HISTOBUN

Canadian Nuclear Society

10th Annual Symposium on Simulation of Reactor Dynamics and Plant Control

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The Tenth Annual Symposium on Simulation of Reactor Dynamics and Plant Control is sponsored by the Nuclear Science and Engineering Division of the Canadian Nuclear Society.

The scope of the symposium covers all aspects of nuclear power plant modelling and simulation. One of the main objectives of the event is to promote free discussion and therefore, emphasis is placed on papers that point to unresolved problems and that discuss methods under development.

This is the first meeting of the CNS to be held in New Brunswick. The location of the meeting recognizes the importance to the Canadian nuclear industry of the Point Lepreau-1 CANDU 600 MW Nuclear Generating Station owned and operated by the New Brunswick Electric Power Commission, and which has been in successful operation for a year. New Brunswick is also the location of Maritime Nuclear, a joint undertaking by AECL and NB Power, investigating the commercial feasibility and pre-planning of a possible additional CANDU 600 unit at Lepreau.

The program will include a visit to the Lepreau-1 CANDU 600 MW Nuclear Generating Station.

Neil Craik, P. Eng., is General Chairman and Organizer of Local Aspects of the Symposium (telephone: 506-453-3027).

Pierre Mercier, Ing., is Technical Program Chairman (telephone: 514-344-4290).

11:00-12:30 **TECHNICAL SESSION II-A**
(Thermohydraulics - Code Validation)

1. "Validation de SOPHT-G2", by C.H. Nguyen, H.M. Huynh
2. "Bruce NGS-B crash cooldown test and SOPHT-BB Validation, by Y.F. Chang
3. "Verification of SOPHT for reactor thermosiphoning flows" by D. Kawa, W.I. Midvidy, P. Sergejewich

11:00-12:30 **TECHNICAL SESSION II-B**
(Neutronics - Code Validation)

1. "SIMEX a module for follow up of reactor operations using in core detector readings and flux mapping routines", by D. McNabb, M.A. Petrilli, G. Parent
2. "Simulation errors in the design of the ROP system at Gentilly 2", by C. Ngo-Trong
3. "Verification of physics computer code simulations used in the analysis of the ROPT system", by R.C. Robinson, R.A. Gibb

12:30-14:00 **LUNCH**

14:00-16:00 **TECHNICAL SESSION III-A**
(Data Management)

1. "Microcomputers and nuclear safety analysis", by D.R. Pendergast
2. "Design of a nuclear power station data base for analysis applications", by A.P. Muzumdar, J.C. Luxat
3. "NSES a concept of program management", by R. Forte
4. "BEPHISTO - Bundle energy and power history program", by D.A. Jenkins

[illegible]0-16:00 **TECHNICAL SESSION III-B**
(Fuel Management)

1. "Two dimensional fuelling studies with SRG2", by G. Hotte, D. McNabb
2. "Fuel management studies for Pickering NGS B with reduced adjuster loading", by G.V. Guardalben, A.L. Wight

BEPHISTO AND HISTOBUN - BUNDLE ENERGY AND POWER HISTORY PROGRAMS

by

D.A. Jenkins and M. Tayal
Atomic Energy of Canada Limited
CANDU Operations
Sheridan Park Research Community
Mississauga, Ontario
Canada L5K 1B2

ABSTRACT

BEPHISTO is a computer program which compiles fuel-bundle energy and power histories from the results of fuel-management calculations performed with RFSP, the Reactor Fuelling Simulation Program used for CANDU-600 reactors. Such histories are very useful when attempting to determine the cause of, or evaluate the probability of, fuel-bundle defects. The program HISTOBUN plots the power histories of fuel bundles (obtained from BEPHISTO). It also calculates the probability of fuel defect due to stress-corrosion-cracking. An updated version of the Penn-Lo-Wood correlation, expressed in algebraic form, is used.

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NOMENCLATURE

A_1 to A_{12}	:	coefficients used in equations for HISTOBUN
n	:	exponent used in curve-fitting for the equation of defect probability
p	:	defect probability for a fuel bundle, due to stress-corrosion-cracking (%)
P	:	linear power of an element in the outer ring of a fuel bundle (kW/m)
P_c	:	effect of CANLUB on P (kW/m)
P_e	:	effective value of P for calculation of defect probability (kW/m). Includes effects of CANLUB, burnup, and dwell time.
ΔP	:	increase in the linear power of an element in the outer ring of a fuel bundle (kW/m)
ΔP_c	:	effect of CANLUB on ΔP (kW/m)
ΔP_e	:	effective value of ΔP for calculation of defect probability (kW/m). Includes effects of CANLUB, burnup, and dwell time.
t	:	dwell time (h) of a bundle at each power level
ω	:	burnup (MW.h/kgU).

1.0 INTRODUCTION

RFSP is a computer program used in fuel management calculations for CANDU reactors. It calculates neutron flux and power distributions in the reactor, using a two-energy-group, three-spatial-dimension diffusion method. It treats each fuel bundle separately, keeping track of its power, burnup and properties.

With RFSP, continuing reactor operating histories, complete with on-power refuelling operations, can be either

1. presimulated in the design and analysis phase, or

2. followed using actual station information from operating plants.

A new module has been added to RFSP (the EXTRACT module) to extract and record the burnup and power data for all bundles in the core at each simulation step.

BEPHISTO uses the data base maintained by EXTRACT to access the information the user desires on fuel-bundle histories.

There are two modes for running BEPHISTO:

1. In the first mode, BEPHISTO retrieves the power and burnup history for particular user-selected bundles, identified by their serial number. This can be done for bundles present in the core or ones which have already been discharged.

2. In the second mode, BEPHISTO retrieves the history of every bundle present in the core at a particular user-selected simulation step. In this case the user need not specify the bundle serial numbers.

An additional feature provided by EXTRACT-BEPHISTO is that "fine structure" can be inserted in the bundle histories by

1. calculating power boosts experienced by bundles during refuelling, and

2. optionally taking into account power changes associated with adjuster-rod movements which were not modelled by RFSP.

