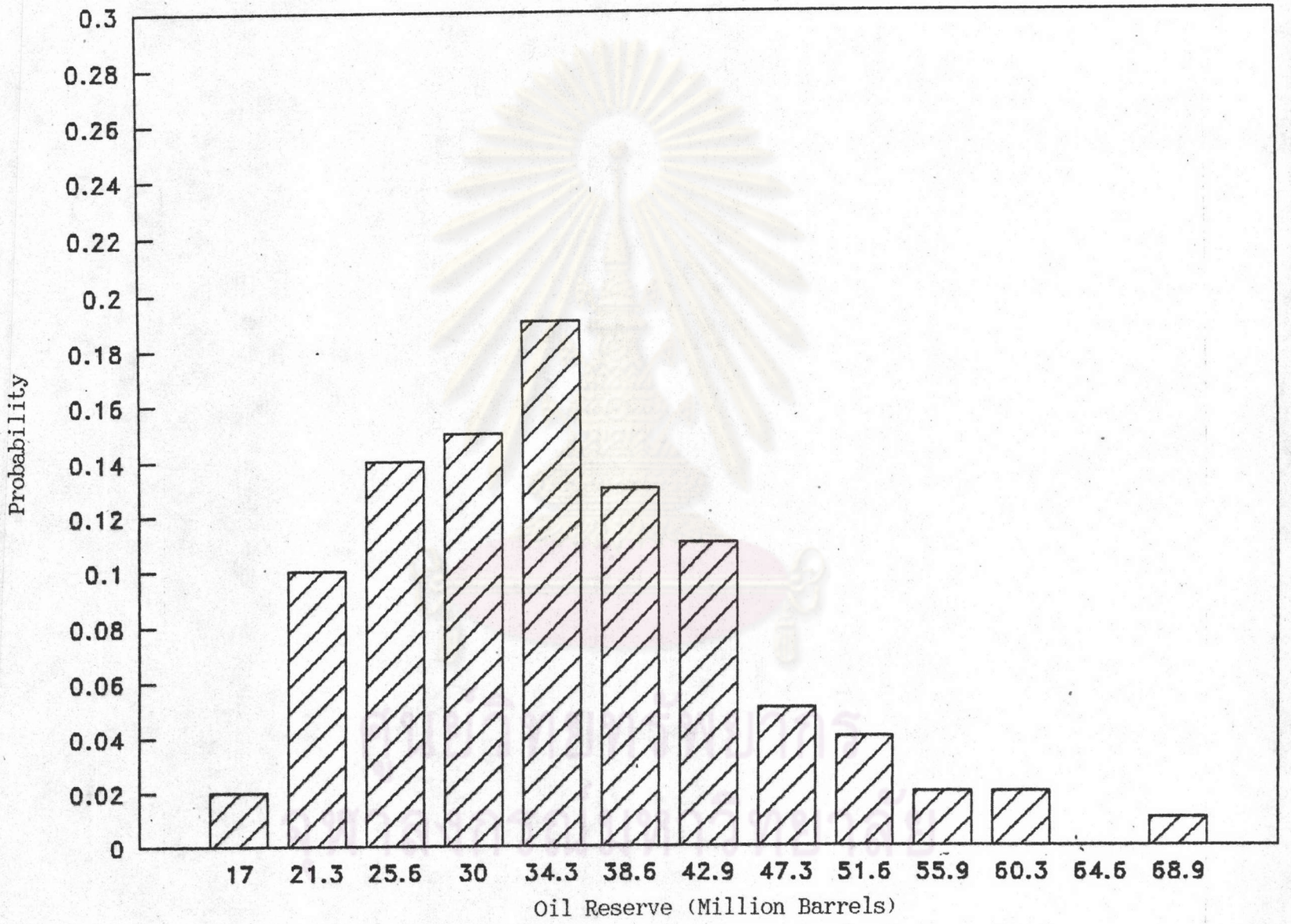

Figure 4.10. Probability density function of oil reserve at number of simulations = 400, without spatial correlation.

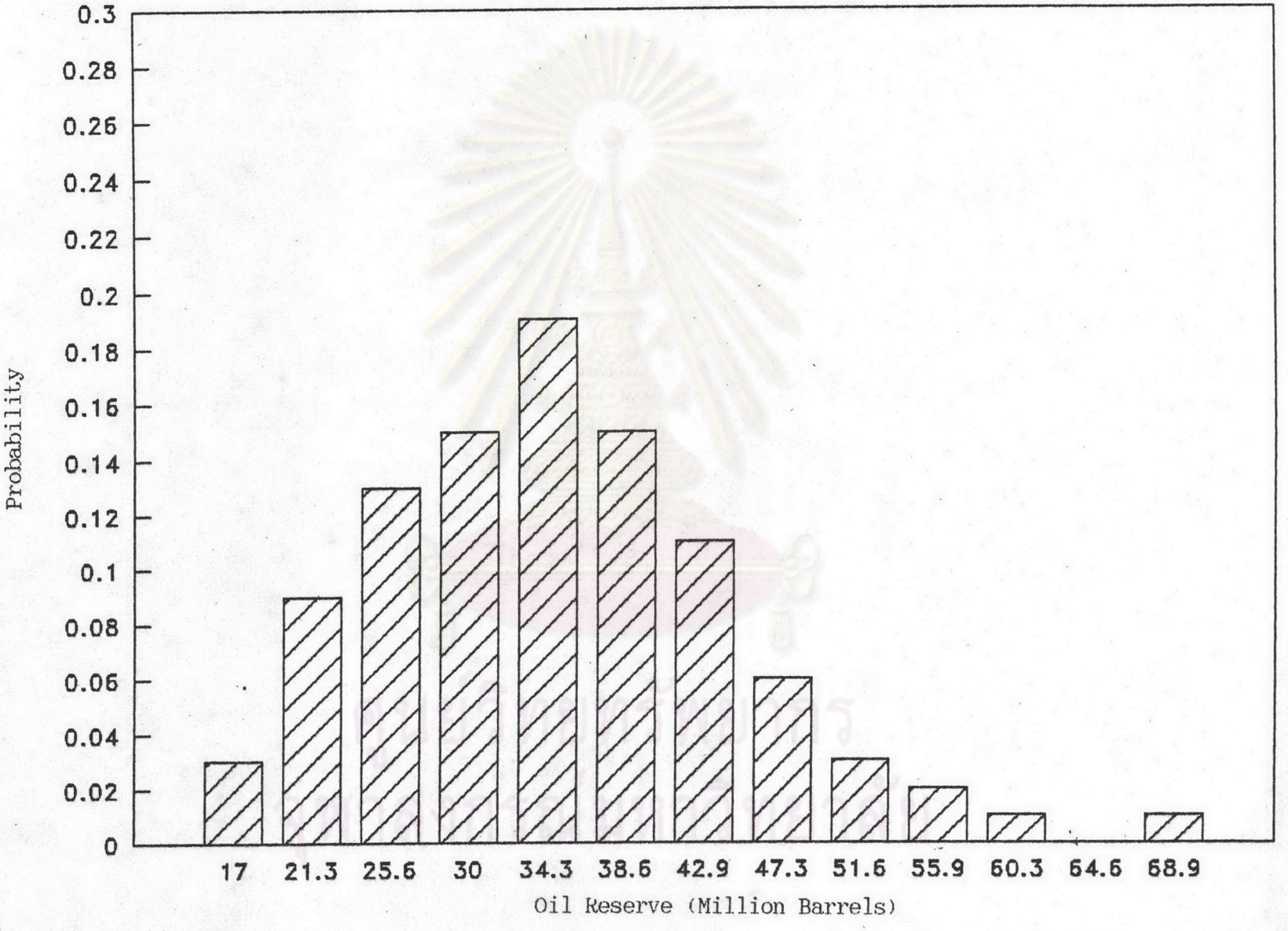

Figure 4.11. Probability density function of oil reserve at number of simulations = 600, without spatial correlation.

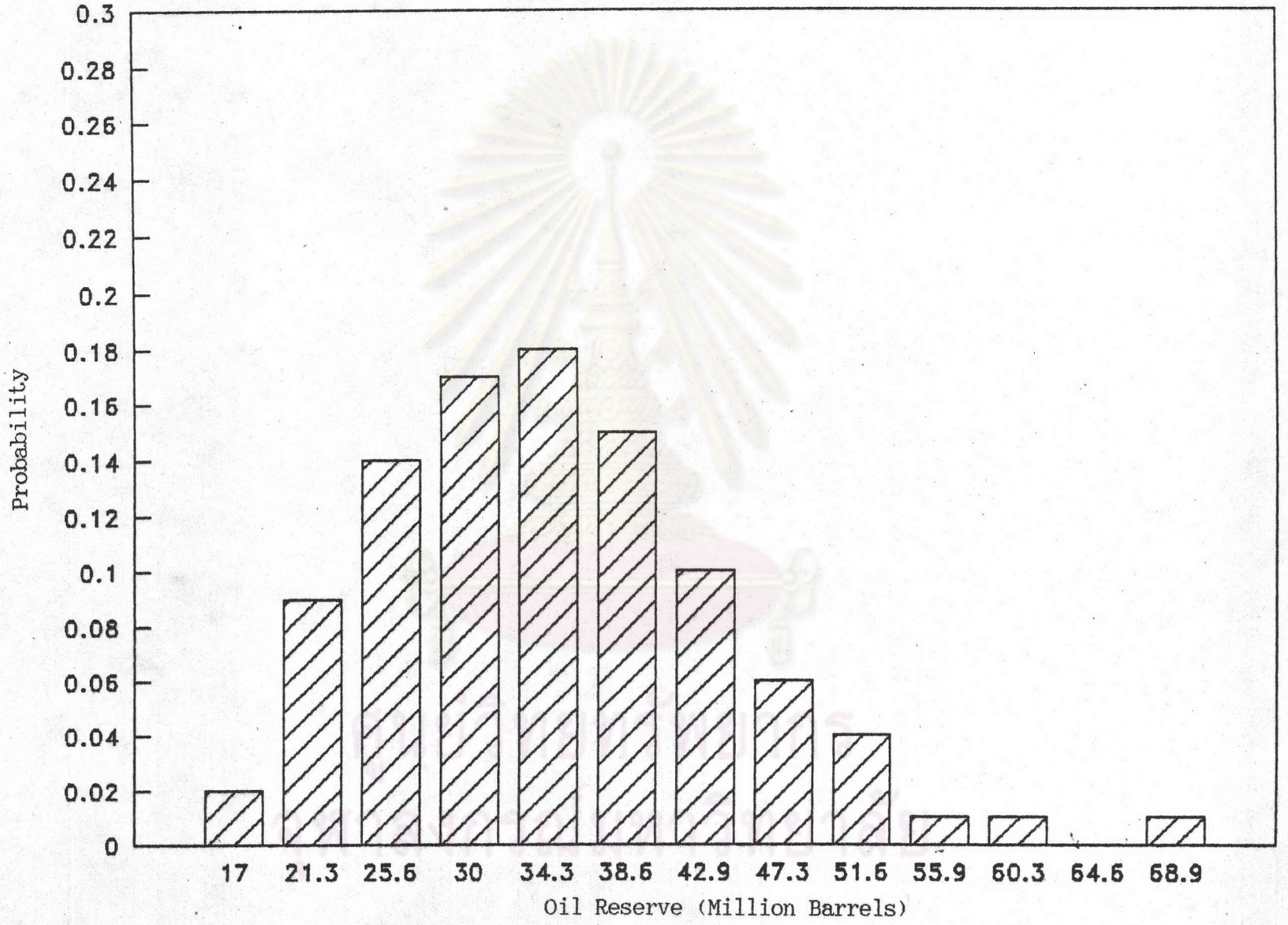

Figure 4.12. Probability density function of oil reserve at number of simulations = 800, without spatial correlation.

