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Development and Testing Of A Model for Fire Potential in Nuclear Power Plants

Prepared by R. W. Hockenbury, M. L. Yeater

Department of Nuclear Engineering
Rensselaer Polytechnic Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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Prepared by
R. W. Hockenbury, M. L. Yeater

Department of Nuclear Engineering
Rensselaer Polytechnic Institute
Troy, NY 12181

Prepared for
Division of Systems and Reliability Research
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ABSTRACT

Approximately 235 fire events have been examined, classified and analyzed for various probability factors related to fires in nuclear facilities. The fire incident data bank is computerized thus making the information readily accessible for simple sorting. The observed fire events have been used to aid in the construction of preliminary models for estimating the risk due to fires in nuclear power plants. Various aspects of the models are presented, including features to incorporate in second-phase modeling efforts.

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ACKNOWLEDGEMENTS

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- Section B R.H.V. Gallucci - Modelling and time-dependence
  D.J. Parker - Time-dependence
- Section C and D P.S. Jackson - Fire Data Bank and probability factors

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A. Introduction

The objective of this research has been to identify and evaluate important fire potential parameters in nuclear power plants primarily,based on fire records, to carry out preliminary analyses of selected fire scenarios;and to begin work on models for estimating the potential risk of nuclear accidents due to fires. This provides a base for a continuing program of model development, plant evaluation and fire protection optimization. The scope and specific tasks under this contract are described in RPI Proposal No. 132 (78K) B31(12) dated November, 1977.

A study of fire data has been made based on records of two hundred thirty-five fires at nuclear power plants. One hundred fifty of these have occurred in commercial plants during construction and operating phases.(1) The data used are based primarily on nonproprietary information from the files of the plant insurers, supplemented by NRC records.(2) A computerized data base has been developed to expedite the retrieval of statistical information. These data have been evaluated and classified to obtain probability factors related to parameters such as cause, location, combustible and method of extinguishment. The time dependence of fires in the construction and operational phases has been examined.

In order to carry out a detailed study of the risk of a nuclear accident due to fires, the large number of fire areas and systems of a nuclear power plant must first be assigned some type of priority. Two schemes for doing this are given and their implication are discussed. A framework for the detailed scenarios and sequences to be studied in a second stage is presented in the form of event trees. These event trees identify the major branches and possible system damage in a typical fire scenario. The branching possibilities (safety-related damage, extinguishment, propagation to adjacent equipment as zones, etc.) thus identify the type of information required for the study. Some of this information will come from observed fire data as conditional probabilities, some from fire equipment reliability and some from fire tests on specific materials.

This report describes the status of the work in the 15 months of the contract period and also plans for the next stage.

B. Modelling Strategies

B.1. Overall Methodology

A fire event may be viewed as a sequence consisting of initiation, detection, possible fire effects on plant systems, and possible releases and extinguishment. A model of a fire is then defined in the following way.

1. Probability of a certain type fire in a given location.
2. Probability of degrading effect on plant control, i.e. loss of control and/or scram and shutdown function.
3. Resulting sequence of events such as continued loss of safety systems, propagation to adjacent equipment in same fire zone and to adjacent fire zones finally producing some type of release.
4. Possible releases resulting from the sequence of events.

The construction of a model capable of including all of the above is a major task. However the elements of such a model can be laid out as a framework identifying, in the process, all the necessary sub-tasks and requirements for data. This section describes this overall framework as it is viewed at present, details the most important sub-tasks and presents our progress to date in these tasks.

The flow chart in Figure B.1 shows the long range plans for the development and application of a fire risk assessment methodology. An initial model (Box 1) is being developed at present using the fire data and fire reviews with reference to an existing BWR plant. (Further details of this modelling now in progress are presented later in this section). This model will then be extended to a PWR (SURREY). Following this, the model will be examined and revised if necessary (Box 2) for application to other plants. The application of this revised model (Box 3) to a few selected plants (old, new and proposed designs) will be a final test (Box 4) before establishing the final methods (Box 5) and procedures to be used. The end results of this study will be a set of procedures to assess the fire risk to existing plants, new plants and modifications to existing plants.