The power histories obtained from BEPHISTO can be used directly by the program HISTOBUN which performs two tasks. Firstly, it plots the power history. Secondly, it estimates the probability of fuel failure when subjected to the above power history. Stress-corrosion cracking (scc) is considered as the failure mechanism. For scc calculations, HISTOBUN uses an updated version of the Penn-Lo-Wood correlation[(1)], expressed in an algebraic form. The plots also contain the results of the calculations of defect probability.

Figure 1 shows how the computer programs are linked. Note that the three codes are linked to each other via data storage files in the computer. This minimizes the need for manual handling of data. In the following three sections, we describe the details of EXTRACT, BEPHISTO and HISTOBUN.

2.0 EXTRACT MODULE OF RFSP

This module has been added to RFSP to extract burnup and power data required by BEPHISTO. Whether following an operating station's history or presimulating at the design phase, an RFSP simulation usually progresses in steps of, say, 5 to 10 full power days (FPD). At each of these simulations the power and burnup of each bundle is recalculated, reflecting the time step taken and any refuellings since the last simulation. The EXTRACT module initially creates and subsequently updates two files. The first contains mostly data for in-core bundles, the second only data for bundles discharged.

For programming purposes each bundle is referenced throughout the reactor operating history by two numbers specific to the bundle: its serial number and an additional index, representing a unique bundle number (1, 2, 3, ..., 4560, 4561, ...).

2.1 File Structure

The data which is stored on the "in-core-bundle" file is

A. Data pertaining to every bundle (including discharged ones)

- (a) Bundle serial number
- (b) Bundle fuel type (index distinguishing different manufacturers' fuel loaded into core)
- (c) Indicator if bundle is discharged or still in-core
- (d) Minimum and maximum energy over which bundle's history extends, and the number of refuellings during the bundle's residence in the core.

B. Data pertaining to bundles in core

- (a) Current bundle power distribution in entire core
- (b) Entire history of each bundle including location in core, burnup, and power, for each RFSP simulation step during the bundle's residence in the core.

The data which is stored on the discharged-bundle file is only item B(b) above for each discharged bundle.

As the RFSP simulation approaches equilibrium-core conditions (350-400 FPD) the in-core-bundle file grows slowly because its major component, B, remains approximately constant in size (the average length of a bundle history becomes fairly constant). The discharged-bundle file grows more quickly since complete bundle histories are continually added in.

2.2 Refuelling Perturbation

The EXTRACT module also estimates the power boost experienced by bundles which are in channels réfuelled during the current simulation step. The powers (before refuelling) obtained from B(a) above at each bundle position through which the bundle will pass during refuelling are compared and the maximum found. This maximum value, its position, and the bundle's burnup at the time of refuelling are stored as a special entry in the bundle's history and included as part of item B(b) above. For refuellings which take place between RFSP simulations (as most do) the bundle's burnup is linearly interpolated from the energies at the two closest simulation points.

2.3 Techniques For Programming Efficiency

The files described above contain a lot of information and can quickly become very large. It is therefore important to reduce the demands on the computer resources.

The space required on the files and in computer central memory is kept to a minimum by packing several items into one word of memory whenever possible. For example, items A(c) and A(d) are packed into one word, similarly, each entry in item B(b) occupies only one word of memory for each bundle.

To minimize the peripheral-processor (IO) time required to execute the EXTRACT module, the bundle histories are updated in the order in which they occur on the in-core file from the previous execution of the EXTRACT module (except of course in the initial case). Bundles which still remain in the core after the latest RFSP simulation have their history expanded on the updated in-core-bundle file. Bundles which were discharged as a result of the latest simulation have their entire history written to the out-of-core file. New bundles are added to the end of the new in-core file.

Thus, once refuelling starts, the order of bundles on the in-core file no longer corresponds to the order in RFSP. This mismatch is accounted for by storing on the in-core file an array linking the unique bundle index described earlier to each in-core position. This array is updated during each execution of the EXTRACT module to reflect refuellings.

2.4 Module Execution

The EXTRACT module would normally be executed in the same RFSP run as the simulation from which data is desired. However, because of the structure of RFSP, which maintains a mass storage file containing data from previous simulations, the EXTRACT module can be run retroactively. This allows for the compilation of bundle histories from past RFSP runs.

The average central processor (CP) and IO times required by the EXTRACT module executed on an RFSP simulation at equilibrium-core conditions (by which time the average bundle history length will have stabilized) are 4 seconds and 60 seconds respectively on the CRNL CYBER 170. These are small fractions of the total times for an RFSP simulation.

3.0 BEPHISTO PROGRAM

The BEPHISTO program has two modes of operation. In the first mode the program accepts as input a list of bundle serial numbers and generates the history of those bundles. In the second mode the program produces the history of all bundles in the core at the time of the latest EXTRACT module execution.

The first mode of operation is likely to be used more often. In this mode the serial numbers input by the user are matched to serial numbers stored on the EXTRACT in-core file. Recall that this file contains the serial numbers of all bundles including those discharged to the pool. The position of a serial number in this array is the unique bundle number stored with each bundle's history (see section 2.1). The order of the unique bundle numbers and corresponding bundle histories on the EXTRACT in-core file will not be sequential, after refuelling starts; however, they are monotonically increasing. Thus, once all the requested serial numbers are matched, they are ordered by their position in the EXTRACT serial-number array. This ordering allows the EXTRACT in-core file to be read only once with no back-tracking required.

If the histories of discharged bundles are requested then the serial numbers are sorted according to the energy at discharge and then according to the unique bundle numbers. In this way the out-of-core EXTRACT file need also be read only once with no back-tracking.

3.1 Fine-Structure Option

BEPHISTO has the option to insert fine structure into the bundle histories by taking into account power changes associated with device movements not modelled by RFSP. This is accomplished by storing sets of ΔP's (bundle power increments) which quantify the power change (from equilibrium core conditions) caused by these device movements. At present the code has ΔP's corresponding to the withdrawal of from 1 to all 7 adjuster banks in the CANDU-600 MW(e) reactor. A perturbation such as a bank movement is specified by supplying the reactor energy at the start of the perturbation, its duration, the reactor power during the perturbation, and the type of perturbation. If a bundle whose history is requested was in-core during a user-defined perturbation then entries are made in the bundle's history at the begining and end of the perturbation, also, the bundle power is updated at any intermediate simulation point. If the start and/or end of the perturbation fall(s) between simulation steps then the power and burnup is interpolated from the bounding simulations.