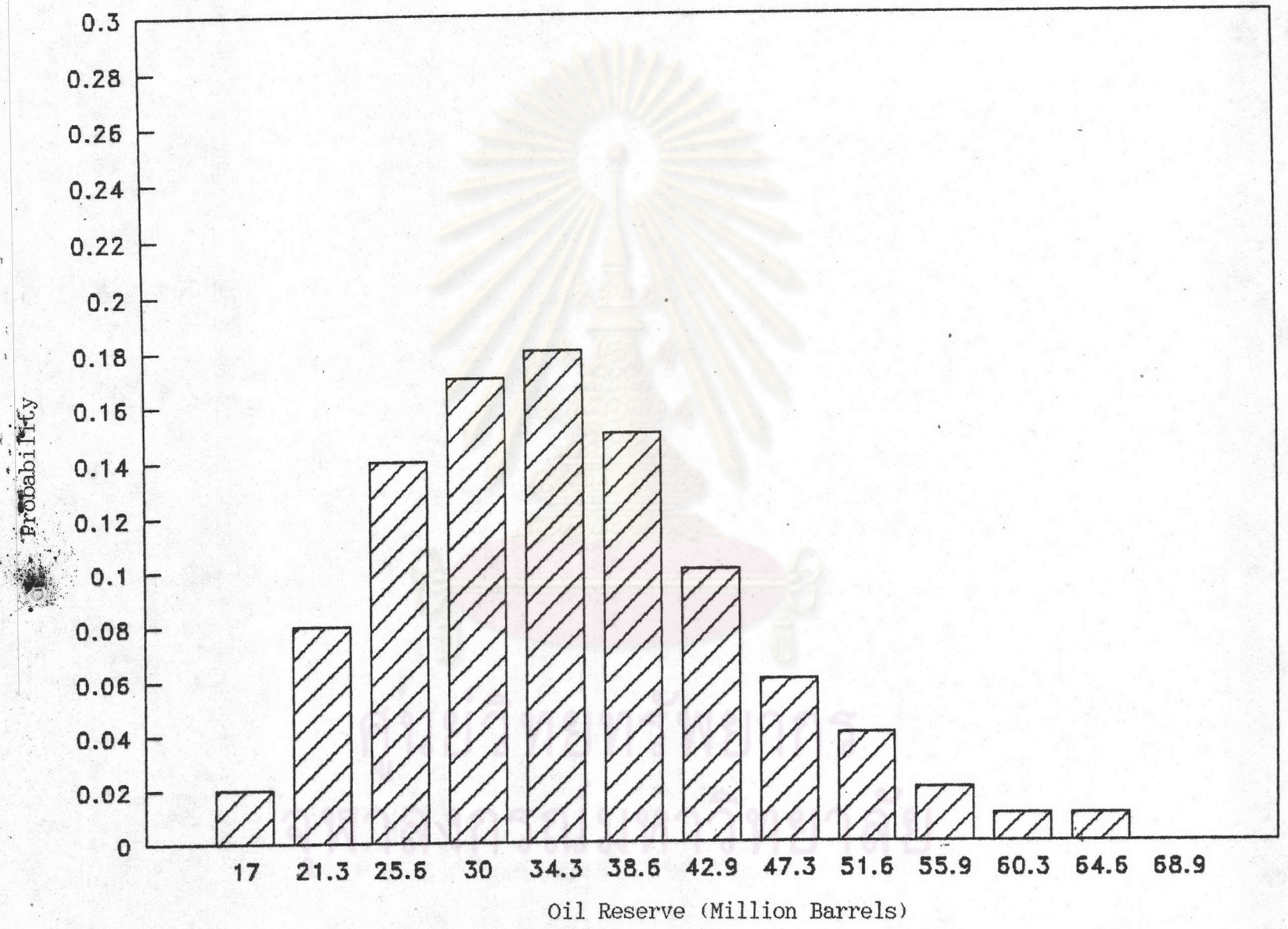

Figure 4.13. Probability density function of oil reserve at number of simulations = 1000, without spatial correlation.

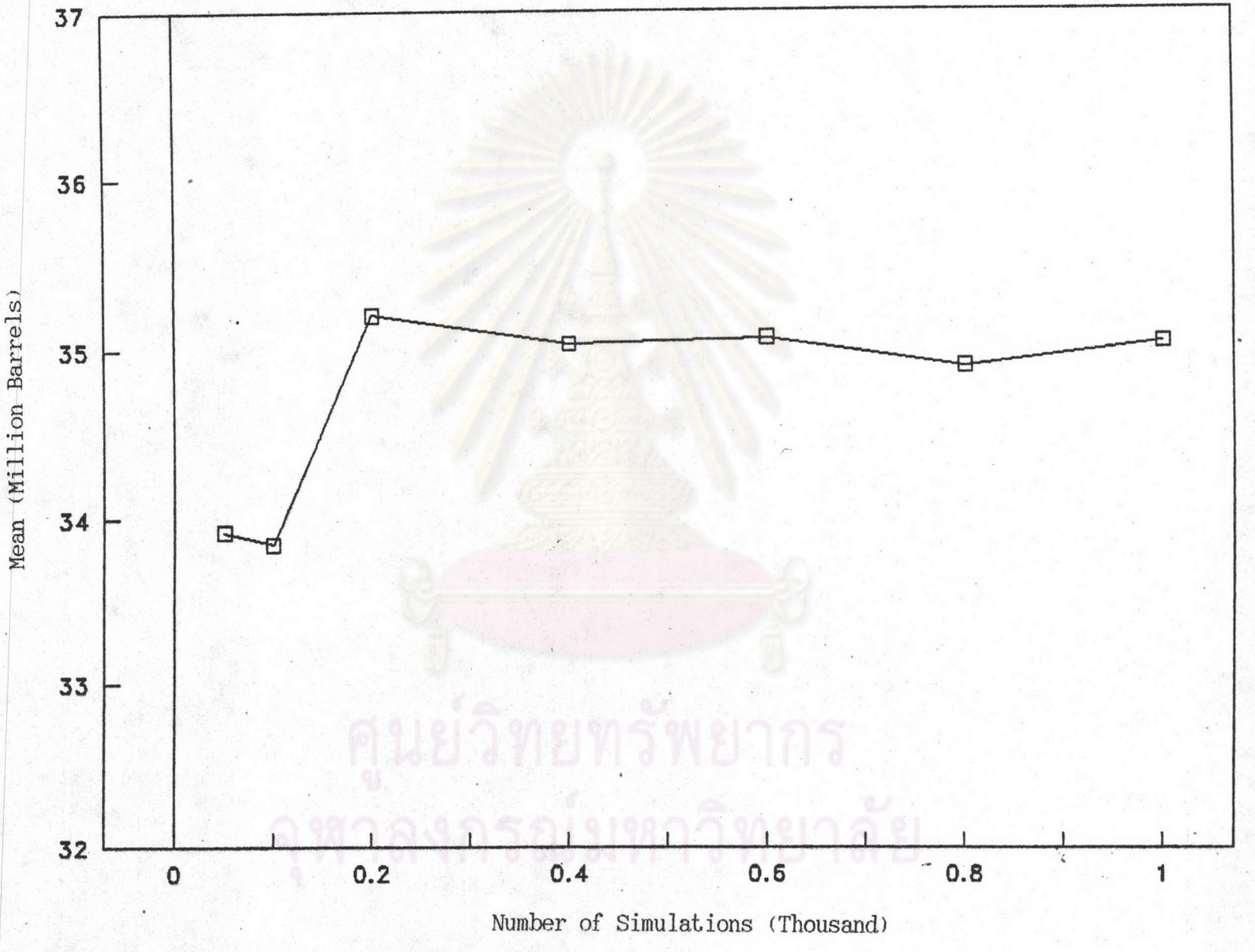

Figure 4.14. Mean vs. number of simulations calculated without spatial correlation.

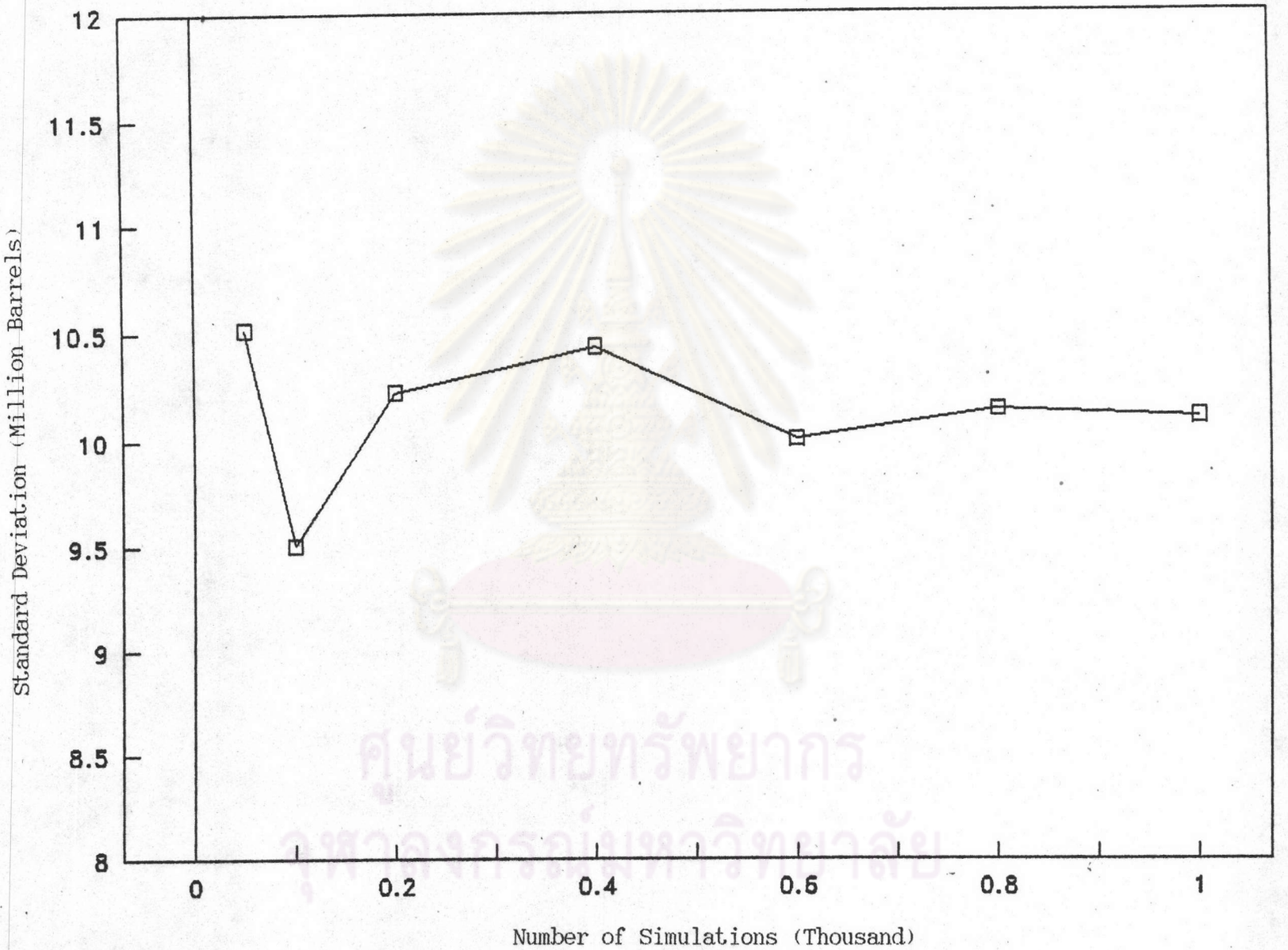

Figure 4.15. Standard deviation vs. number of simulations calculated without spatial correlation.

By comparing the obtained curves at various number of simulations, e.g., 100 and 200, a variation in mean value is 3.898 % and variation in standard deviation is 7.160 % (using reference value at number of simulations of 1,000), whereas variation in mean and standard deviation values when using number of simulations of 600 and 1,000 are only 0.079 % and 1.017 %, respectively, which is significant less than those of smaller number of simulations.

From the first case, we can notice that using the number of simulations at 600 or greater will give similar probability density function curve and difference in mean and standard deviation are insignificant.

In the second case, the calculation of oil reserve with spatial correlation of porosity using number of blocks equal to 25 is considered. The probability density functions of oil reserve are expressed in Figures 4.16 to 4.22 and graphs of mean and standard deviation versus number of simulations are shown in Figures 4.23 and 4.24, respectively.

We find that the results obtained in this case are similar to the first case. The obtained probability density function curves will be smoother and have similar shape when the number of simulations is increased.