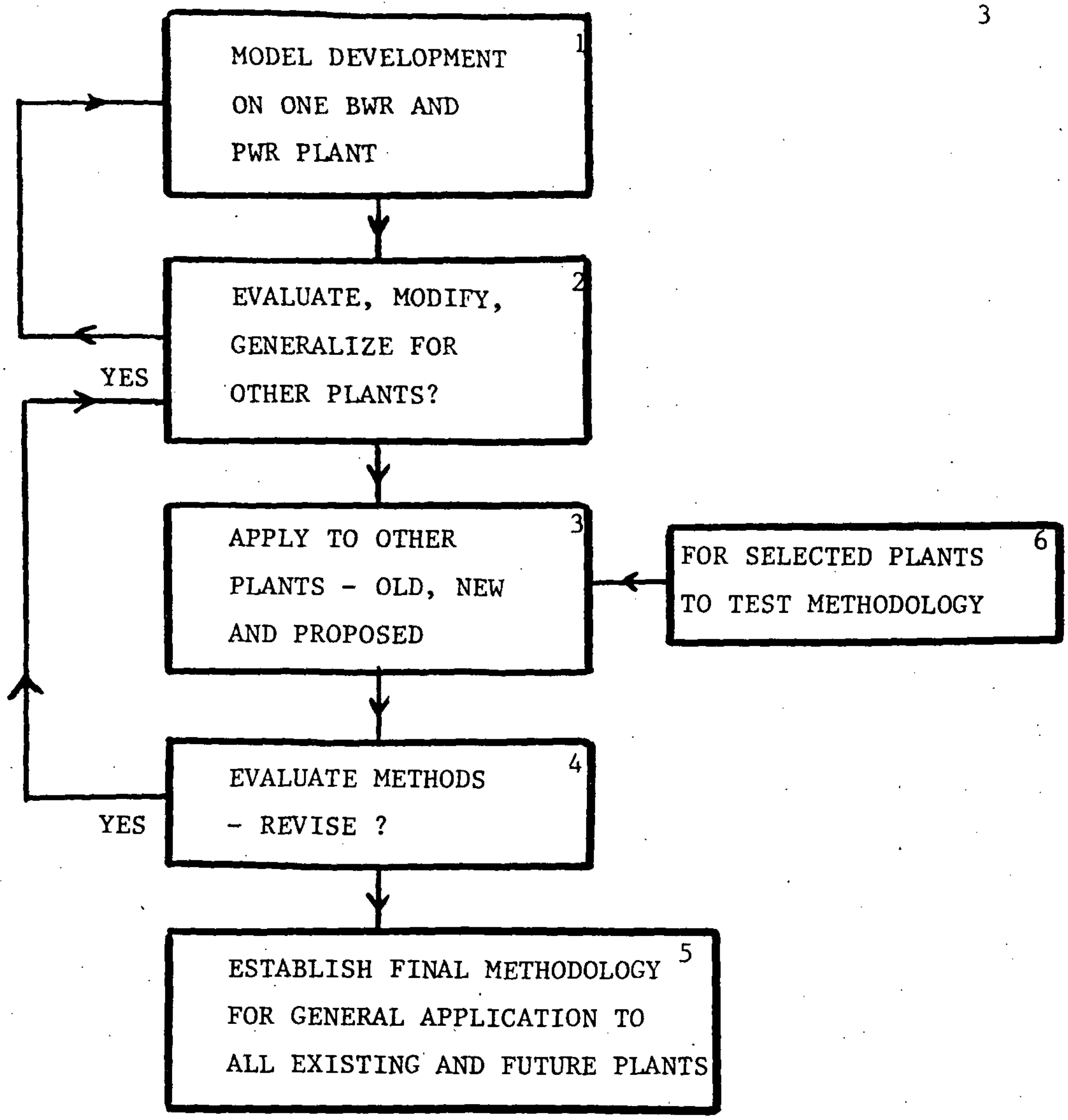

Figure B.1 OVERALL PLAN

B.2 Status of Model Development

The details of the model development are flow charted in Figure B.2 and further illustrated in Figure B.3. An extensive, detailed evaluation of the events, (Box 1) has been completed. The safety functions, systems, locations, combustible loadings, human traffic, detection and extinguishment (automatic and manual) capabilities have been reviewed (Boxes 2, 3) for a BWR power plant using the plant FSAR and the plant fire evaluation report. Every fire zone containing safety-related components has been examined for the factors cited previously and given an initial priority ranking (Box 4). This initial ranking will then be used as a guide to carry out more detailed evaluations. Further evaluation of the initial ranking scheme must be done (Boxes 5, 6) before arriving at an adequate model (Box 7) to be used to arrive at relative and absolute probabilities of a nuclear accident as a result of a fire.

The BWR plant was evaluated zone* by zone to obtain an initial priority ranking based on the following factors:

1. System factor (S_i) - This is a measure of the significance of each component or sub-system in relation to the safety function required for scram, ECCS, shutdown and long term heat removal. Figure B.3 presents a logic diagram relating three functions we have designated as required for plant safety. These functions are scram, shutdown cooling and emergency cooling. For this plant, the long range heat removal requirement is associated with both the E.C.C. and shutdown cooling functions. The systems identified in Figure B.4 have been examined down through their support and electrical sub-systems. Some illustrations of these are shown in Figures B.4 through B.7 where the shutdown cooling system and the electrical supplies are presented in more detail.

The standby liquid control system can be used to illustrate the system factor. As shown in Figure B.4, the plant safety function is:

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* Only safety related zones

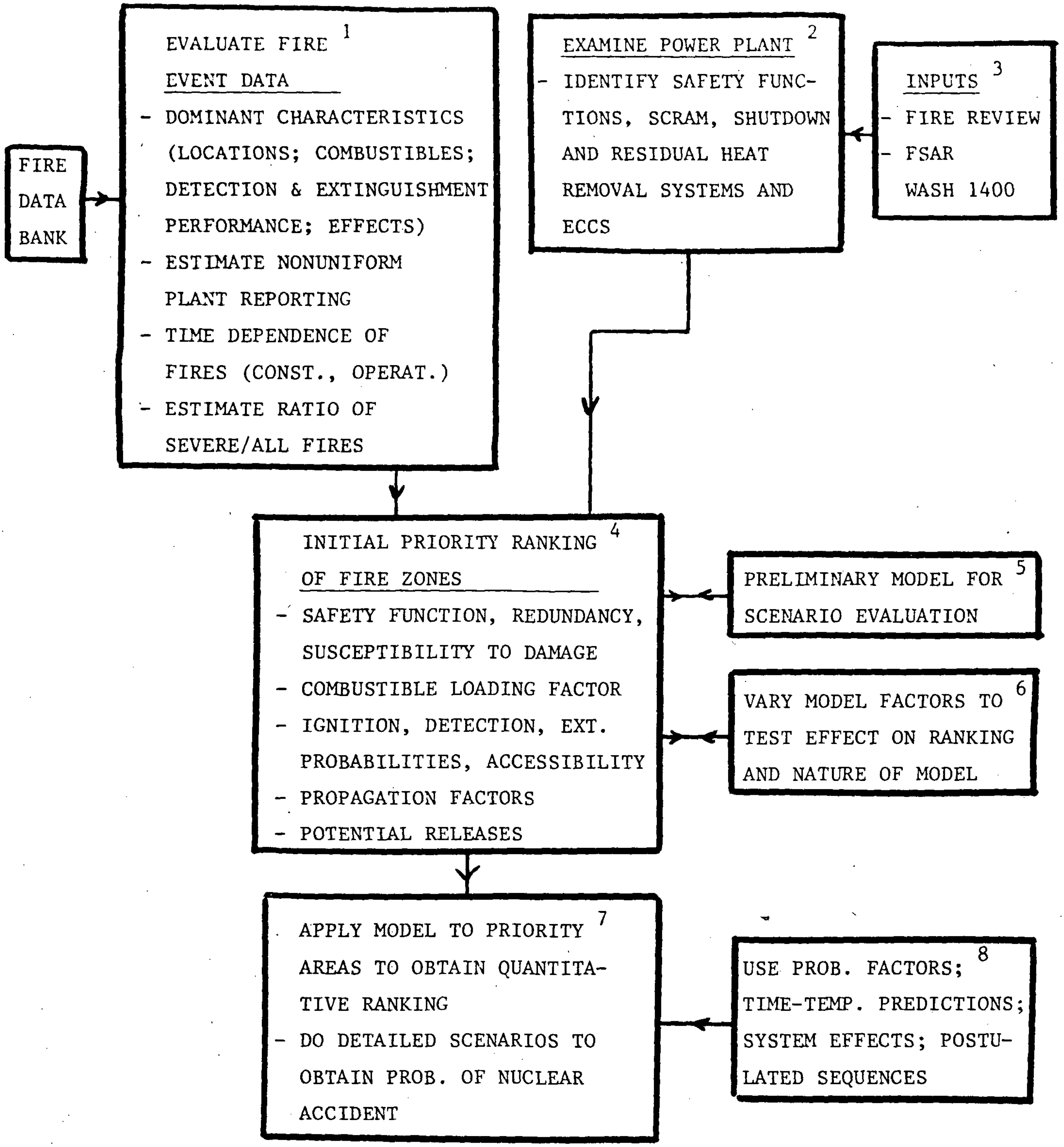

Figure B.2 MODEL DEVELOPMENT

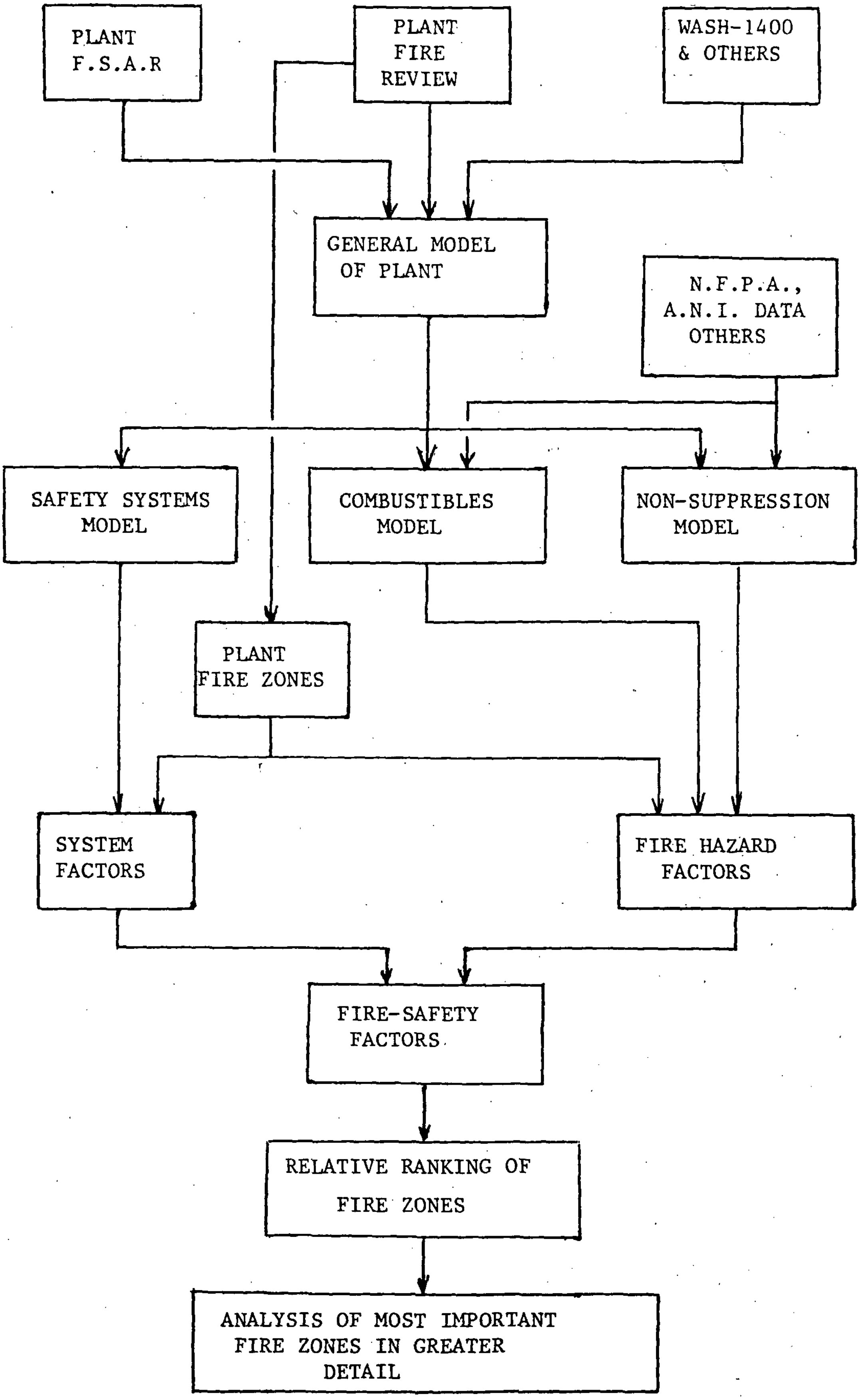

Figure B.3 Model for Preliminary Ranking of Fire Zones

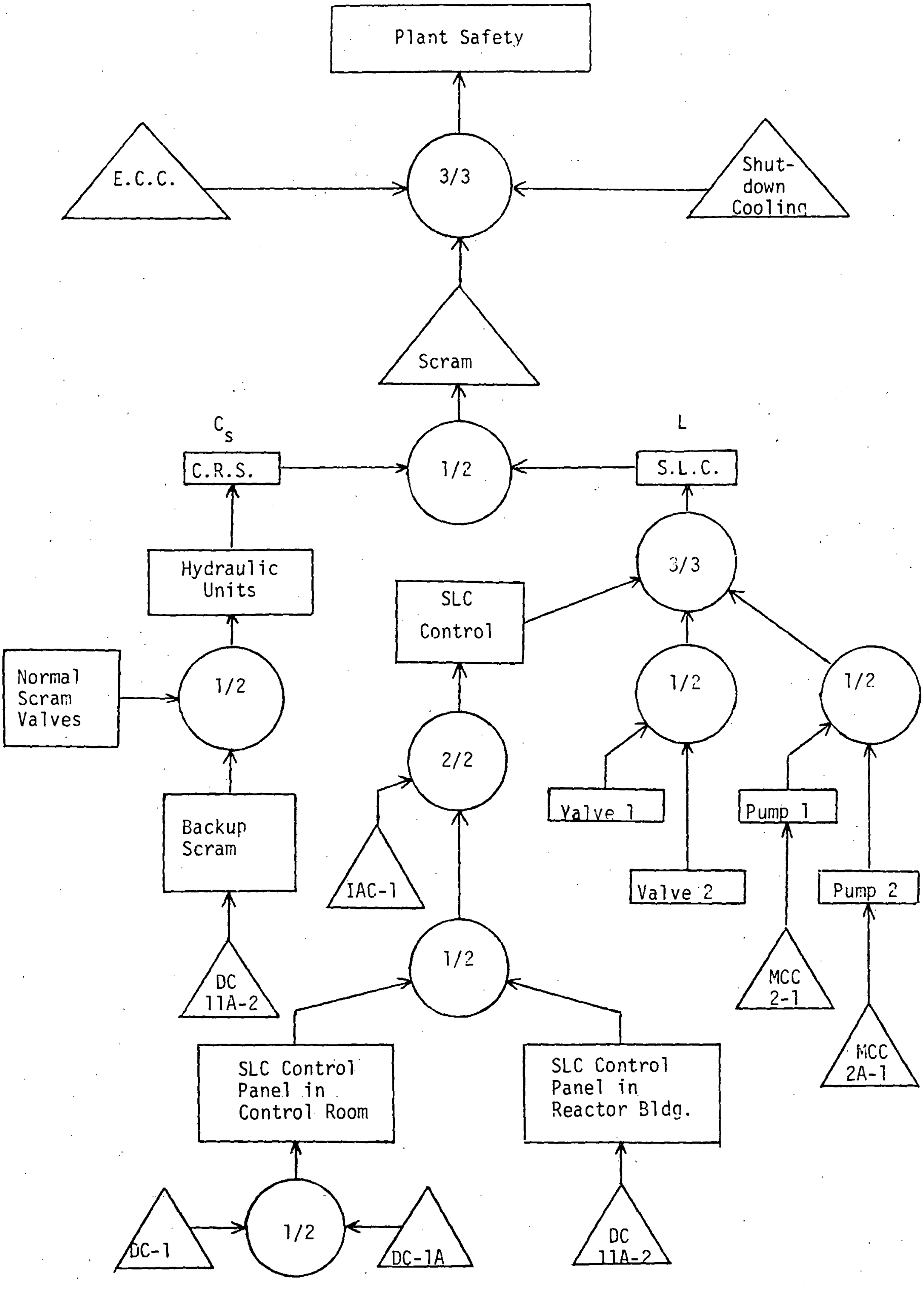

Figure B.4 Safety Functions

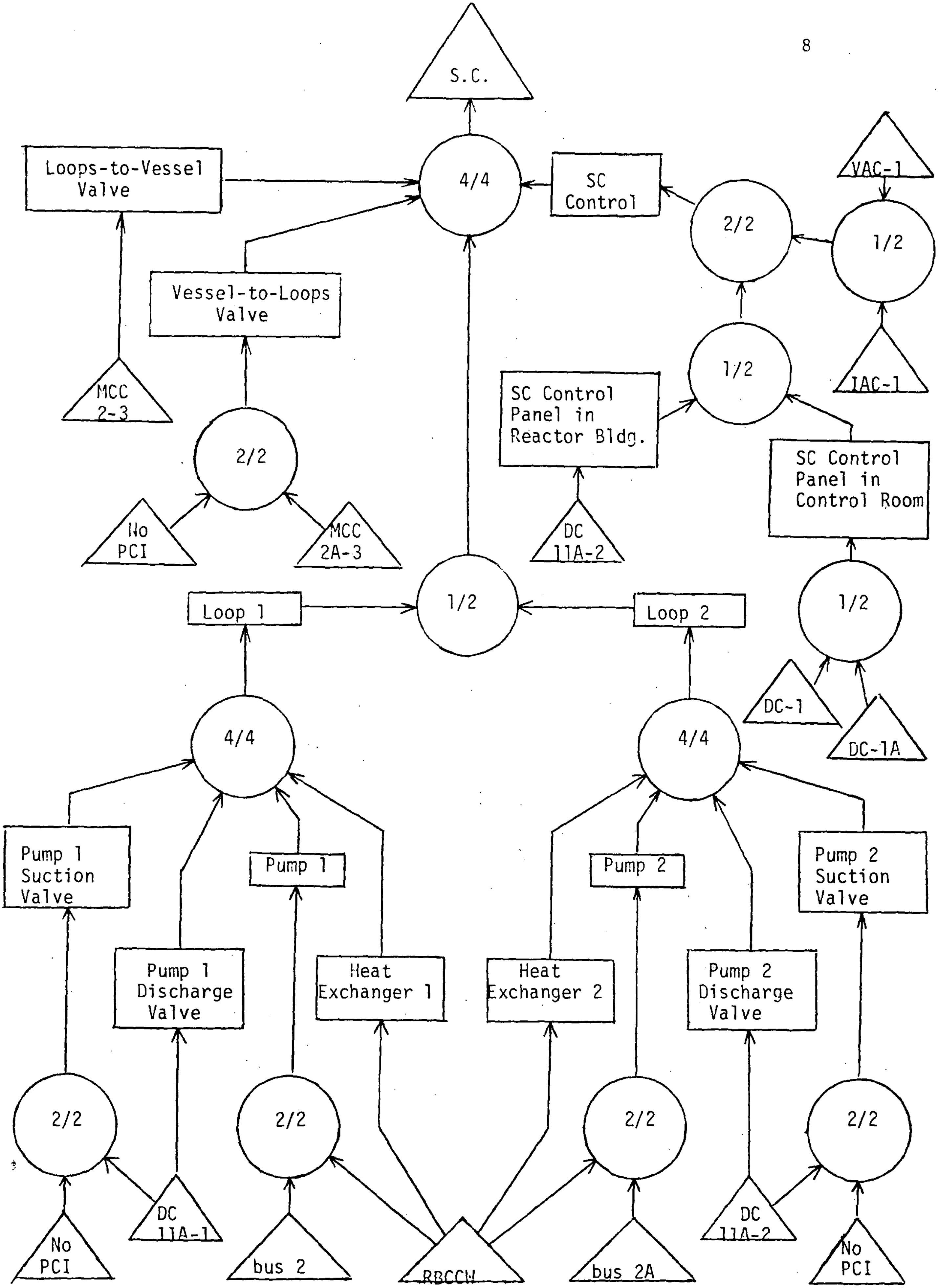

Figure B.5 Shutdown Cooling Function

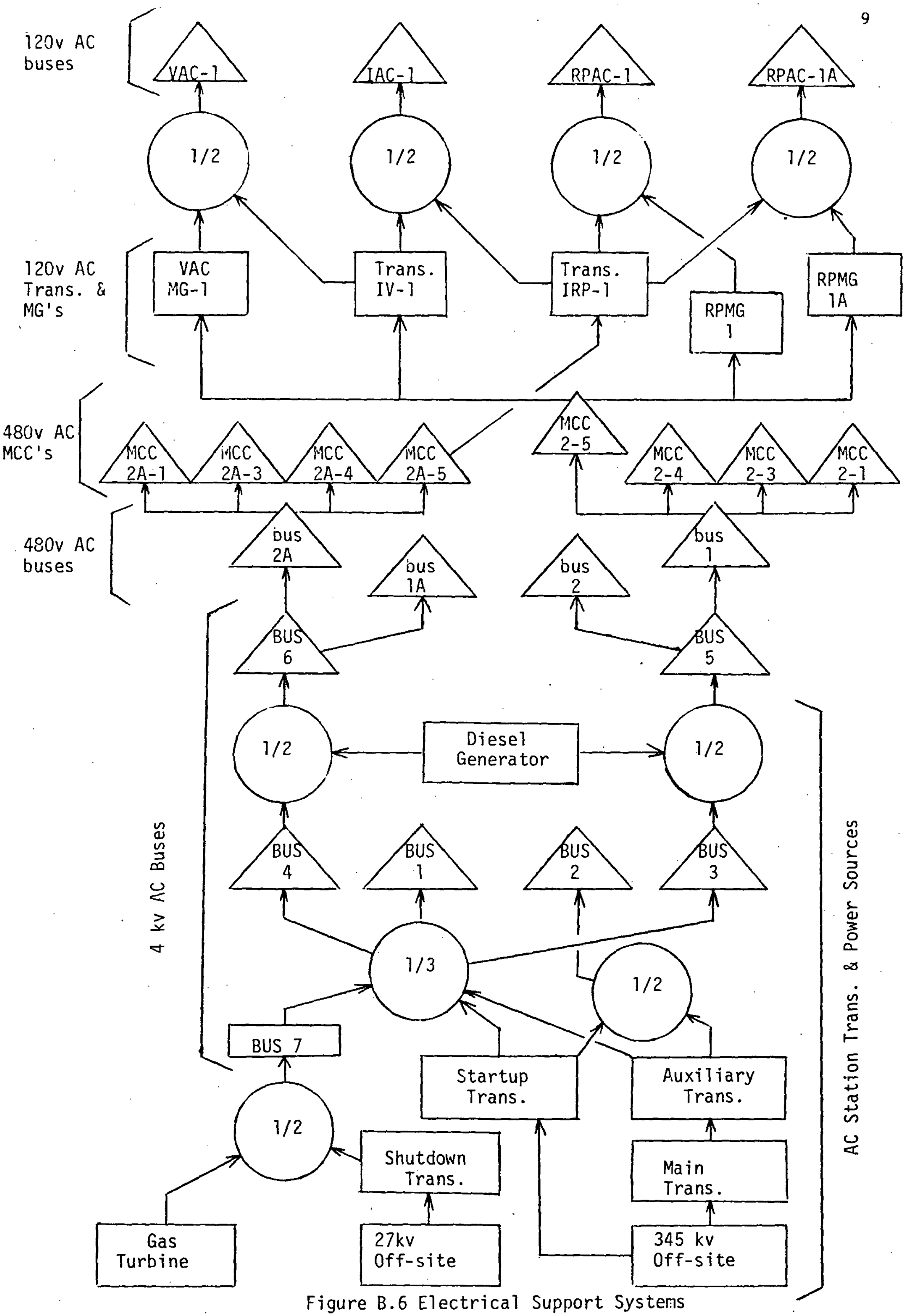

Figure B.6 Electrical Support Systems

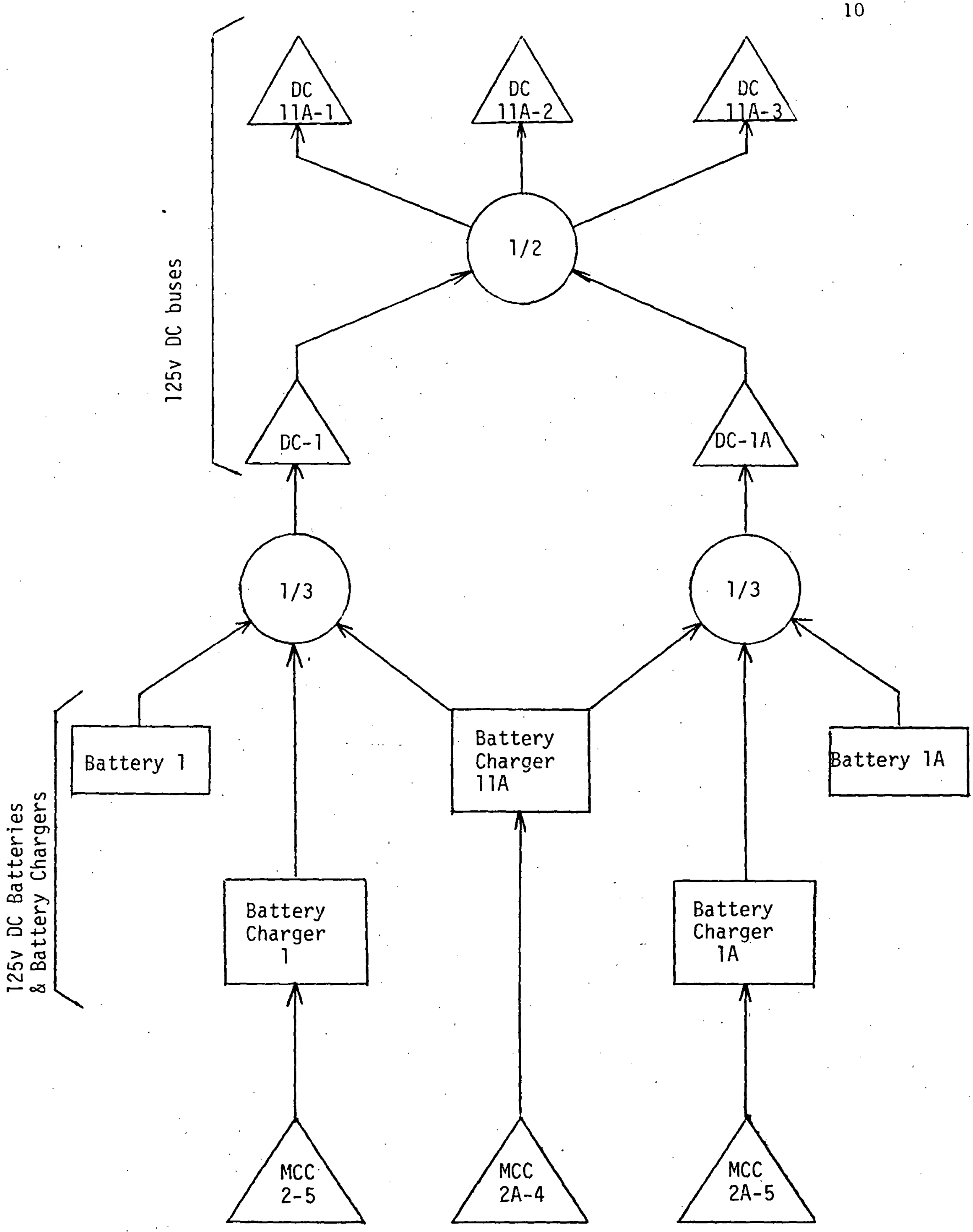

Figure B.7 D.C. Supply

$$\text{Plant Safety} = (\text{Scram})(\text{E.C.C.})(\text{Shutdown Cooling}) = S_m \cdot E \cdot S_h \qquad \text{B.2.1}$$

The scram function S_m is composed of the control rod scram system C_s and the standby liquid control system (L) as a redundant backup. Thus S_m can be written