3.2 Outer Element Power and Burnup

The powers and burnups stored for each bundle refer to the bundle as a whole. However, HISTOBUN requires powers and burnups for elements on the outer ring of the bundle. To this end a set of burnup-dependent outer-element-to-average ratios for burnup and power are stored in BEPHISTO. These ratios are obtained from the LATREP program[2].

3.3 BEPHISTO Execution Time

Typical CP and IO times (on a CDC CYBER 170 computer) required to retrieve a bundle history are .4 seconds and 1.5 seconds respectively.

3.4 Sample Case

A sample output from BEPHISTO is shown in Table 1. This particular bundle's history is taken from a CANDU-600 presimulation. The history shows all facets of the EXTRACT-BEPHISTO programs including refuelling perturbations and the insertion of fine structure (adjuster bank movements).

4.0 HISTOBUN

The power history obtained from BEPHISTO is processed by the computer code HISTOBUN. HISTOBUN performs two tasks. Firstly, it plots the power, and the increase in power, as a function of burnup. Secondly, it estimates the probability of failure of fuel sheaths at circumferential ridges. Stress-corrosion-cracking (scc) is considered as the failure mechanism. For scc calculations, HISTOBUN uses an updated version of the empirical correlation of Penn, Lo, and Wood[1], expressed in algebraic form. Both the above tasks are done only for elements in the outer ring of the bundle, because the outer elements have the highest power and thus the highest probability of defect due to scc. In this section, all powers and burnups refer to outer elements. Curves of defect probability are superimposed on the plots of power history. Thus the defect probabilities of a large number of bundles can be estimated easily and rapidly, and displayed in the forms of tables and graphs.

In the following sections, we describe details of the above tasks.

Figure 2 shows a fuel bundle and identifies its main components. It also shows a schematic of a circumferential ridge.

4.1 Plotting

HISTOBUN generates two plots for each bundle:

- linear power vs burnup.
- step increases in linear power vs burnup.

Each plot also contains curves representing the following defect probabilities for graphite CANLUB fuel: 1, 3, 5 and 10%.

Figure 3 shows an example.

For convenience, the plot for ΔP shows a different symbol depending on whether or not the defect probability is above a preset value; 3% is used in Figure 3 for illustration. Thus, an inverted triangle (∇) is plotted if the defect probability is less than 3%, a square (□) if it is equal to or more than 3%. Note that for a square to be plotted, the power and the power increase must both be above the relevant curve for defect probability (in this case 3%). This is discussed further in section 4.2.

4.2 Defect Probability

As noted earlier, HISTOBUN estimates defect probabilities, due to stress corrosion cracking, by using an updated form of the empirical correlation of Penn, Lo, and Wood. The correlation of reference 1 estimates defect probabilities from known values of: power (P), power increase (ΔP), burnup (ω), and dwell time(t). The correlation used in HISTOBUN also considers the presence or absence of a thin layer of a coating of graphite called CANLUB. The coating is usually applied at the inner surfaces of fuel sheaths.

The correlation is formulated for 'normal operating conditions'. That is, the effects of high temperature transients are not considered.

Table 2 lists the key factors that affect stress corrosion cracking, and how the correlation incorporates them. They include[1,3]: stress in the sheath, the severity of the corrosive environment, access of the corrodant to the sheath, duration of stress while the active environment is present, and the metallurgical condition of the sheath.

A full description of the correlation can be obtained from reference 1. Briefly: Penn, Lo, and Wood first analyzed the power histories of defected and of intact fuel from Douglas Point and from Pickering-A reactors. Then they combined this analysis with times-to-failure measured in laboratory tests on stress-corrosion-cracking of zircaloy. From this, they derived a correlation for the probability of fuel failure, as a function of P, ΔP, ω and t. The correlation is presented in reference 1 as a series of graphs called 'fuelograms'.

4.2.1 Equations For Defect Probability

As noted earlier, the correlation of reference 1 is mainly a graphical method. The method has been converted to a set of algebraic equations suitable for computer programming (see Acknowledgements). This was achieved by fitting curves to the fuelograms. This "numerical" version of the fuelograms includes the dependence of defect probability p. on power and step increases in power, which themselves are functions of burnup and dwell time.

For instance, the form of the dependence on power P is as follows:

$$p = A_1 + A_2 P^n \qquad \text{for } 0 \leq P \leq 16 \text{ kW/m} \qquad (1)$$

$$= \frac{A_3 \exp\ [A_4\ (P + A_5)]}{1 + \exp\ [A_6\ (P + A_7)]} \qquad \text{for } P > 16 \text{ kW/m}$$

Similar expressions are used to correlate the defect probability to ΔP.

The overall probability of defect is taken as the lower of: the defect probability due to P, and the defect probability due to ΔP. The reason for using the lower value is that scc occurs only when sufficient P (i.e. iodine) and sufficient ΔP (i.e. stress) exist simultaneously. See reference 1 for a detailed discussion of this topic.

The value of P and ΔP to be used in eq. (1) come from BEPHISTO, except that for CANLUB fuel a modification is needed as explained in the next section.

4.2.2 Effect of CANLUB

When the correlation of reference 1 was formulated, fuel sheaths did not contain any CANLUB. However, fuel used today does contain a layer of CANLUB. CANLUB fuel has a lower probability of failure[4] than non-CANLUB fuel. Hence a correction was applied to the preceding equations, to reflect the beneficial effect of CANLUB.

Reference 4 presents curves for the minimum power, and for the minimum increase in power, that caused fuel defects during irradiation experiments in the NRU reactor at CRNL. The curves are presented as a function of burnup, for both CANLUB and non-CANLUB fuel. The difference between the two curves (CANLUB vs non-CANLUB) was measured and fitted to an equation of the following form:

$$P_c = A_8 + \frac{A_9}{A_{10} + \omega} + \frac{A_{11}}{A_{12} + \omega}$$

A similar form of this equation was used for ΔP_c. The coefficients A_8 to A_{12} were then obtained by curve-fitting.

The values of P_c and of ΔP_c are subtracted from P and ΔP to yield 'effective' values, P_e and ΔP_e, which are to be used in eq.(1).