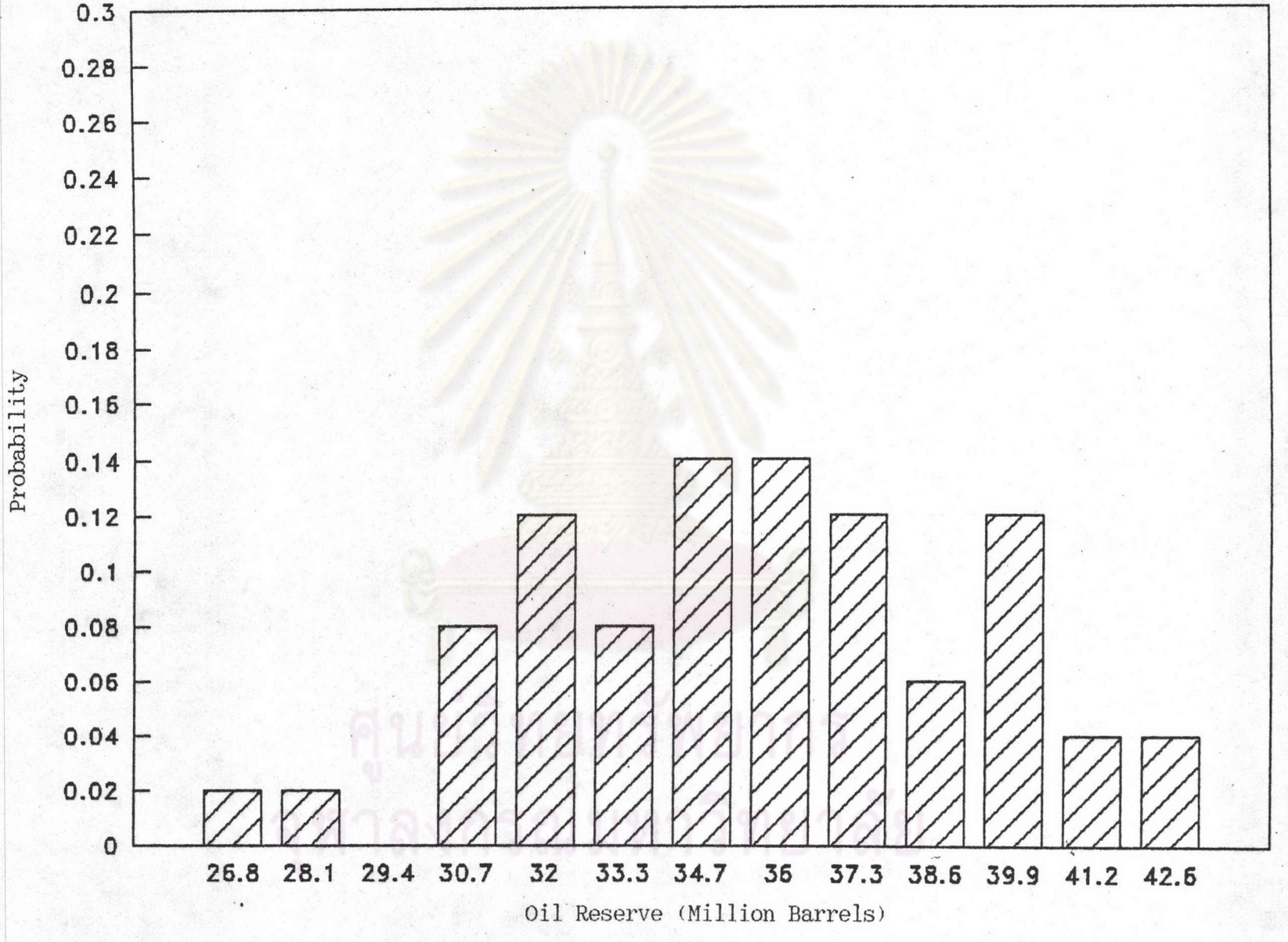

Figure 4.16. Probability density function of oil reserve at number of simulations = 50, with spatial correlation (number of blocks = 5x5).

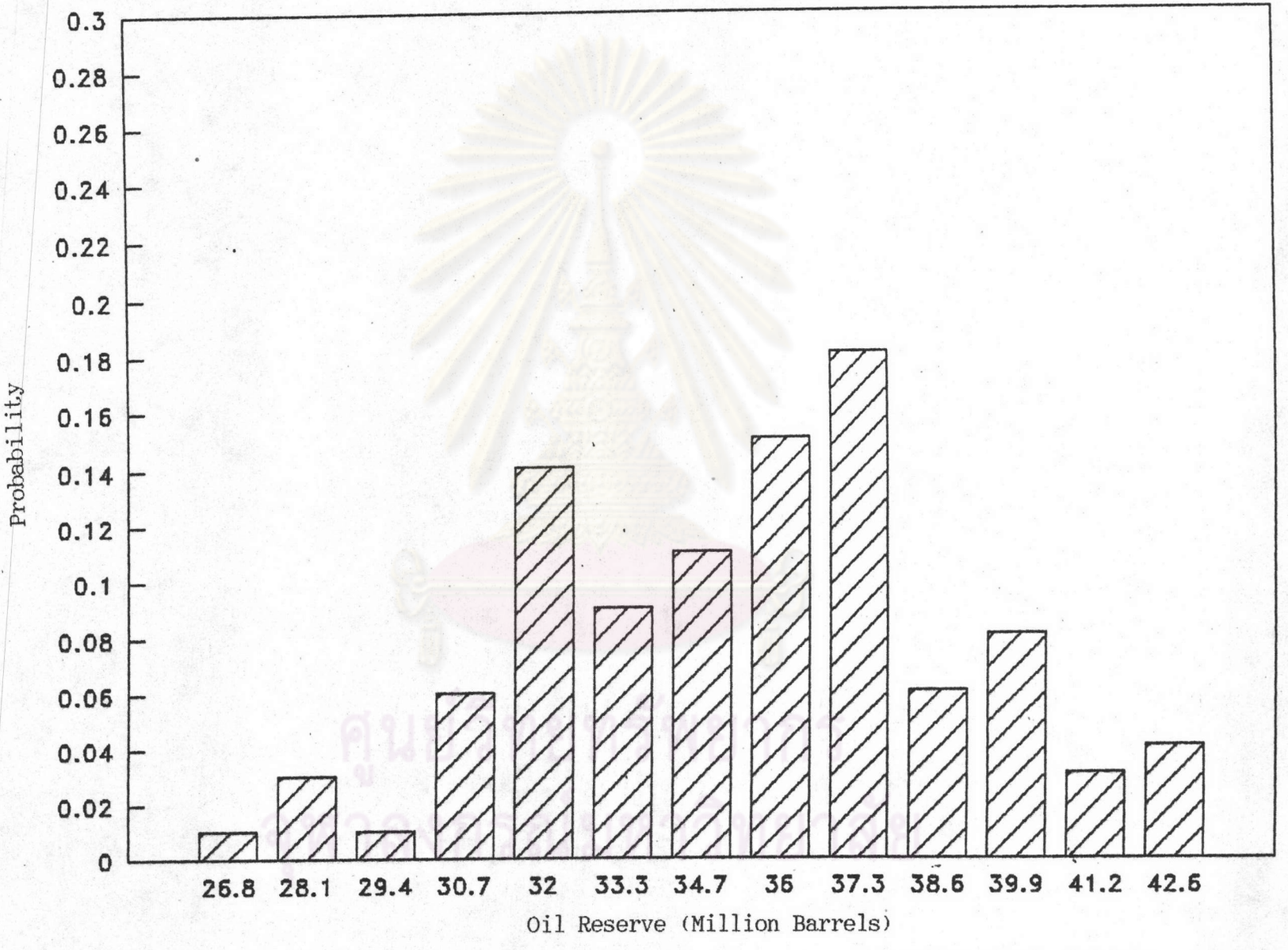

Figure 4.17. Probability density function of oil reserve at number of simulations = 100, with spatial correlation (number of blocks = 5x5).

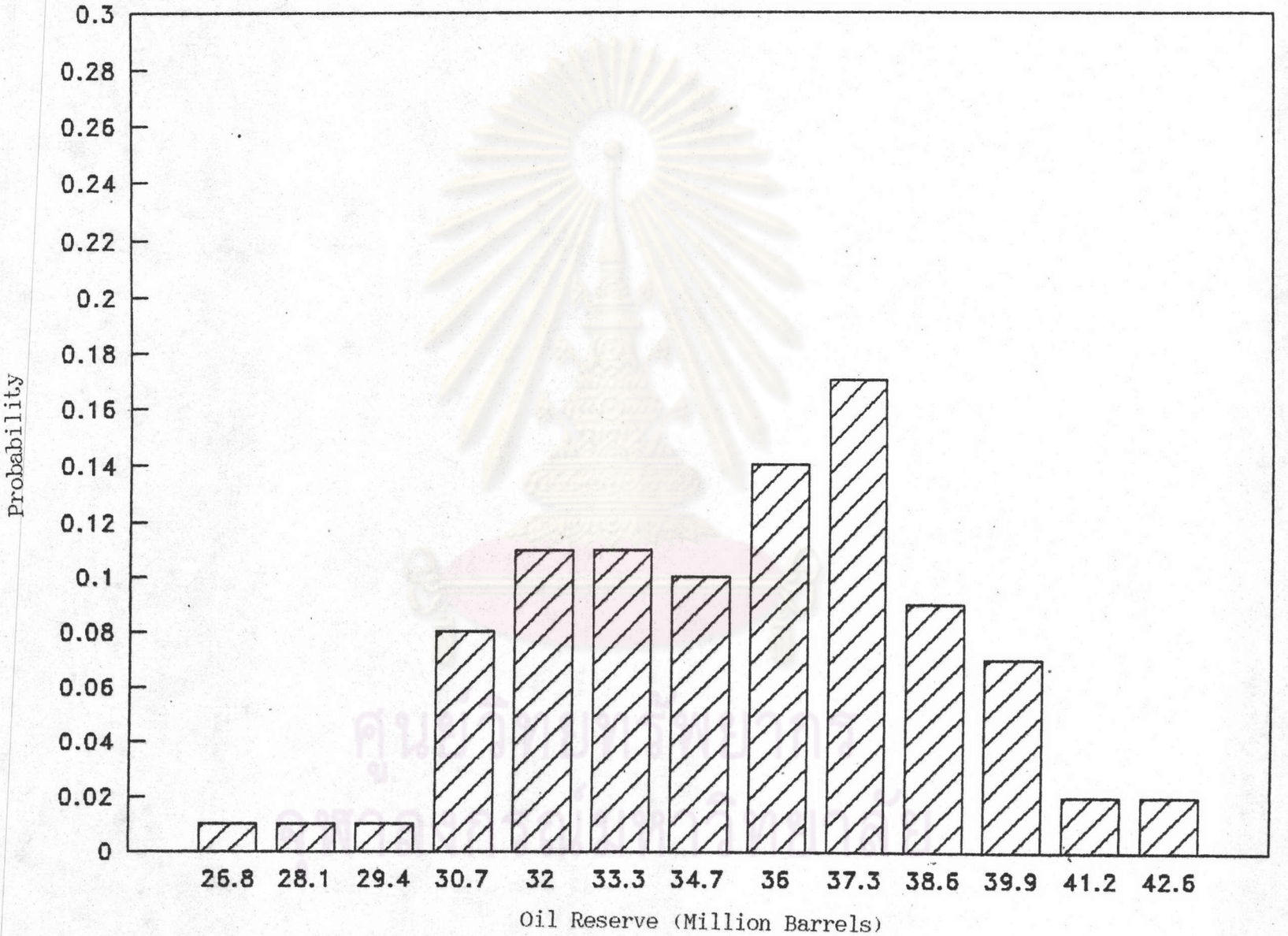

Figure 4.18. Probability density function of oil reserve at number of simulations = 200, with spatial correlation (number of blocks = 5x5).