$$S_m = C_s + L \qquad \text{B.2.2}$$

If one associates a weight of unity with plant safety, then each factor $S_m = E = S_h$ also has unit weight because of the 3-of-3 requirement. Then because of the logical relation above of C_s and L to S_m; a weight of $\frac{1}{2}$ is associated with each:

$$S_m = C_s + L \qquad \text{B.2.3}$$

or

$$1 = \frac{1}{2} + \frac{1}{2} \qquad \text{B.2.4}$$

The major components of the standby liquid control system are shown in Figure B.8. The boolean expression for success can be written

$$L = (P_1 + P_2)\ell(V_1 + V_2) = \frac{1}{2} \text{ (weight)} \qquad \text{B.2.5}$$

where ℓ refers to the control part of the system. Since L is the logical AND of $(P_1 + P_2)$, ℓ and $(V_1 + V_2)$, each of these is assigned a weight of $\frac{1}{2}$. Therefore if:

$$P_1 + P_2 = \frac{1}{2} \text{ (weight)} \qquad \text{B.2.6}$$

then

$$P_1 \text{ (weight)} = \frac{1}{2}\left(\frac{1}{2}\right) = \frac{1}{4} \qquad \text{B.2.7}$$

and similarly for P_2, V_1, and V_2.

Finally, since the two pumps P_1 and P_2 are located in the same fire zone, this zone is assigned a system factor of $\frac{1}{2}$. Since this zone also contains unknown safety cables, the liquid tank and other safety components, the actual assigned weight is temporarily set to ≥ 0.5.

This process was continued for all the systems and their components related to safe shutdown with the resulting system factors shown in Table B.1.