4.2.3 Nomograms

Nomograms are a modified version of fuelograms. Like fuelograms, nomograms provide a graphical method of estimating defect probabilities. Their starting point is fuelograms, but they include the effect of CANLUB (similar to section 4.2).

4.2.4 Analysis of Power History

For steady-state powers, the bundle is assumed to remain at the current power until the next burnup step. Transient powers, such as during refuelling, are modelled into a single equivalent power step with peak power being used in defect-probability calculations. This is illustrated in Figure 4. The parameter t is set equal to the actual duration of the transient.

Table 3 shows an illustrative output.

For flexibility, the structure of HISTOBUN permits six calculations of defect probabilities at each point on the power history. The method described in section 4.2.1 above is shown in Table 3 by 'Defect Probability(1)'. The other five calculations are presently under development. An appropriate structure in the code has been provided so that improved models may be added as they become available with minimal additional programming.

4.3 Verification

This section discusses how accurately HISTOBUN coding reflects the Penn-Lo-Wood correlation. However, the accuracy of the correlation itself is not the subject of this section - it is discussed in reference 1. Note that the correlation is based on fuel defect data from commercial reactors.

HISTOBUN's calculations for defect probability were compared to values obtained from nomograms. Arbitrary power histories were used in the comparison of HISTOBUN vs nomograms.

The results are shown in Figure 5. The figure shows that HISTOBUN predictions are in reasonable agreement with the nomograms. This provides an independent check for the accuracy of the coding of HISTOBUN.

4.4 Cost

A typical run of HISTOBUN on the CDC/CYBER-170 computer requires approximately 1 CP second for set-up, plus an additional 1 CP second per bundle for analysis and plotting. If plots are not required, i.e. only defect probability calculations are done, then the following time is required: 0.4 CP second for set-up, plus 0.02 CP second per bundle for analysis.

5.0 CONCLUSIONS

The EXTRACT-BEPHISTO-HISTOBUN combination sets up a data base which can provide a great deal of information about fuel bundles which have passed through the core of a CANDU reactor. Histories of bundles of interest (e.g. defective bundles) are readily available. Also available are plots of the histories, and estimates of defect probabilities.

6.0 ACKNOWLEDGEMENTS

We thank M. Gacesa and G. Kugler for defining the rationale and scope of this project and for their constant help and encouragement.

Special thanks to B. Rouben for his many useful suggestions for the programming of EXTRACT and BEPHISTO.

The equations used in HISTOBUN were formulated by S. Lee in an unpublished work, at Westinghouse Canada Incorporated, under contract to Atomic Energy of Canada Limited and to Ontario Hydro. We also thank J.L. Norton, D.B. Richter, and K. Turchan, all of AECL, for their help in coding and testing HISTOBUN.

7.0 REFERENCES

1. W.J. Penn, R.K. Lo, J.C. Wood, "CANDU Fuel Power Ramp Performance Criteria", Nuclear Technology, Vol. 34, 1977 July, Pages 249-268.

2. J. Griffiths, "LATREP", Atomic Energy of Canada Limited Report AECL-7603, 1983 June.

3. J.H. Gittus, D.O. Pickman, "Power Ramp Failures in Water Reactor Fuel Elements: Experience from Power Reactors, Likely Mechanisms and Potential Remedies", presented to IAEA Specialists' Meeting on "Power Ramping and Power Cycling of Water Reactor Fuel and its Significance to Fuel Behaviour", Arles, France, 1970 May 14 to 18, Paper 12.

4. D.G. Hardy, J.C. Wood, A.S. Bain, "CANDU Fuel Performance and Development", Atomic Energy of Canada Limited. Report AECL-6213, 1978 June.

TABLE 1 SAMPLE BEPHISTO OUTPUT

SERIAL NO. = POOMAAABMM   FUEL TYPE = 37ELEM NAT

ENERGY (MW.H)	TIME STEP (HR)	TOTAL POWER (MW)	OUTER ELEMENT POWER(KW/M)	OUTER ELEMENT BURNUP(MW.H/KGU)	POSITION	OPERATIONAL ID
5343148 R	0.00	2061.4	12.839	0.00	Q 7 1	NORMAL
5442096	48.00	2061.4	12.866	.61	Q 7 1	NORMAL
5936832	240.00	2061.4	12.685	3.73	Q 7 1	NORMAL
6431568	240.00	2061.4	12.622	6.80	Q 7 1	NORMAL
6926304	240.00	2061.4	12.378	9.84	Q 7 1	NORMAL
7421040	240.00	2061.4	11.626	12.85	Q 7 1	NORMAL
7915776	240.00	2061.4	11.029	15.66	Q 7 1	NORMAL
8410512	240.00	2061.4	10.723	18.33	Q 7 1	NORMAL
8905248	240.00	2061.4	10.438	20.93	Q 7 1	NORMAL
9399984	240.00	2061.4	10.440	23.46	Q 7 1	NORMAL
9894720	240.00	2061.4	9.916	25.98	Q 7 1	NORMAL
10389456	240.00	2061.4	9.696	28.38	Q 7 1	NORMAL
10884192	240.00	2061.4	9.150	30.73	Q 7 1	NORMAL
11378928	240.00	2061.4	8.871	32.94	Q 7 1	NORMAL
11873664	240.00	2061.4	8.642	35.09	Q 7 1	NORMAL
12368400	240.00	2061.4	8.681	37.19	Q 7 1	NORMAL
12566294 R	96.00	2061.4	46.584	38.02	Q 7 7	NORMAL
12863136	144.00	2061.4	42.544	44.09	Q 7 9	NORMAL
13357872	240.00	2061.4	42.998	54.40	Q 7 9	NORMAL
13852608	240.00	2061.4	42.316	64.83	Q 7 9	NORMAL
14347344	240.00	2061.4	40.058	75.06	Q 7 9	NORMAL
14842080	240.00	2061.4	40.353	84.75	Q 7 9	NORMAL
15089448 * T	120.00	1958.3	38.279	89.64	Q 7 9	BANK 1 OUT
15329148 * T	122.40	1875.9	37.264	94.37	Q 7 9	BANK 2 OUT
15336816 T	4.09	1875.9	37.275	94.52	Q 7 9	BANK 2 OUT
15571511 * T	125.11	1958.3	38.349	99.24	Q 7 9	BANK 1 OUT
15736011 * E	84.00	1958.3	38.155	102.54	Q 7 9	BANK 1 OUT
15831552	46.35	2061.4	40.470	104.46	Q 7 9	NORMAL
16326288	240.00	2061.4	40.747	114.25	Q 7 9	NORMAL
16821024	240.00	2061.4	39.247	124.11	Q 7 9	NORMAL
17315760	240.00	2061.4	38.871	133.55	Q 7 9	NORMAL
17810496	240.00	2061.4	38.456	142.96	Q 7 9	NORMAL
18305232	240.00	2061.4	41.781	152.26	Q 7 9	NORMAL
18799968	240.00	2061.4	40.813	162.37	Q 7 9	NORMAL
19294704	240.00	2061.4	38.599	172.25	Q 7 9	NORMAL
19789440	240.00	2061.4	36.095	181.61	Q 7 9	NORMAL
20284176	240.00	2061.4	36.229	190.36	Q 7 9	NORMAL
20581017 R	144.00	2061.4	36.216	195.62	Q 7 9	NORMAL
20581014	-.00	2061.4	0.000	195.62	POOL	NOT APPLIC