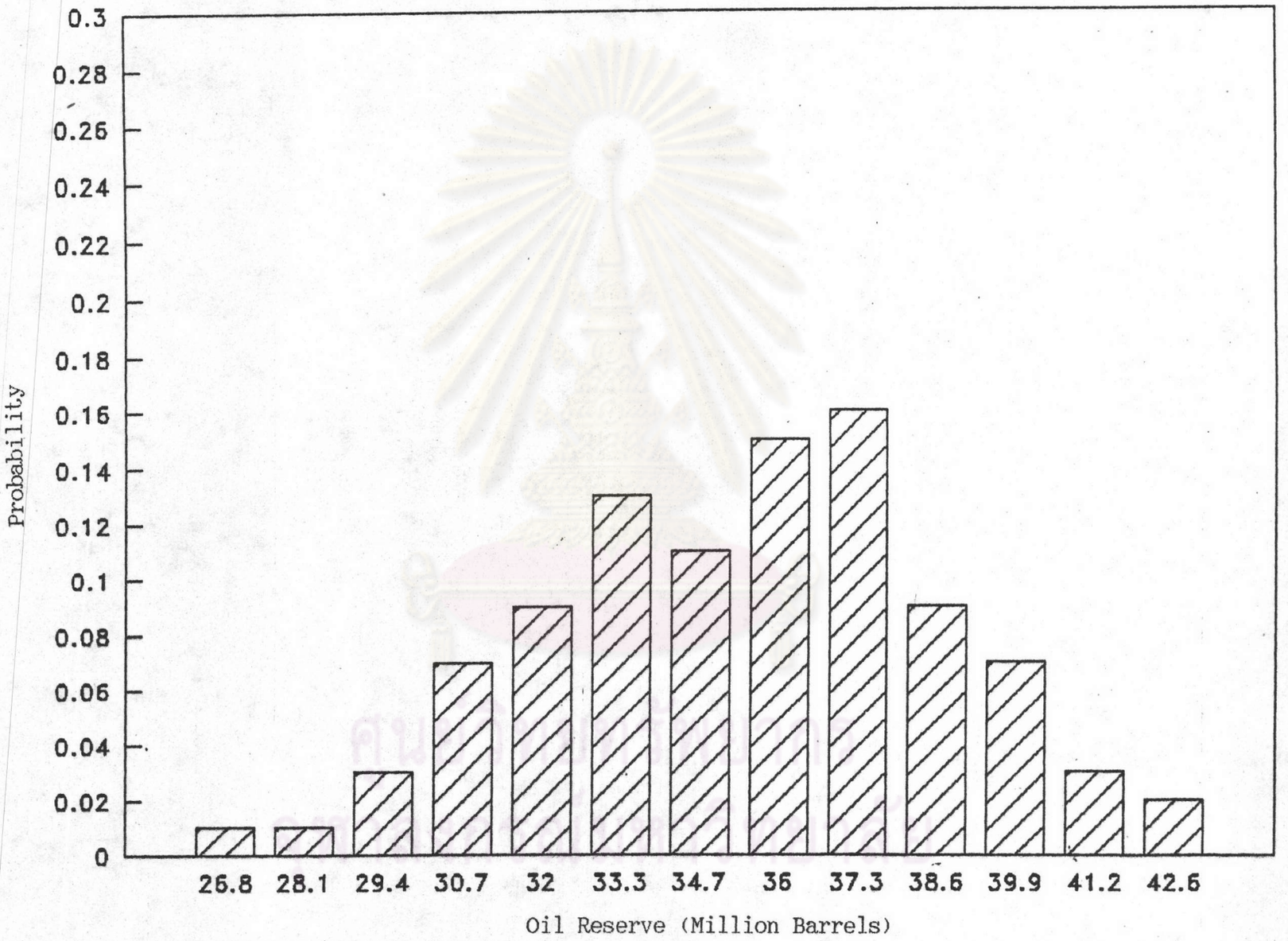

Figure 4.19. Probability density function of oil reserve at number of simulations = 400, with spatial correlation (number of blocks = 5x5).

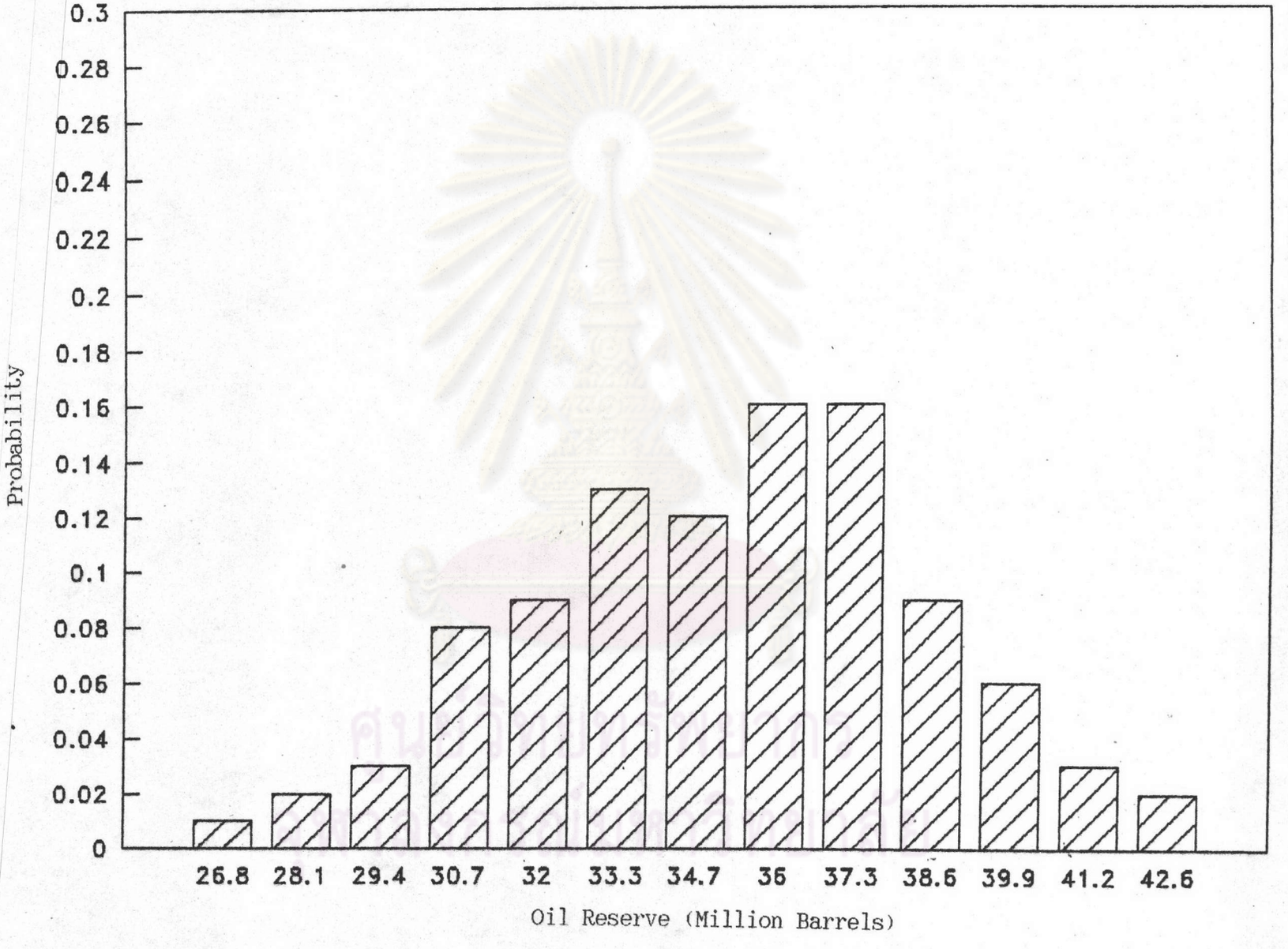

Figure 4.20. Probability density function of oil reserve at number of simulations = 600, with spatial correlation (number of blocks = 5x5).

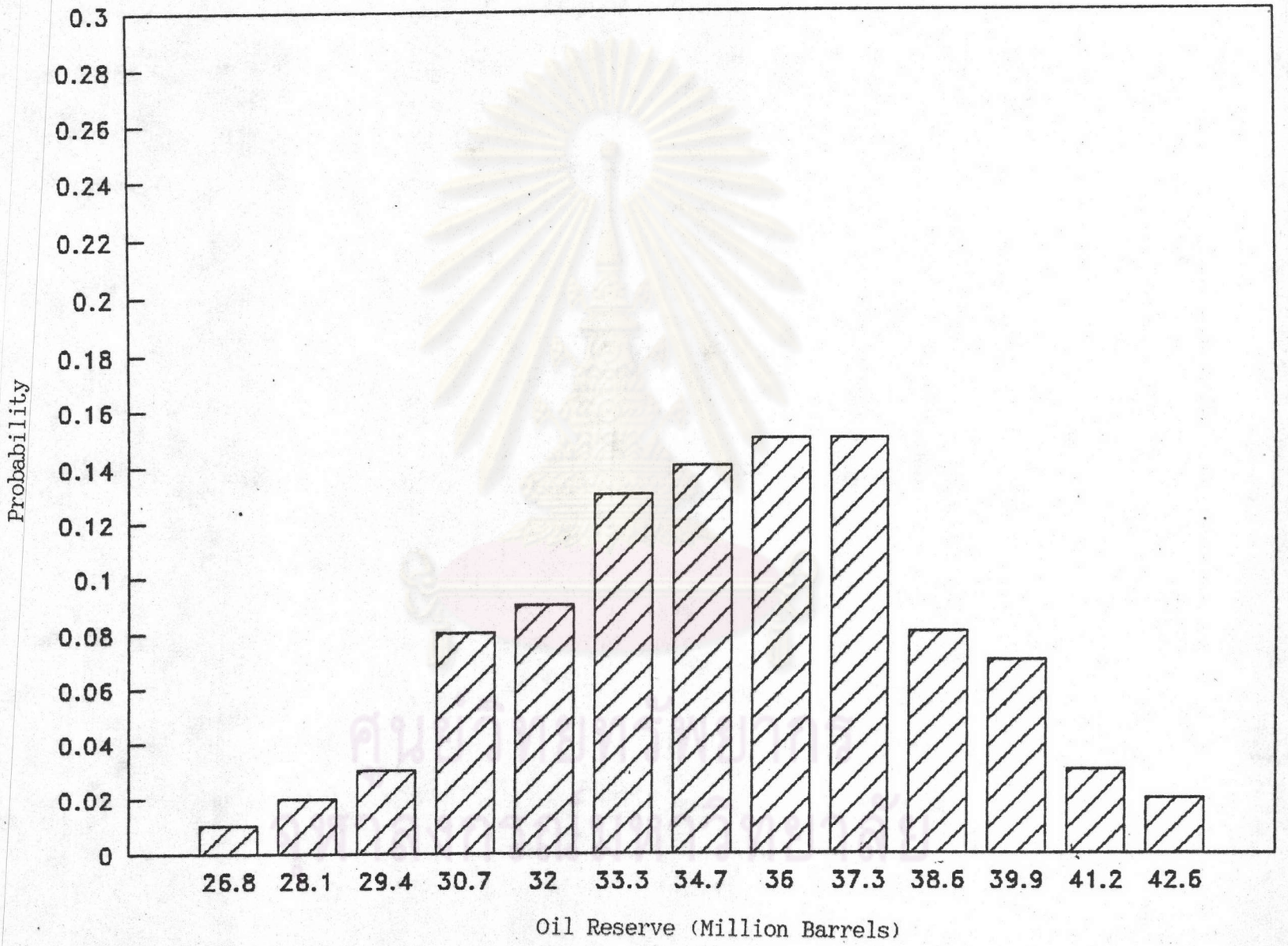

Figure 4.21. Probability density function of oil reserve at number of simulations = 800, with spatial correlation (number of blocks = 5x5).