TABLE B.1

PRELIMINARY RANKING OF FIRE ZONES (MODEL I)

RANK	FIRE ZONE	FIRE CLASS	COMBUST. FACTOR	NON-SUPP. FACTOR	SYSTEM FACTOR	RATING	RATINGS (NORMALIZED)
1.	Fire Pump House	B C	.141 .0033	.238 .445	.250	$8.76\text{x}10^{-3}$	1.0
2.	4 kV Sw.Gear(A)	A B C	$6.3\text{x}10^{-4}$ $3.5\text{x}10^{-3}$ $3.9\text{x}10^{-2}$	0.086 .086 .0038	1.0	$5.05\text{x}10^{-4}$	.058
3.	Cable Vault	C	.103	.0032	1.0	$3.32\text{x}10^{-4}$	.038
4.	4 kV Sw.Gear(B)	C	.063	.0038	1.0	$2.38\text{x}10^{-4}$	.027
5.	Two Drive Water Pumps	A	.0043	.0985	0.5	$2.12\text{x}10^{-4}$	.024
6.	D.G.Day Tank Room	B	.397	$9.4\text{x}10^{-4}$	0.5	$1.87\text{x}10^{-4}$	.021
7.	4 kV SW Gear (C)	C	.047	.0038	1.0	$1.76\text{x}10^{-4}$	.020
8.	125 v. BUS	A B	.0029 .0489	.0985 $7.0\text{x}10^{-5}$	$\geq .50$	$\geq 1.45\text{x}10^{-4}$	.017
9.	480 v. AC M.C.C.* TBSCW Pumps**	A B C	.0045 .054 .037	.0031 $2.4\text{x}10^{-4}$ .0032	1.0	$1.42\text{x}10^{-4}$	.016
10.	480 v. AC M.C.C.,C.R. Hyd.Units,SC Reactor Bldg. Control Panel	A C	$2.3\text{x}10^{-4}$ .026	.0043 .0052	← 1.0	$1.36\text{x}10^{-4}$	.016

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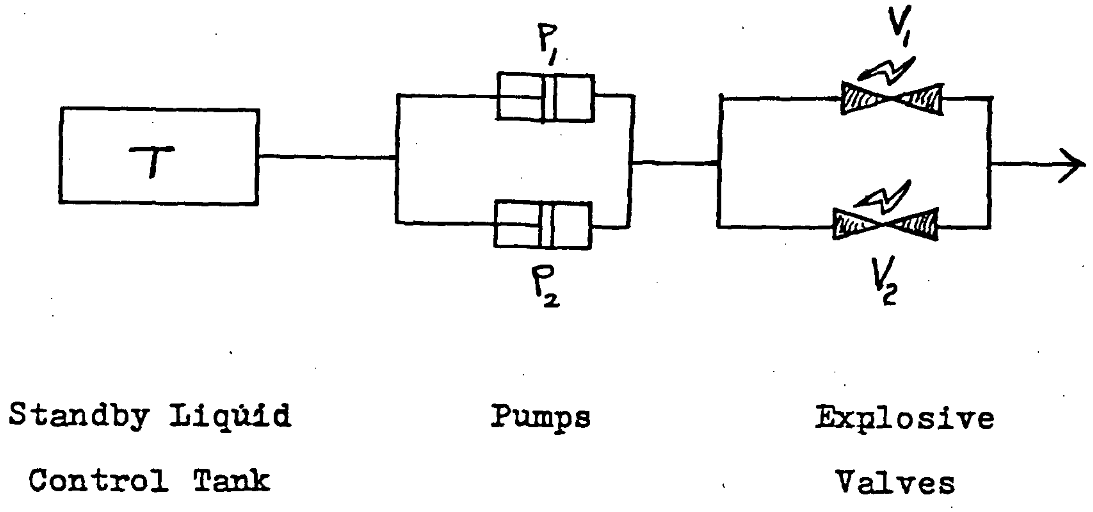
* Motor Control Centers

** Turbine building secondary cooling water pumps

STANDBY LIQUID CONTROL SYSTEM



SUCCESS = $T \bullet (P_1 + P_2 - P_1 \bullet P_2) \bullet (V_1 + V_2 - V_1 \bullet V_2)$

ASSUME P_1 and V_2 disabled by fire:

SUCCESS = $T \bullet P_2 \bullet V_1$

THUS

System is successful.

Figure B.8 Standy Liquid Control System

2. Non-suppression factor - ($\overline{P}_{s,x}$) - The fire detection and extinguishment factor, including manual and automatic equipment and an estimate of human response, is the overall probability of failure to extinguish a fire for all classes of fires appropriate for each zone.

$\overline{P}_{s,x}$ = (non-suppression prob. by manual means)(non-suppression probl. by auto. systems) B.2.8

Note that either probability equals 1 if absent. The symbol x denotes the class of fire (A-D).

Example - For one switchgear room:

$\overline{P}_h$ = probability that human response is unavailable

$\overline{P}_h$ = 0.061 - Note that this is the 5% lower confidence limit on an estimate of the fraction of fires at which human response was unavailable (For the ANI data, 14 out of 143 events). The exact numbers are not as important at this stage of our study as is the methodology.

$\overline{P}_d$ = probability that the automatic detectors fail on demand

$\overline{P}_d$ = 0.0363 - From preliminary insurance statistics

$\overline{P}_{e-m,x}$ = non-extinguishment probability for a manual extinguisher on a class x fire

$\overline{P}_{e-m,x} = 6.3\text{x}10^{-4}$ for this area

Then $\overline{P}_{s,x}$ is:

$$\overline{P}_{s,x} = \overline{P}_h\overline{P}_d + (P_h + P_d - P_hP_d)\overline{P}_{e-m,x} \qquad \text{B.2.9}$$

$\overline{P}_{s,x} = 2.8\text{x}10^{-3}$ for one switchgear room - Note, as stated above these probabilities are useful for preliminary ranking but should not be taken as final values.

For this area, the night-time $\overline{P}_h$ was taken as 0.0979 and this leads to:

$\overline{P}_{s,x}(\text{night}) = 4.2\text{x}10^{-3}$

And a weighted overall value is:

$$\overline{P}_{s,x}(\text{average}) = \frac{1}{3}\,\overline{P}_{s,x}(\text{day}) + \frac{2}{3}\,\overline{P}_{s,x}\ (\text{night}) \qquad \text{B.2.10}$$

$$\overline{P}_{s,x}(\text{average}) = 3.8\text{x}10^{-3}$$

This value and those for other zones are listed in Table B.1.

3. Combustible factor ($CF_{s,x}$) - This factor is the product of (1) the relative frequency of each class of fires, (2) the combustible loading of all classes of fires in the zone and the rate of occurrence for all types of fires:

$$CF_{s,x} = \frac{x}{N}\left(\frac{C_L}{240{,}000}\right) u \qquad \text{B.2.11}$$

where: x = no. of fires of class x since first criticality

N = total no. of fires of all types

C_L = combustible loading $\frac{BTU}{ft^2}$ and is divided by 240,000 to make CF relative to a 3 hour fire rating

u = u(t) = fire occurrence rate for all fires, based on the non-homogeneous Poisson model$^{(3)}$ (note that this time dependent factor cancels out when performing a relative ranking of zones).