R - REFUELLING PERTURBATION
* - INTERPOLATED VALUES
T - TRANSIENT IN EFFECT
E - END OF TRANSIENT

Table 2

Factors Affecting Stress Corrosion Cracking

Factor	Incorporated via
Sheath stress	ΔP , CANLUB
Amount of iodine in the pellet/sheath gap	ω , P
Access of iodine to the sheath	CANLUB
Time available for crack nucleation and growth	t
Initial sheath condition , i.e. embrittlement , etc.	ω

TABLE 3 : Sample output from HISTOBUN

HISTOBUN VERSION 1 DATE 81-12-04

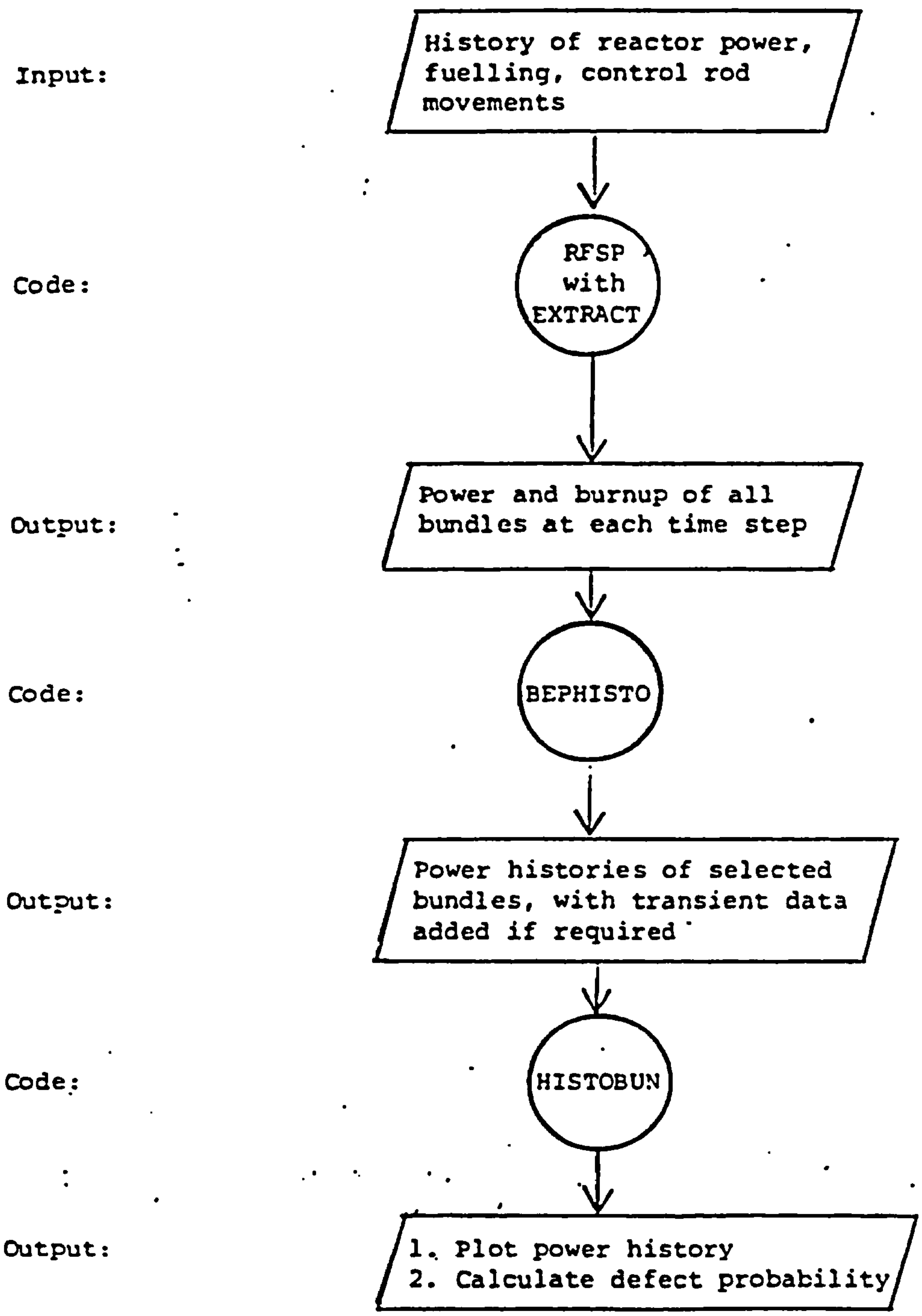
HISTOBUN SAMPLE RUN. INPUT FROM TAPE7. TEN BUNDLES WITH PLOTS.