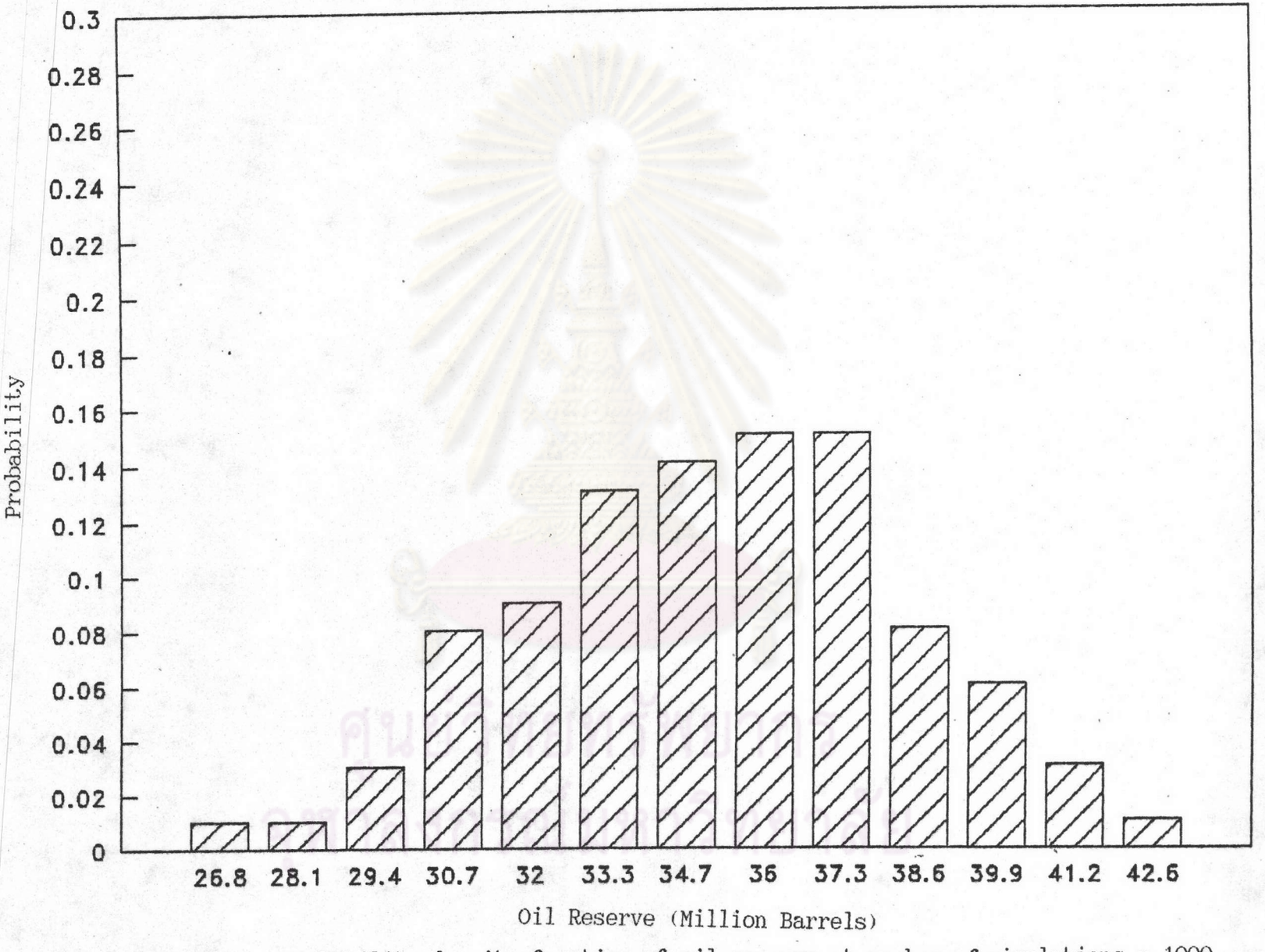

Figure 4.22. Probability density function of oil reserve at number of simulations = 1000, with spatial correlation (number of blocks = 5x5).

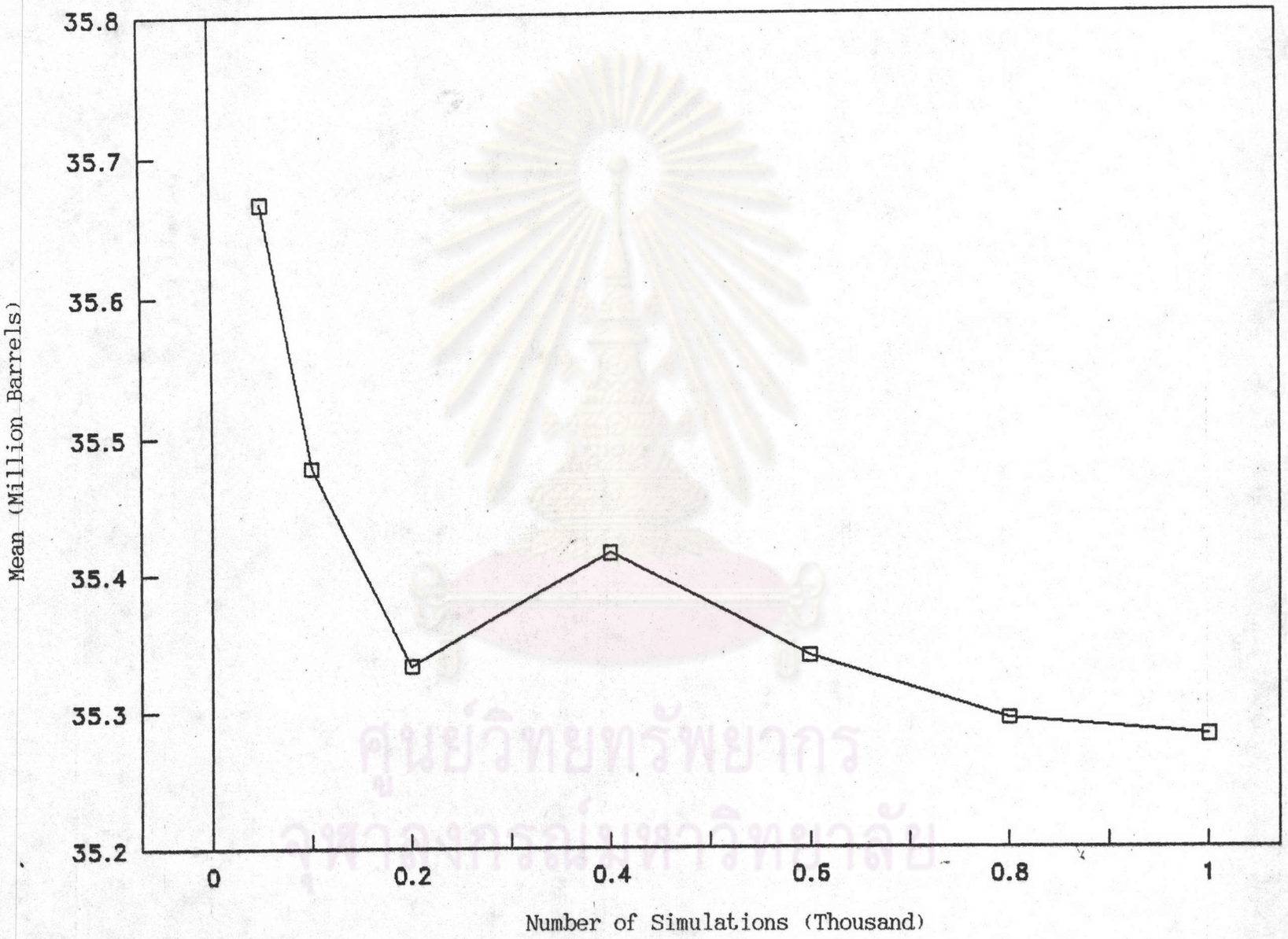

Figure 4.23. Mean vs. number of simulations calculated with spatial correlation (number of blocks = 5x5).

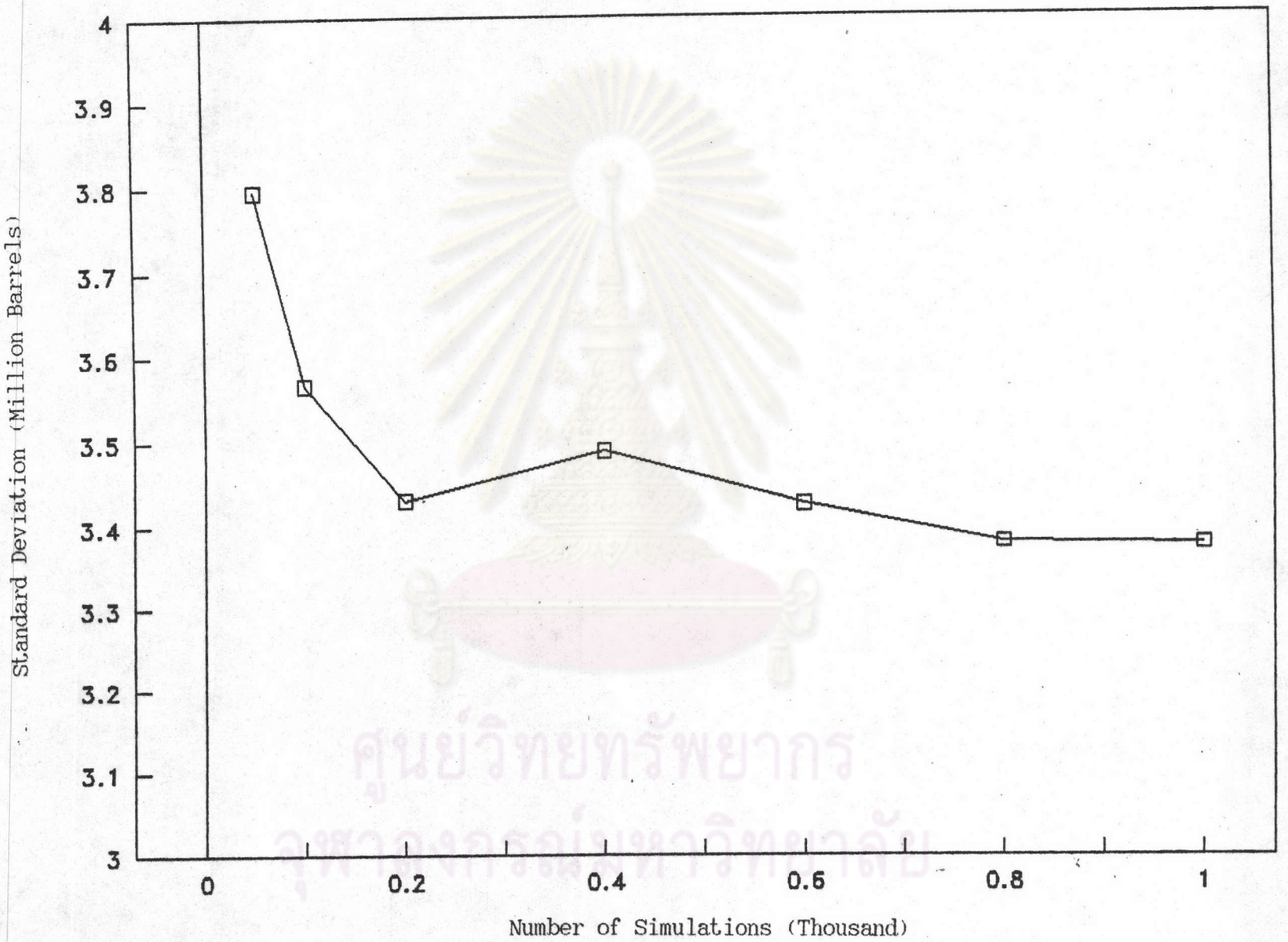

Figure 4.24. Standard deviation vs. number of simulations calculated with spatial correlation (number of blocks = 5x5).

At number of simulations of 100 and 200, a variation in mean and standard deviation are 0.409 % and 4.019 %, respectively (using reference value at number of simulations is 1,000), whereas the variation in mean and standard deviation values when using number of simulations of 600 and 1,000 are only 0.168 % and 1.449 %, respectively. We then conclude that the number of simulations to be used in this case is 600 since differences in mean and standard deviation are insignificant at number of simulations of 600 or higher.

In the third case, for the calculation of oil reserve with spatial correlation of porosity at number of blocks equal to 625, the probability density functions of oil reserve are expressed in Figures 4.25 to 4.31 and graphs of mean and standard deviation versus number of simulations are shown in Figures 4.32 and 4.33, respectively.

It can be seen that the results obtained in this case are similar to that of the first and the second cases. The values of mean and standard deviation of reserve are rather uniform when the number of simulations increases.