These factors were combined, for each zone, to obtain a relative ranking, R_i:

$$R_i = \sum_x (CF_{s,x})(\overline{P}_{s,x}) \quad S_i \quad \text{summed over all classes for zone } i \qquad \text{B.2.12}$$

$$i$$

Estimate of $CF_{s,x}$, $\overline{P}_{s,x}$ and S_i were obtained and R_i was determined for all the zones in order to identify (according to the above assumptions) the most critical zones which can then be examined in more complete detail.

With regard to this ranking, it is important to make the following comments:

a) The model used here is limited to a few factors, which, though important, do not represent a complete model. Other factors which should also be considered are described later.

b) This model permits attention to be focused on the most important areas. Although a more complete model may change the order or ranking, any such changes and the underlying reasons for them will be of interest in themselves.

c) One vital factor, the cables in each zone, has not yet been adequately included. In order to do a complete evaluation, the cables, their function and their locations must be known in each zone. This problem has been recognized from the beginning of this project but has been deferred until other aspects of the model were more complete.

The estimates* for the three factors previously described are presented in Table B.1 for the top ten zones. These estimates are presented for the purpose of discussion and comparison and not in the sense of final results.

This preliminary scheme gives the highest rating to the fire pump house with no credit allowed for the fire pumps' role in fire protection. This high rating results from the minimal amount of extinguishment available (one 20 lb. portable dry chemical extinguisher) combined with a high combustible factor due to the diesel fuel oil present. The presence of switchgear rooms and the cable vault near the top is not unexpected. The diesel generator day tank room appears sixth because of its combustible factor and its importance to operation of the diesel generator. The appearance in fifth place of the area containing two drive water pumps is due to the relatively high non-suppression factor (no extinguishers available in this zone).

In this scheme, the diesel generator room is ranked fifteenth due to the relatively low non-suppression factor. The same comment applies to the control room which is ranked nineteenth.

* The actual conditions in this plant may have changed since the study began.

B.3 Alternate Ranking Schemes Examined

Before discussing weighting factors to be included with the preliminary model presented in section B.2, it is useful to consider some alternate ranking schemes.

B.3.a. Ranking by Observed Fire Rates in Components

Step 1. The fire data were examined to determine the probability of when a fire will occur in a specific component. The non-homogeneous Poisson model was applied to 44 fires which occurred in nuclear plants after first criticality. The parameters λ and β were obtained as described in section B.4.2 giving $u(t)$, the number of fires per plant month at time t:

$$u(t) = \lambda \beta t^{\beta-1} \qquad \text{B.3.1}$$

$$u(t) = .0594\ t^{.319}$$

Step 2. The number of fires in each component was found and the ratio of this number to the total number of fires becomes an estimate of the conditional probability. For 9 pump fires with a total of 44 fires, the estimated probability of a pump fire given that a fire has occurred is 9/44 = 0.205.

The probability of a pump fire occurring in a plant within a specified time period from t_o to t is then:

$$P_{t_o}(t) = \frac{(\text{no. pump fires})}{(\text{total no.})} \int_{t_o}^{t} u(t)dt \qquad \text{B.3.2}$$

This assumes that pumps (and other components) have the same time-dependence as the total fire rate. For this example and letting $t_o = 95$, $t = 96$, we have

$$P_{95}(96) = (9/44) \int_{95}^{96} 0.0594\ t^{.319}dt = 0.00283$$

for the probability of a pump fire/plant in the 96th month of operation.

Step 3. The calculation in Step 2 is extended to include the component (pump) and all of its supporting equipment in the zone, such as cables, breakers, relays and cooling water. For convenience, the complement of this probability is then used to arrive at the probability of failure due to fire in zone i as follows:

$$\overline{P}_i(\text{pump}) = \overline{P}_{p,i}\ \overline{P}_{c,i}\ \overline{P}_{b,i}\ \overline{P}_{r,i} \qquad \text{B.3.3}$$

where:

$\overline{P}_i(\text{pump})$ = overall probability of no failure by fire in pump in zone i

$\overline{P}_{p,i}$ = probability of no fire in pump itself in zone i

$\overline{P}_{p,i} = 1 - P_{p,i}$

$P_{p,i} = \dfrac{\text{no. pump fires}}{\text{total no.}} \displaystyle\int_{t_o}^{t} u(t)dt$ from Step 2.

and similarly for:

$\overline{P}_{c,i}$ = probability of no fire in pump cable in zone i

$\overline{P}_{b,i}$ = probability of no fire in pump breaker in zone i

$\overline{P}_{r,i}$ = probability of no fire in breaker relay in zone i

where we assumed that zone i contains the electrical cable to the motor-driven pump, the electrical breaker and the breaker relay. Each of the conditional probabilities can be estimated from the observed fire data as for the pump fires. For those components in which fires have not been observed, a conservative estimate can be made by assigning 1 fire to each or using an estimate from a similar component.

Step 4. The probabilities, $\overline{P}_i$(component), from Step 3 can be used to arrive at the probability of any failure due to a fire in zone i, $P_{f,i}$:

$$P_{f,i}^{*} = 1 - \overline{P}_i(\text{component 1})\ \overline{P}_i(\text{component 2})\ldots\overline{P}_i(\text{component n}) \qquad \text{B.3.4}$$

Example 1. Two non-redundant pumps p_1 and p_2 in zone A

$$P_{f,A} = 1 - \overline{P}_A(p_1)\ \overline{P}_A(p_2) \qquad \text{B.3.5}$$

Example 2. Two redundant cables C_1 and C_2 in zone B

$$P_{f,B} = 1 - [\overline{P}_B(C_1) + \overline{P}_B(C_2) - \overline{P}_B(C_1)\ \overline{P}_B(C_2)] \qquad \text{B.3.6}$$

This scheme was applied to the same BWR plant as in Section B.2. Since we are interested, at this stage, more in the modelling process than in numerical results, only the highest rated zones will be discussed. The general characteristics of the rest will also be mentioned. Table B.2 gives the ranking for several of the highest rated zones.