BUNDLE POOMAAABDL V37UNANYTG

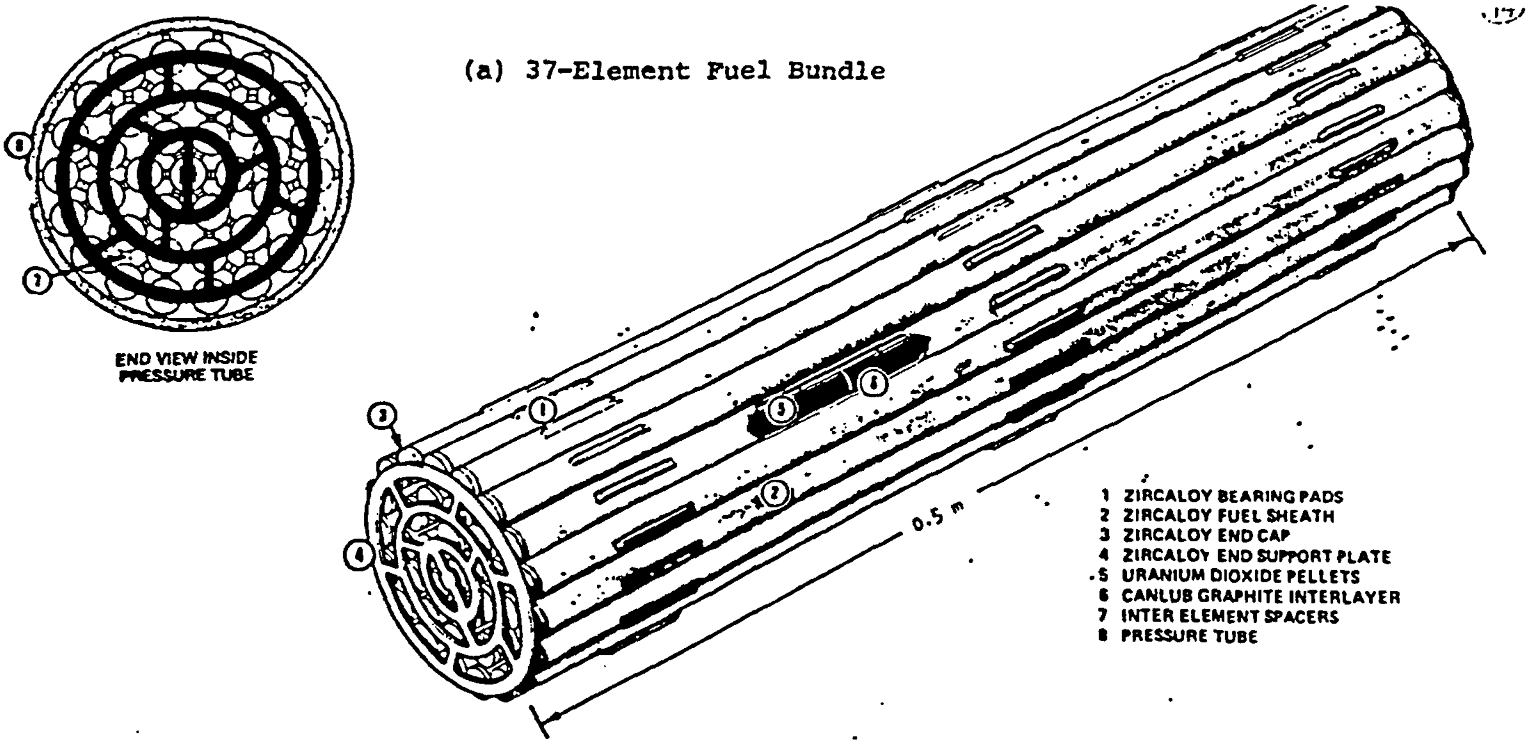
BURNUP. (MW.H/KGU)	INITIAL POWER (KW/M)	FINAL POWER (KW/M)	POWER INCREASE (KW/M)	TIME AT FINAL POWER (H)	****DEFECT PROBABILITY (%)**** (1) ACTUAL TIME	(2) T=2.5H	(3) MOD. SS POWER	(4) ****MEMORY**** 20.FPD	(5) 40.FPD	(6) 60.FPD
0.00	0.00	44.61	44.61	24.00	0.00					
1.13	44.61	49.03	4.42	240.00	0.00					
12.98	49.03	51.40	2.36	240.00	0.00					
25.44	51.40	54.28	2.88	240.00	0.00					
33.57	54.28	54.15	-.13	240.00	0.00					
51.69	54.15	55.36	1.21	240.00	0.00					
63.11	55.36	55.47	.10	240.00	0.00					
73.52	55.47	54.78	-.69	240.00	0.00					
91.76	54.78	52.05	-2.72	240.00	0.00					
104.36	52.05	50.15	-1.91	240.00	0.00					
115.49	50.15	50.04	-.11	240.00	0.00					
123.59	50.04	48.67	-1.37	240.00	0.00					
140.36	48.67	49.65	.97	240.00	0.00					
152.36	49.65	51.03	1.39	240.00	0.00					
164.70	51.03	50.33	-.70	120.00	0.00					
173.80	50.33	53.14	2.81	73.70	1.00					
174.36	53.14	52.71	-.43	54.93	0.00					
175.90	52.71	52.40	-.31	67.87	0.00					
179.96	52.40	52.62	.21	122.80	0.00					
183.24	52.62	47.37	-5.25	93.95	0.00					
133.79	47.37	46.81	-.56	47.25	0.00					
139.49	46.81	49.26	2.45	135.00	1.02					
135.23	49.26	51.31	2.04	122.80	1.01					
199.48	51.31	52.86	1.55	22.73	1.00					
200.17	52.86	52.77	-.09	155.27	0.00					
204.76	52.77	49.66	-3.11	122.80	0.00					
209.50	49.66	46.26	-3.40	68.89	0.00					
211.25	46.26	45.77	-.49	66.11	0.00					
213.50	45.77	43.56	-2.20	141.20	0.00					
219.42	43.56	48.16	4.59	96.29	1.63					
222.26	48.16	48.64	.49	26.51	0.00					
223.30	48.64	47.72	-.93	122.80	0.00					
223.36	47.72	46.51	-1.21	73.70	0.00					
231.52	46.51	45.75	-.76	37.02	0.00					
235.11	45.75	42.38	-3.37	240.00	0.00					
243.37	42.38	42.61	.24	240.00	1.00					
253.68	42.61	42.94	.22	192.00	1.01					
261.96	42.94	43.39	.55	-.00	1.04					
251.96	43.39	0.00	-43.39	999.00	0.00					

(12)