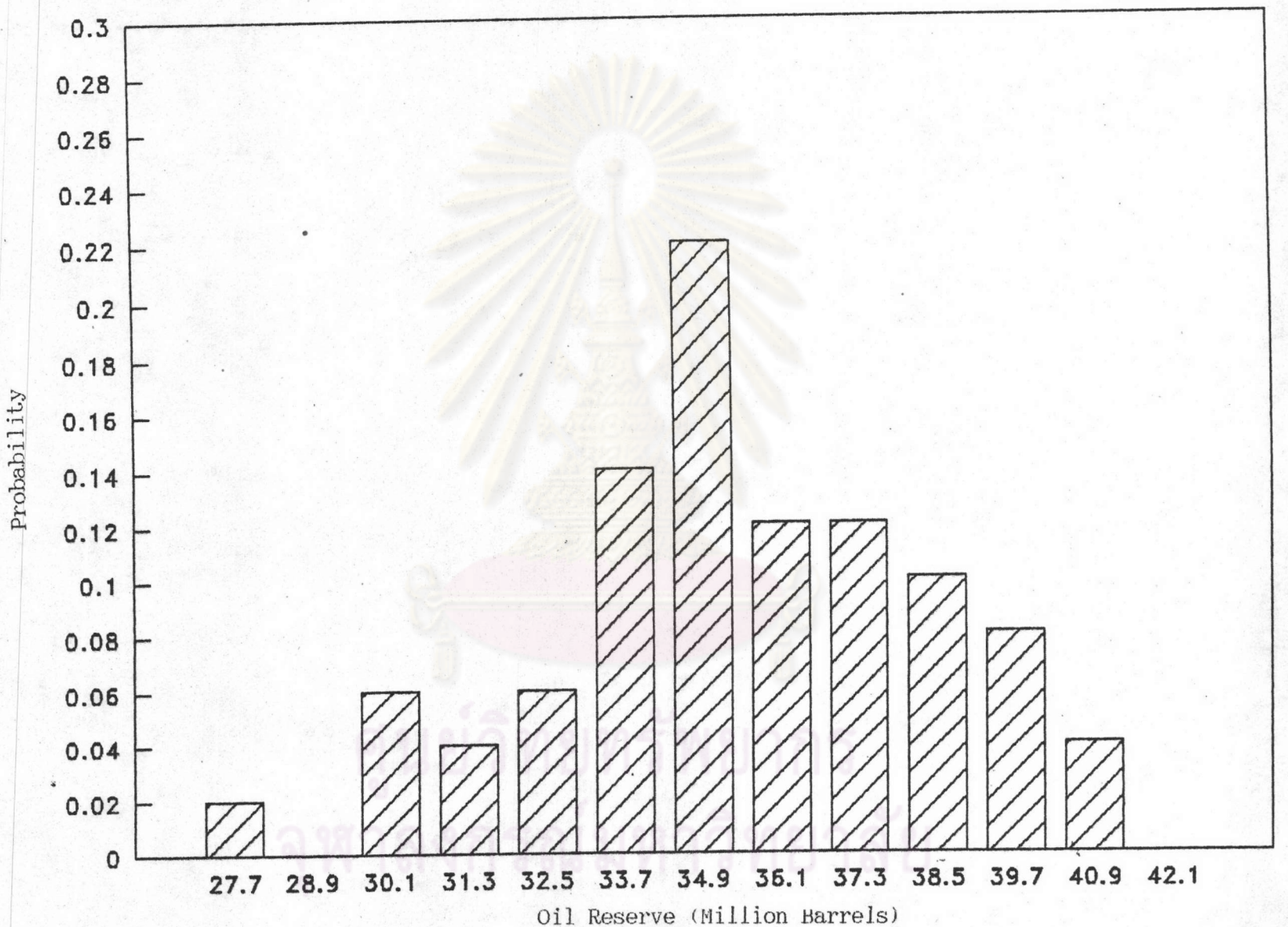

Figure 4.25. Probability density function of oil reserve at number of simulations = 50, with spatial correlation (number of blocks = 25x25).

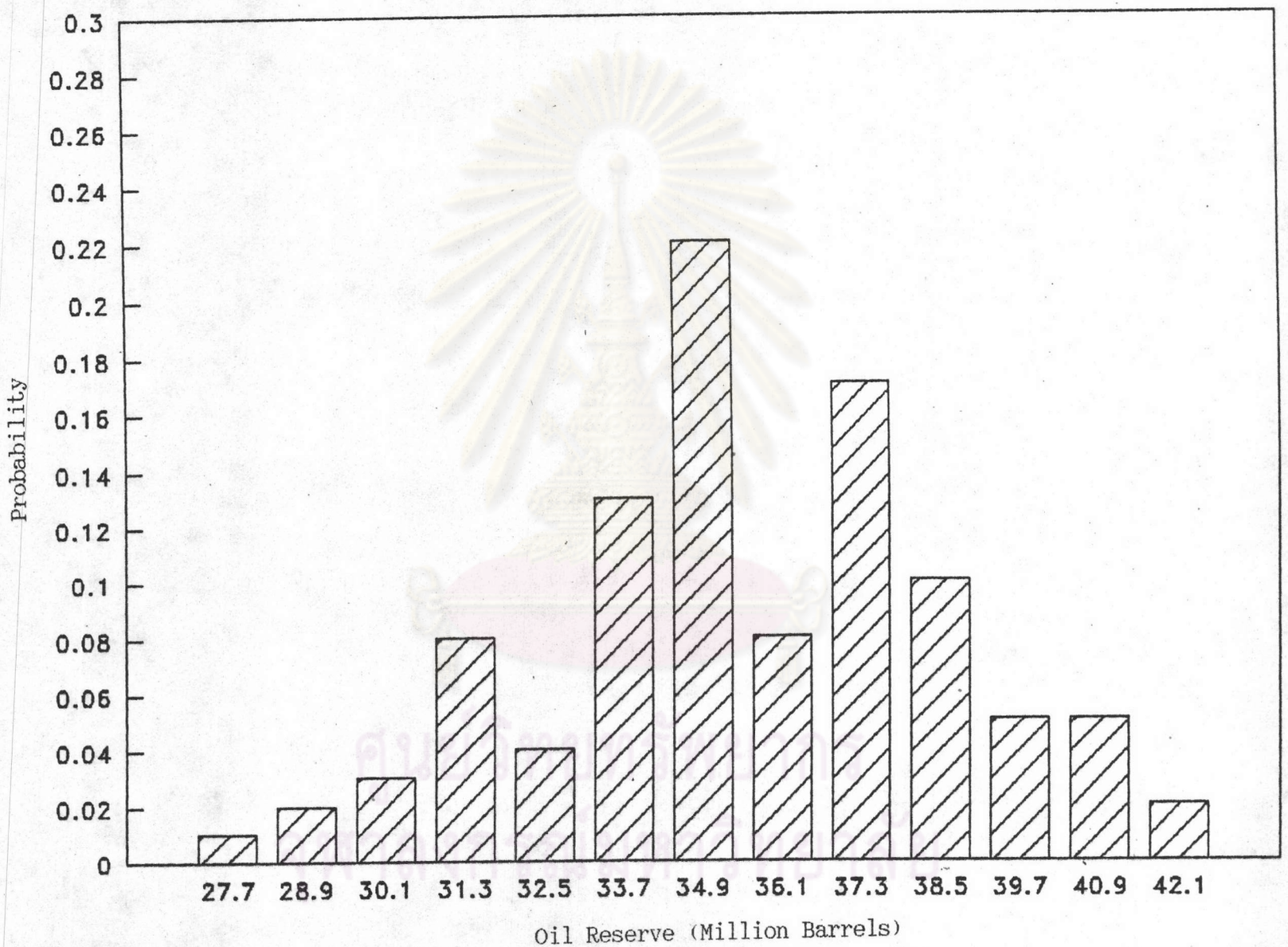

Figure 4.26. Probability density function of oil reserve at number of simulations = 100, with spatial correlation (number of blocks = 25x25).

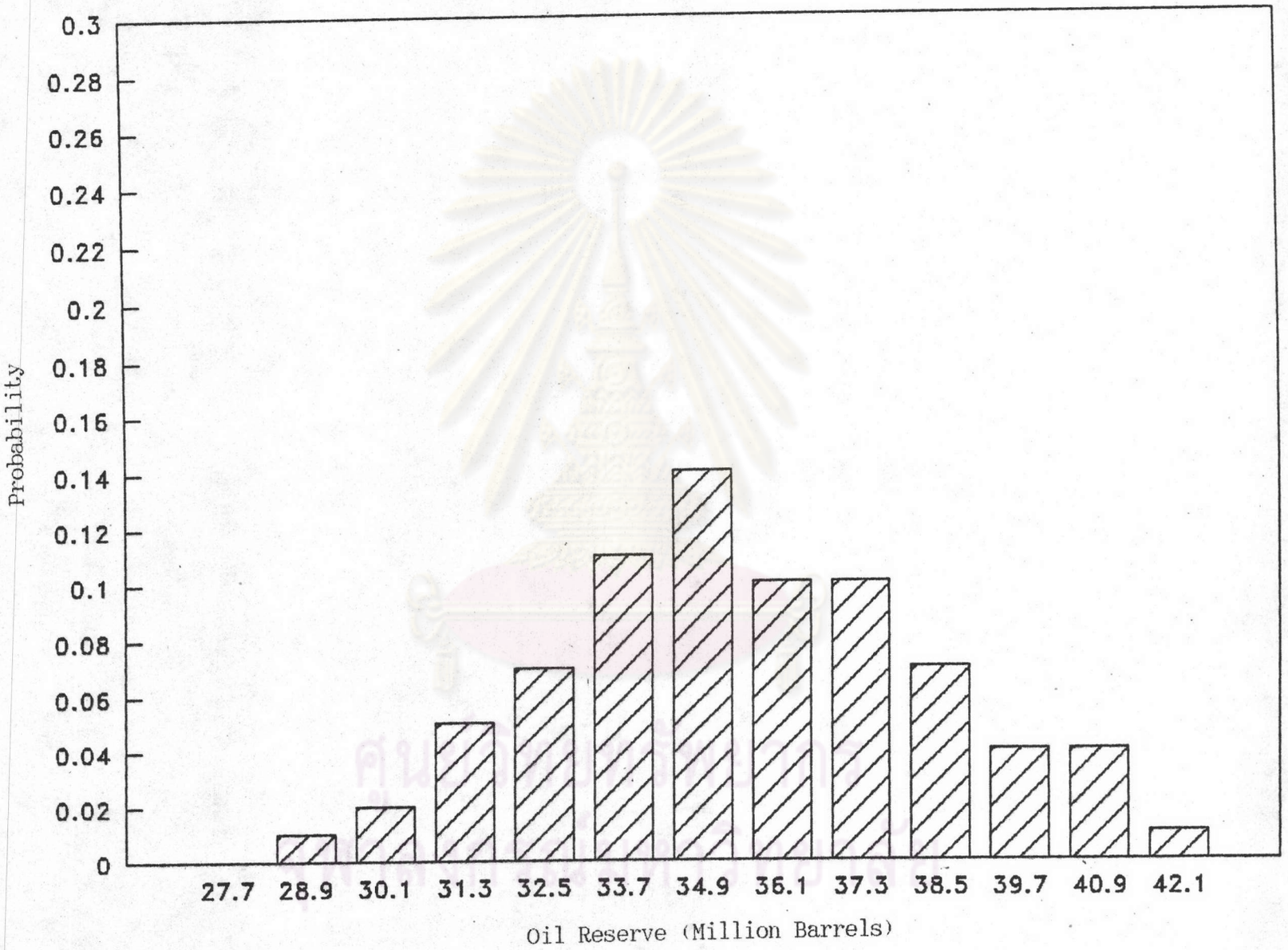

Figure 4.27. Probability density function of oil reserve at number of simulations = 200, with spatial correlation (number of blocks = 25x25).

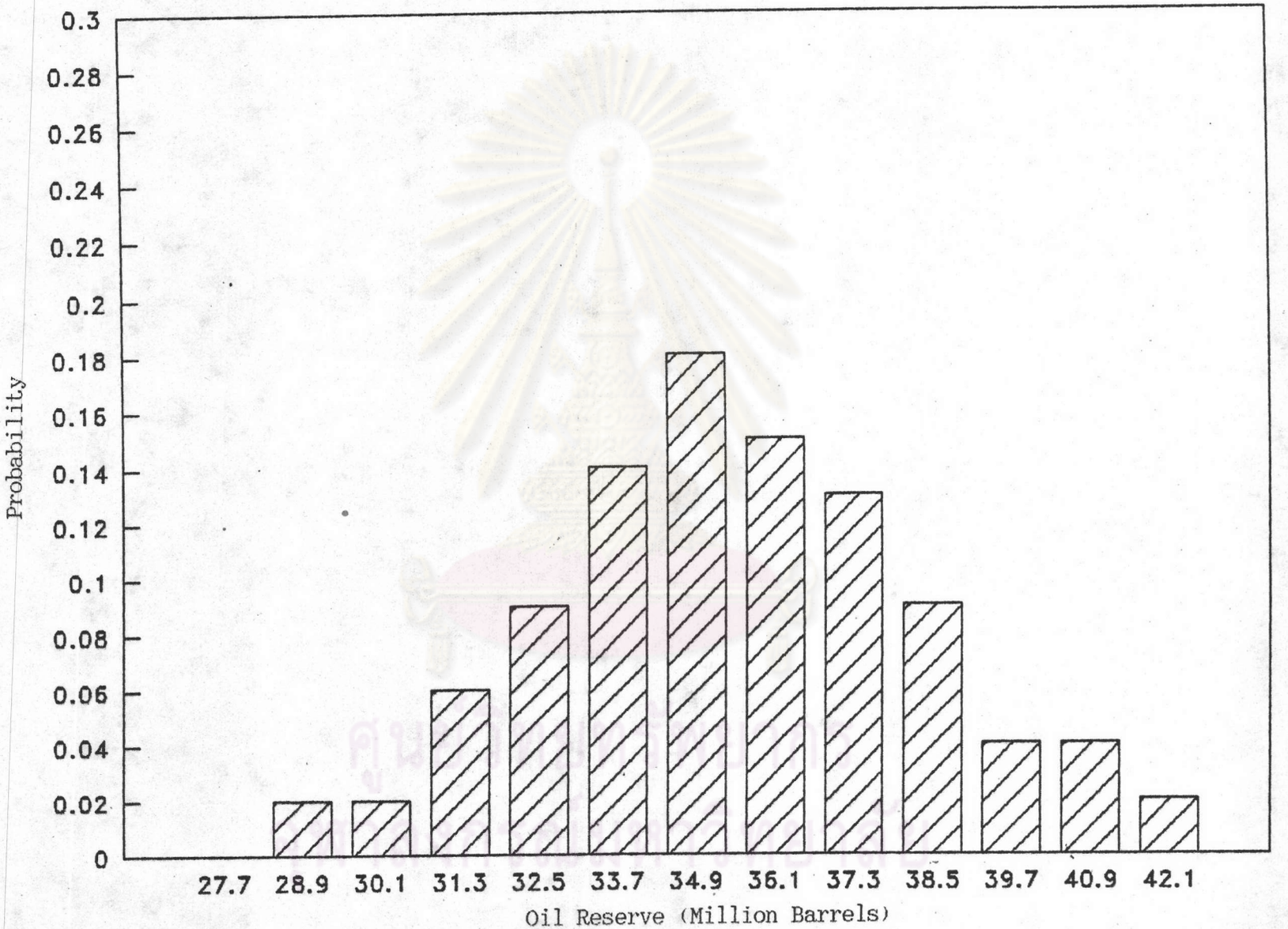

Figure 4.28. Probability density function of oil reserve at number of simulations = 400, with spatial correlation (number of blocks = 25x25).

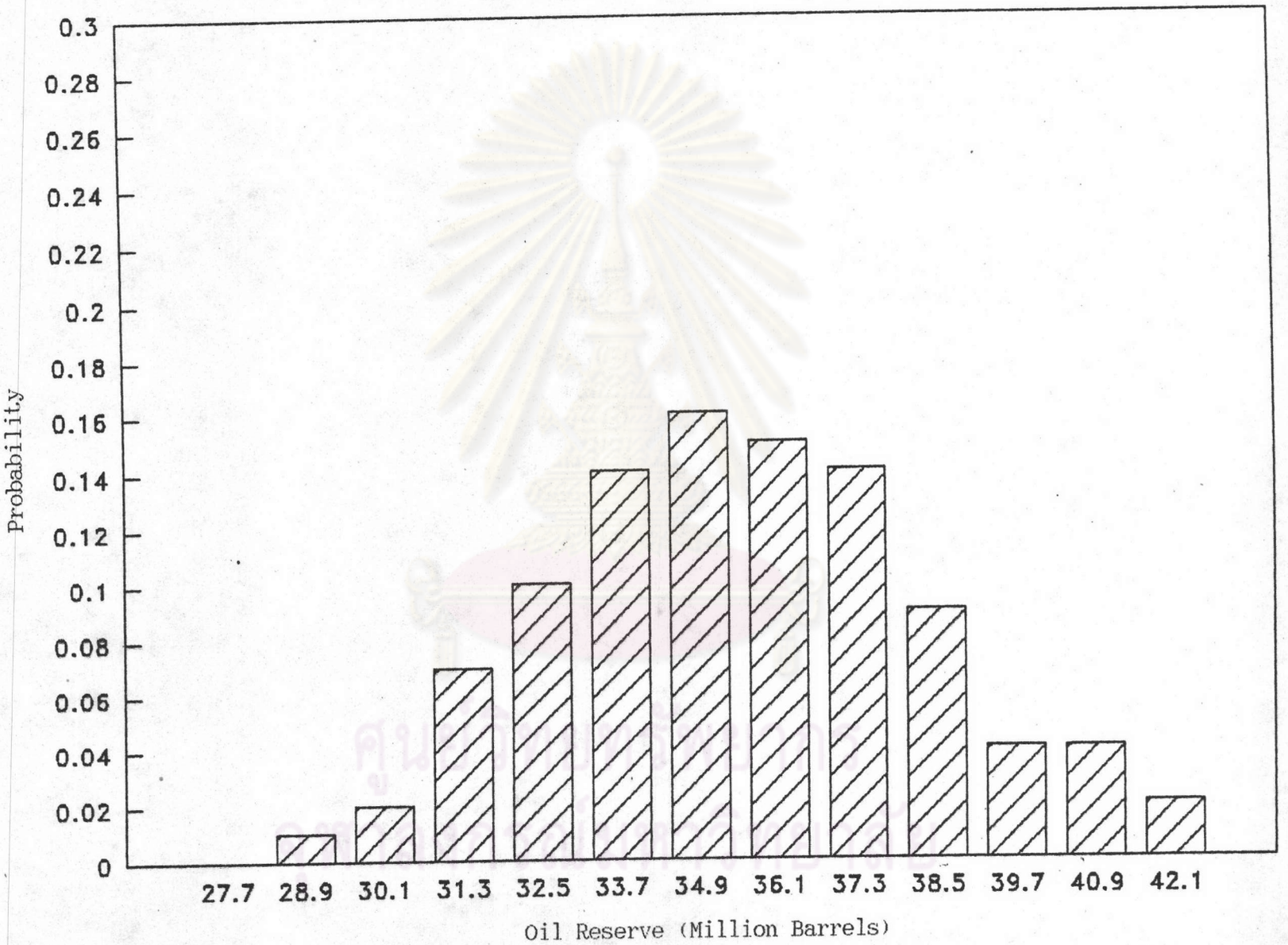

Figure 4.29. Probability density function of oil reserve at number of simulations = 600, with spatial correlation (number of blocks = 25x25).

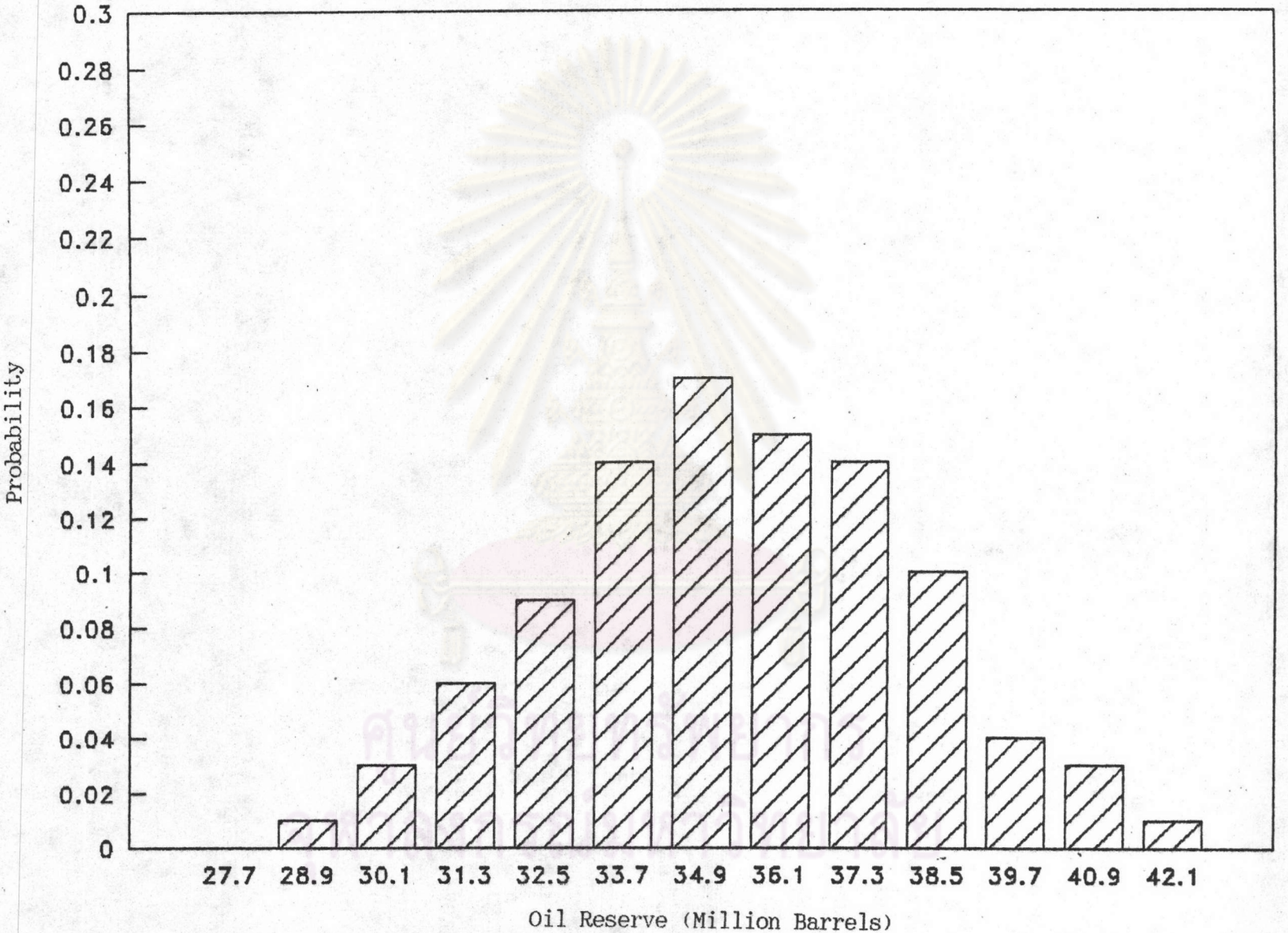

Figure 4.30. Probability density function of oil reserve at number of simulations = 800, with spatial correlation (number of blocks = 25x25).