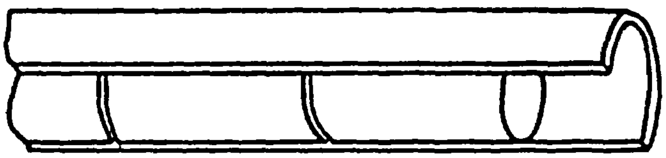
FIGURE 1: INTERACTION OF THE VARIOUS CODES



(a) 37-Element Fuel Bundle



(b) Unirradiated fuel element



(c) Irradiated fuel element

Figure 2: Circumferential ridges in an Irradiated fuel element

SAMPLE

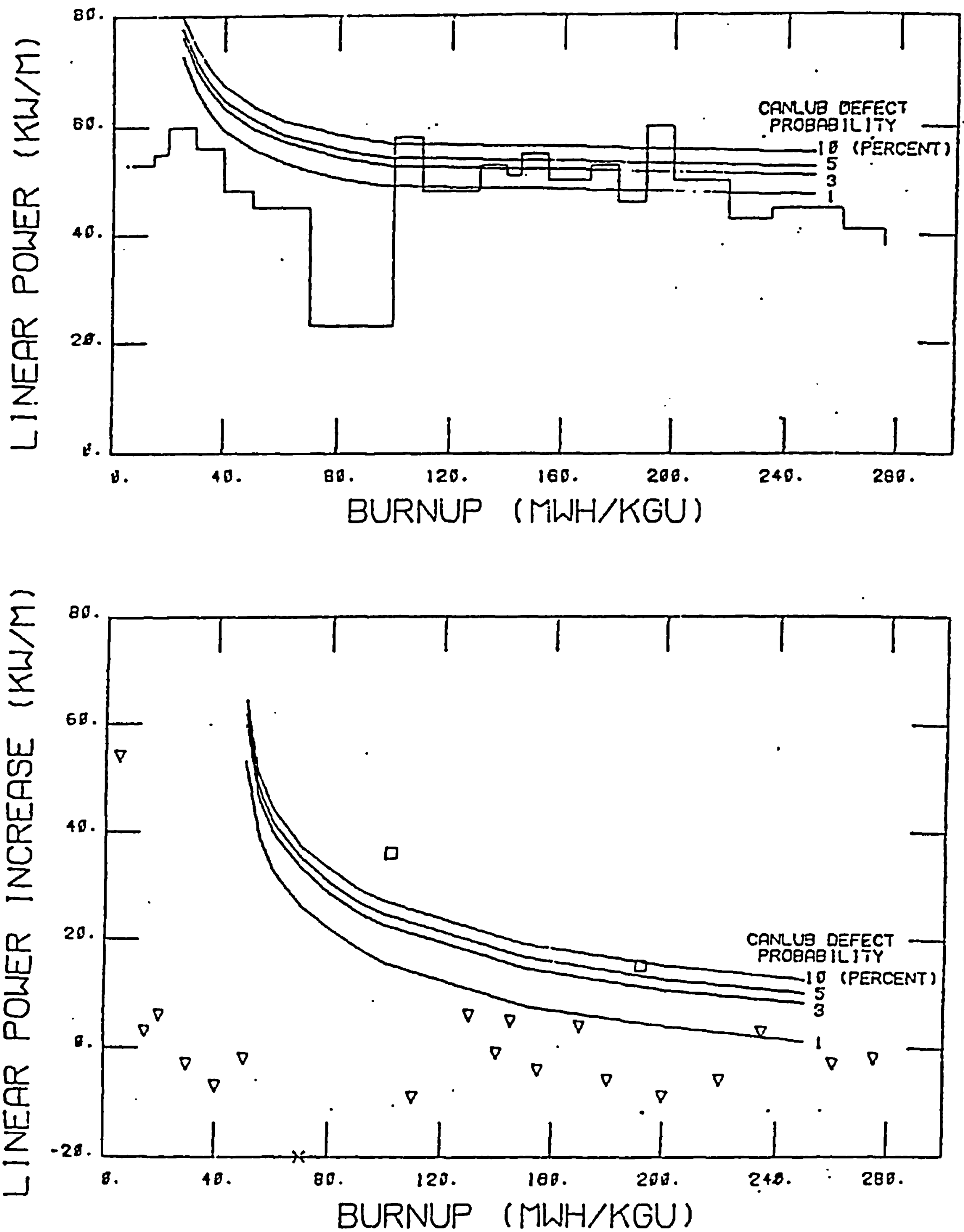


FIGURE 3: Sample plot from HISTOBUN. Inverted triangles represent overall failure probability (P and ΔP combined) less than 3%, squares greater than 3%