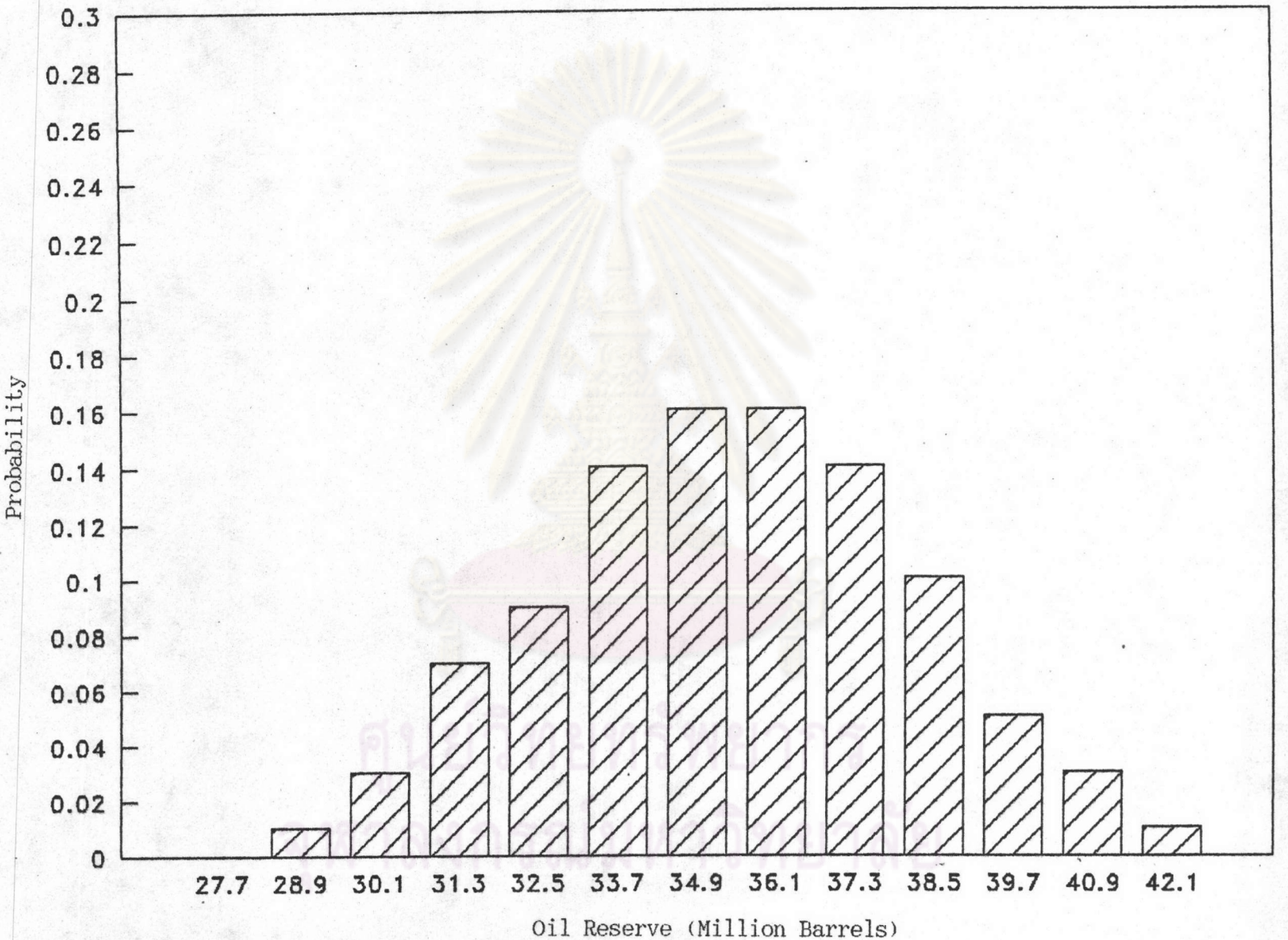

Figure 4.31. Probability density function of oil reserve at number of simulations = 1000, with spatial correlation (number of blocks = 25x25).

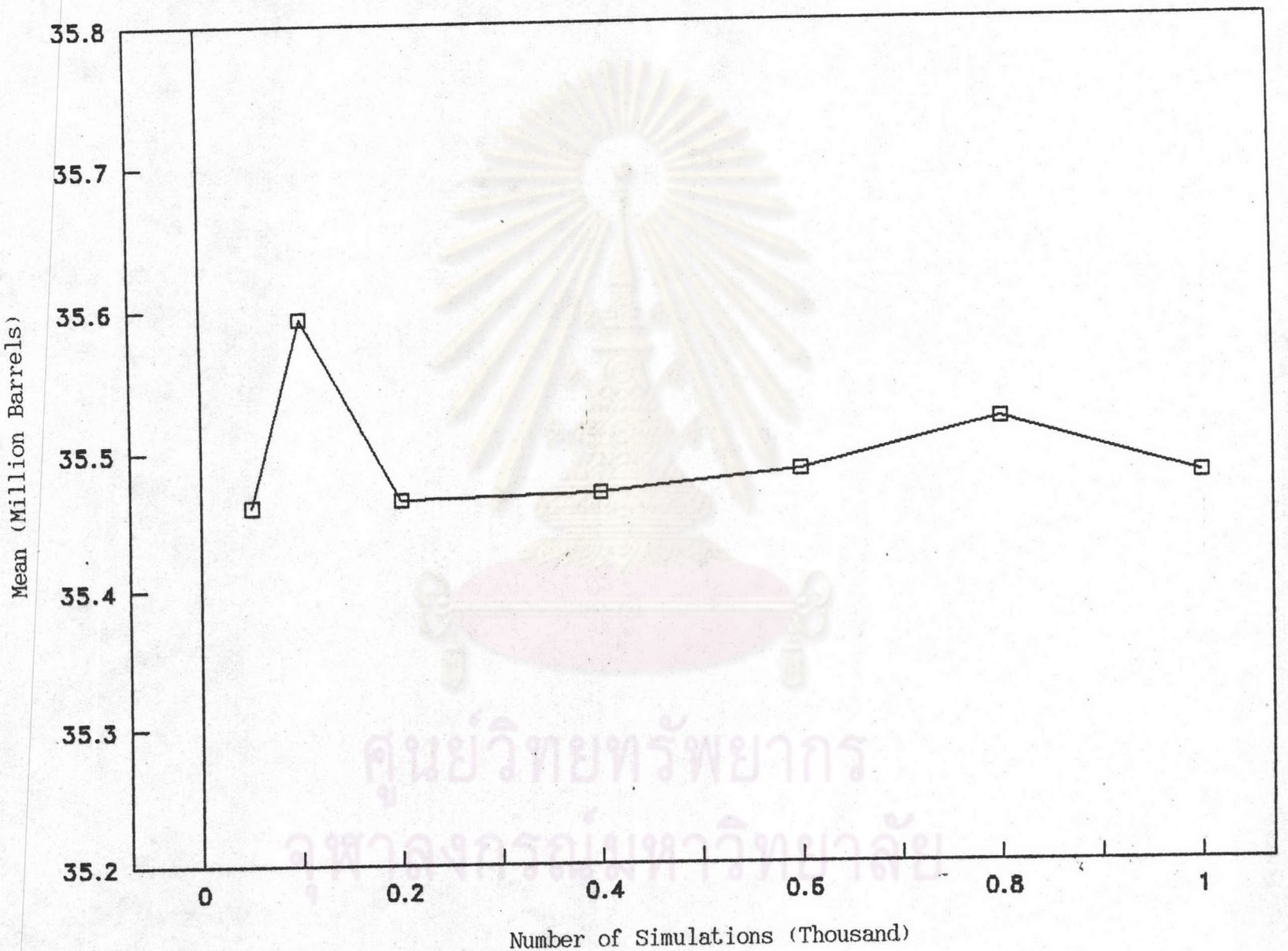

Figure 4.32. Mean vs. number of simulations calculated with spatial correlation (number of blocks = 25x25).

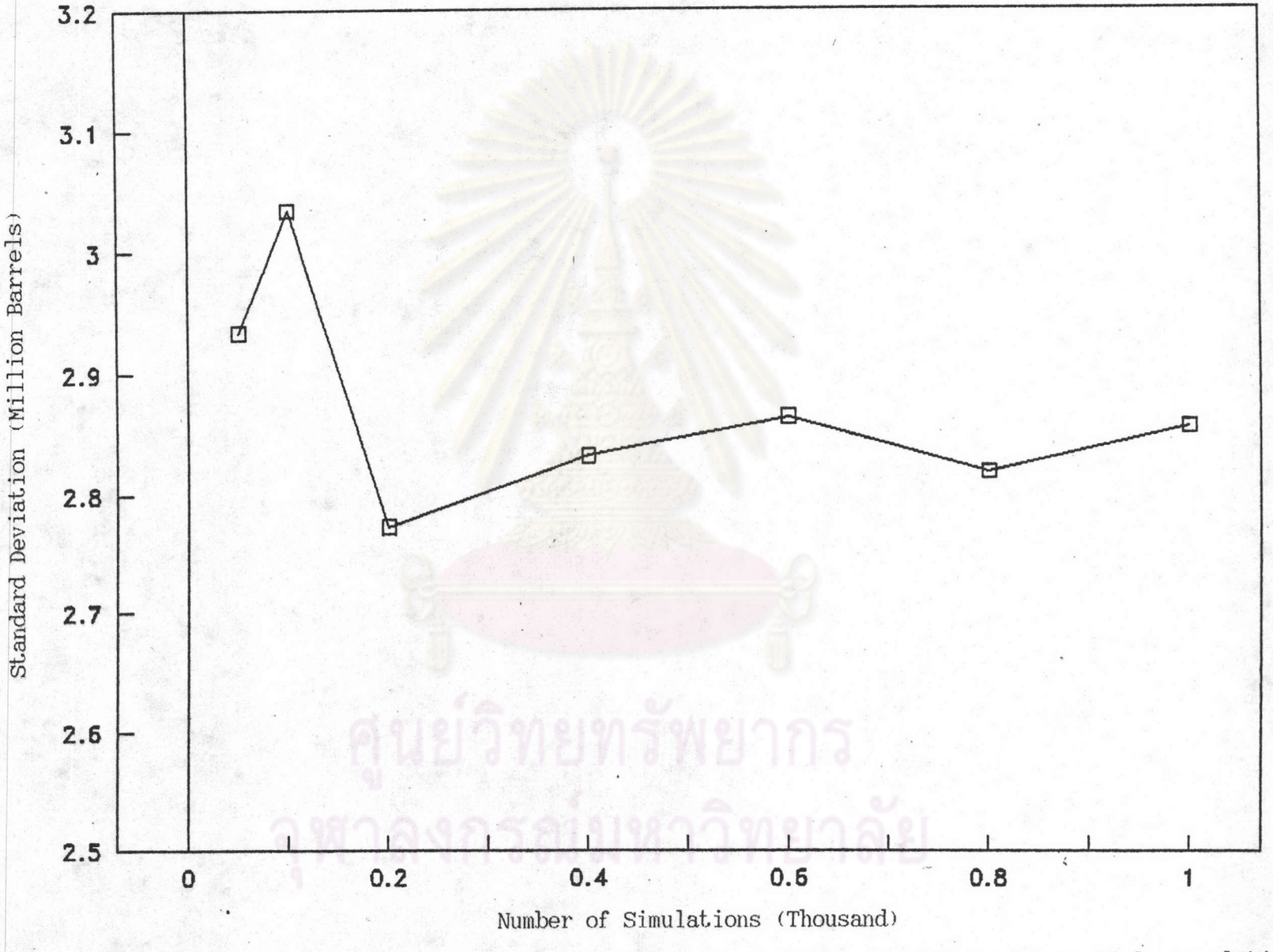

Figure 4.33. Standard deviation vs. number of simulations calculated with spatial correlation (number of blocks = 25x25).

At number of simulations of 100 and 200, the variation in mean and standard deviation are 0.364 % and 9.119 %, respectively (using reference value at number of simulations of 1000) whereas the variations in mean values and standard deviation values when using number of simulations of 600 and 1000 are only 0.015 % and 0.280 %, respectively. Probability density functions of the calculated reserves are rather similar when the number of simulations is at or more than 600. Therefore, the number of simulations in this case should be set at 600 or higher.

From the three cases, the number of simulations that should be used in each case is 600. We can conclude that the appropriate number of simulations is 600. It is believed that using this number of simulations will give the results that are sufficiently reliable.

After number of simulations has been assigned for every case the obtained computer program will be used to study effects of properties of input variables on the calculated oil reserve in the next chapter. There are 3 topics to be presented in the next chapter as follows:

1. The study of effects of a number of blocks on calculated oil reserve,

2. The study of effects of statistical relationship between two input variables, porosity and water saturation, on calculated oil reserve,

3. The study of effects of spatial correlation of an input variable, porosity, on calculated oil reserve.