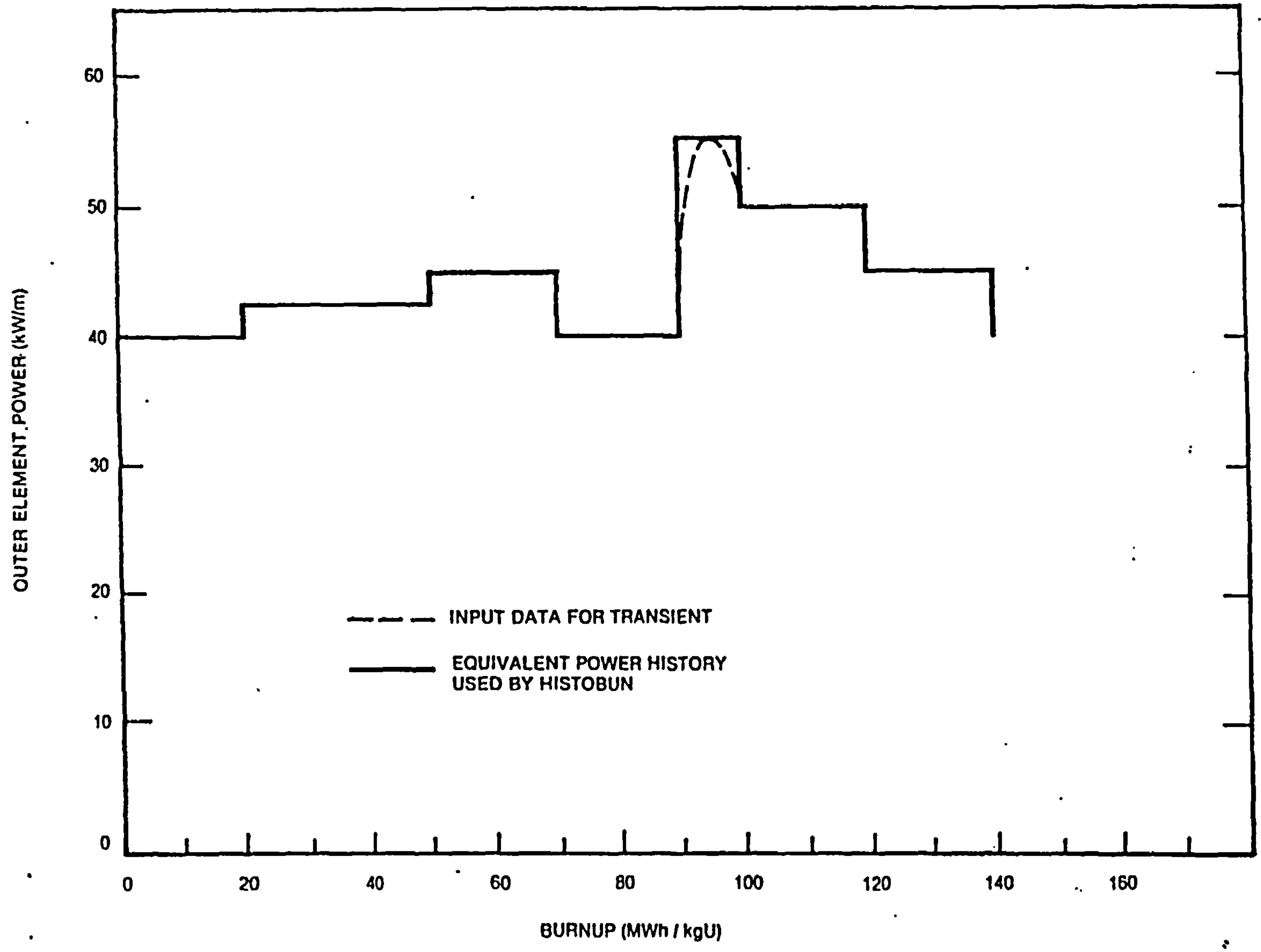


FIGURE 4: MODELLING OF TRANSIENT POWERS

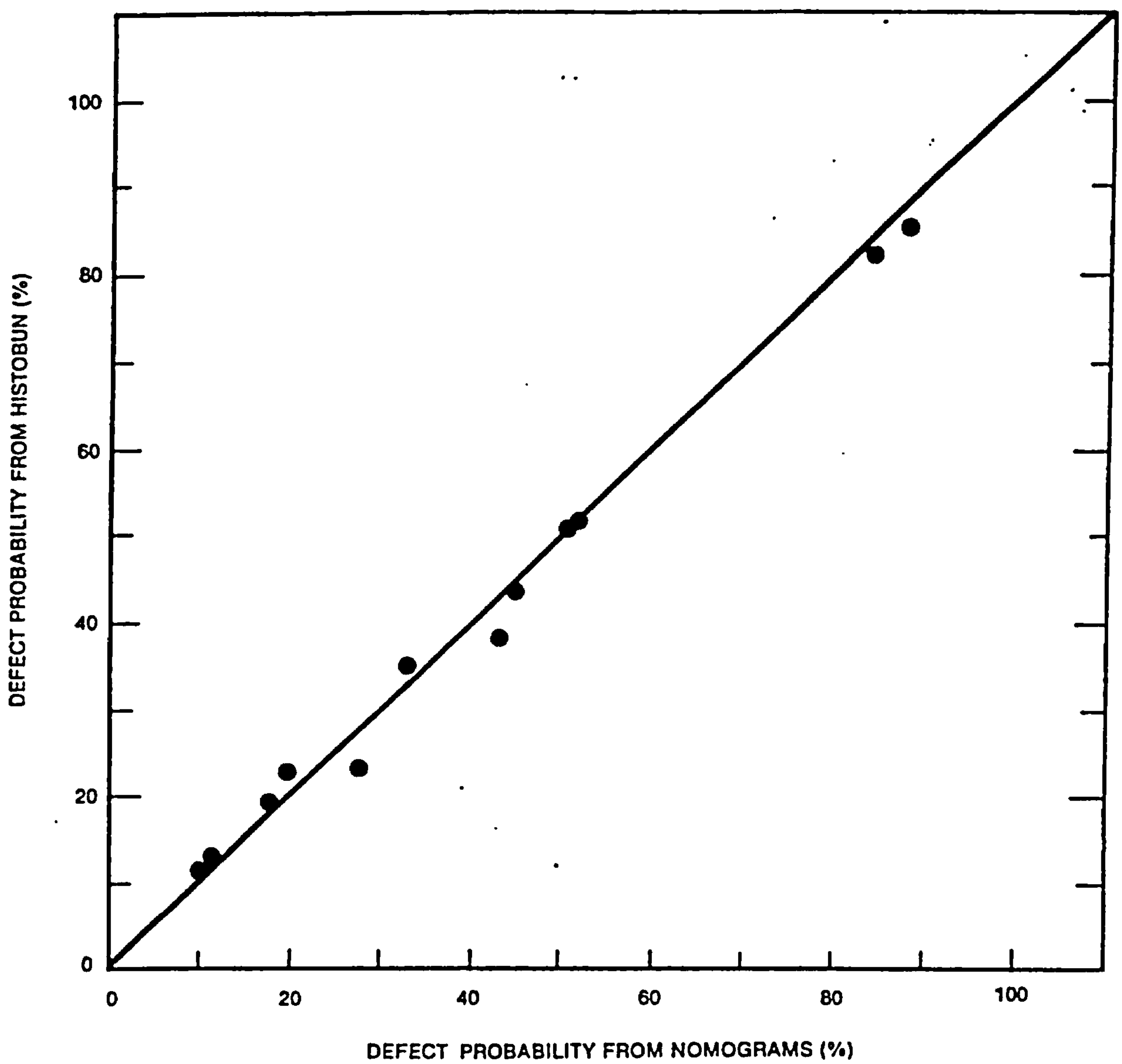


FIGURE 5: HISTOBUN PREDICTIONS VS. NOMOGRAMS