For the top zone (#1), the rating was found as follows:

$$\text{Rating} = 1 - (\overline{P}_{B,1})^2\ (\overline{P}_{C,1})[4\ \overline{P}_{C,1} - 6(P_{C,1})^2 + 4(\overline{P}_{C,1})^3 - (\overline{P}_{C,1})^4] \qquad \text{B.3.7}$$

$\overline{P}_B$ = prob. no failure by fire of a bus

$P_{C,1}$ = prob. no failure by fire of a power cable

For a preliminary estimate, the observed fire data gave:

$$P_{B,1} = \frac{\text{no. bus fire}}{\text{Total fires}} \int_{t_o}^{t} u(t)dt = \frac{1}{44} \int_{95}^{96} 0.0594\ t^{.319}\ dt$$

$$P_{B,1} = 0.00315$$

Thus

$$\overline{P}_{B,1} = 1 - P_{B,1} = .996852$$

And similarly:

$$P_{C,1} = 5/44 \int_{95}^{96} 0.0594\ t^{.319} dt = .001574$$

and $P_{C,1} = .998426$

Substituting:

Rating = 0.0072

This ranking method scores only essential components; a component redundant to another in a different zone is not counted. Thus due to the usual separation principle of redundant trains in nuclear plants, this ranking scheme does not lead to a wide diversity of ratings. In fact, most of the other zones have a rating of $\sim .0016$ due only to the presence of an assumed non-redundant safety cable. A plant visit would, of course, pinpoint cable locations and probably

TABLE B.2

ZONE RANKING - OBSERVED EVENT WEIGHTING

Zone	Contents	Rating	Relative Value
1.	480 v A.C. bus; 4 KV AC bus; 4 redundant power cables; 1 assumed non-redundant safety cable	.0072	1.0
2.	Similar to #1	.0072	1.0
3.	480 v A.C. motor control center; 1 assumed non-redundant safety cable	.0047	0.65
4.	Similar to #3	.0047	0.65
5.	Two redundant shutdown cooling pumps; 1 assumed non-redundant safety cable	.0016	0.22

change these ratings.

Another aspect of this scheme is its tie to events which have actually occurred. This tie is useful but limited by the available statistics. This situation appears to be an opportunity for the application for Bayesian methodology and this is under consideration.

B.3.b. Weighting Factors Not Included in Models to Date

Several important factors have not been included in the models described. These include:

1) Susceptibility of safety-related components to damage by fire. This will vary considerably according to the physical nature of the components (including cables).

2) Accessibility must be included since there is a response time factor implicit in the models (distance to fire event). The size and characteristics of the room in which the fire occurs will also affect manual fire suppression measures.

3) Propagation to other areas must be considered including factors such as doorways, cable penetrations and ventilation.

4) The potential for radioactive release has not been included in the postulated sequences. This will be a function of more than just the initial site of the fire if the model includes the possibility of propagation to other areas.

B.4 Modelling Time Dependence of Fires

B.4.1 Construction Phase

The time dependence of fires during the construction phase was examined for commercial nuclear power plants. Since construction times varied by factors of two, a normalized time scale was used in an attempt to put all construction on approximately the same basis. This normalized time scale consisted of 20 intervals with 100% equal to completion of construction.
(The analysis presented here is an update of that presented in our first progress report(1) where the data were fitted to a linearly increasing time function.)

The number of fires per 5% interval is plotted in Figures B.9 through B.11. In order to further test the possible time dependence of construction fires, these data were grouped in various ways to apply an equal occurrence test for constant number of fires per fractional construction time period. Note that no fires were reported in the initial 10% period for any of the three groups shown in Figure B.9 through B.11. The plants were grouped in six ways and a chi-squared test for equal number of fires per fractional interval from 10% to 100% construction was performed. The chi-square value for 90% confidence for each group is presented in Table B.3. Note that the hypothesis of an equal or constant occurrence rate is not rejected for groupings 1, 2, 4 and 6. The hypothesis is rejected for groups 3 and 5 at the 90% confidence level but is acceptable at a 95% confidence level.

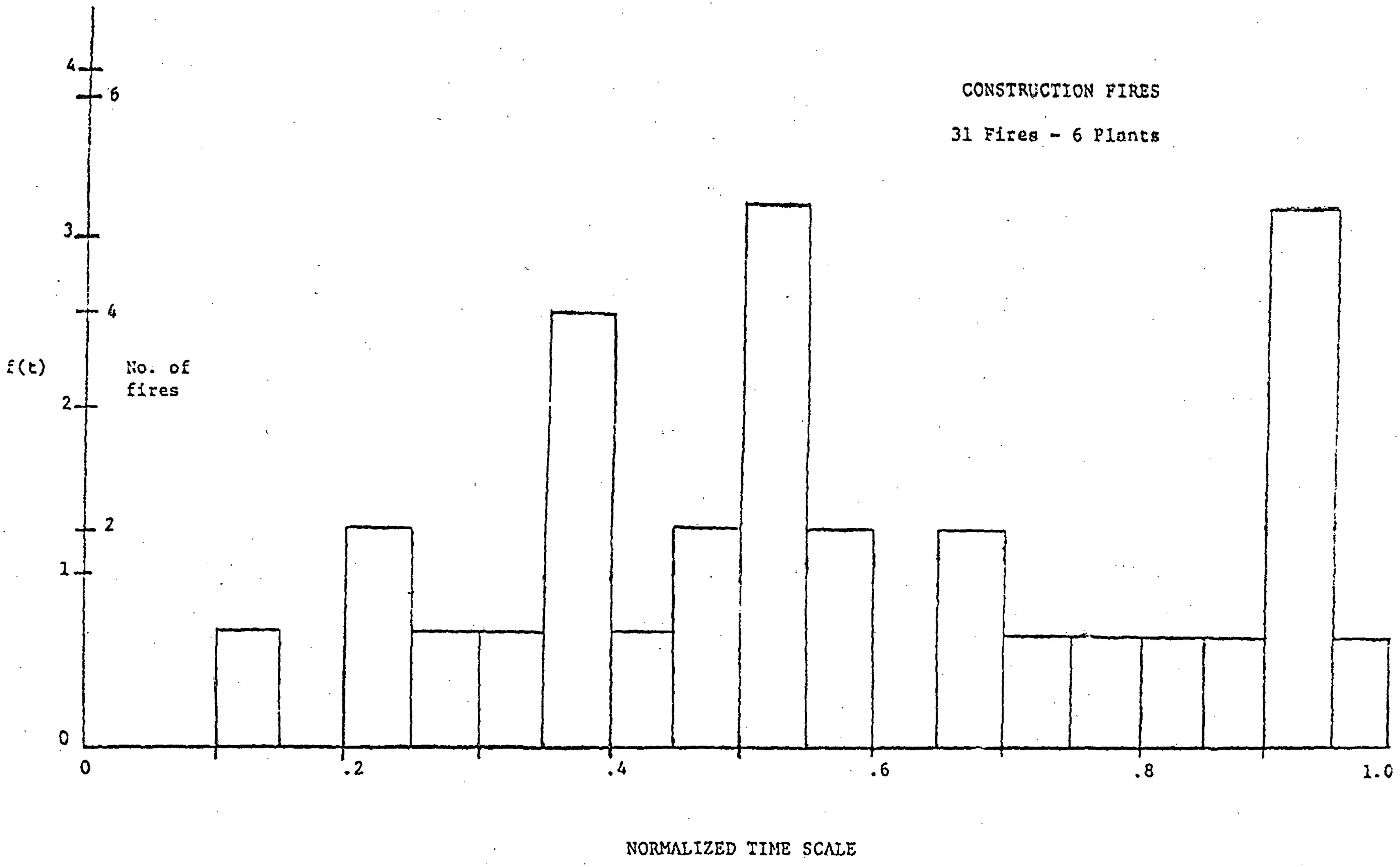
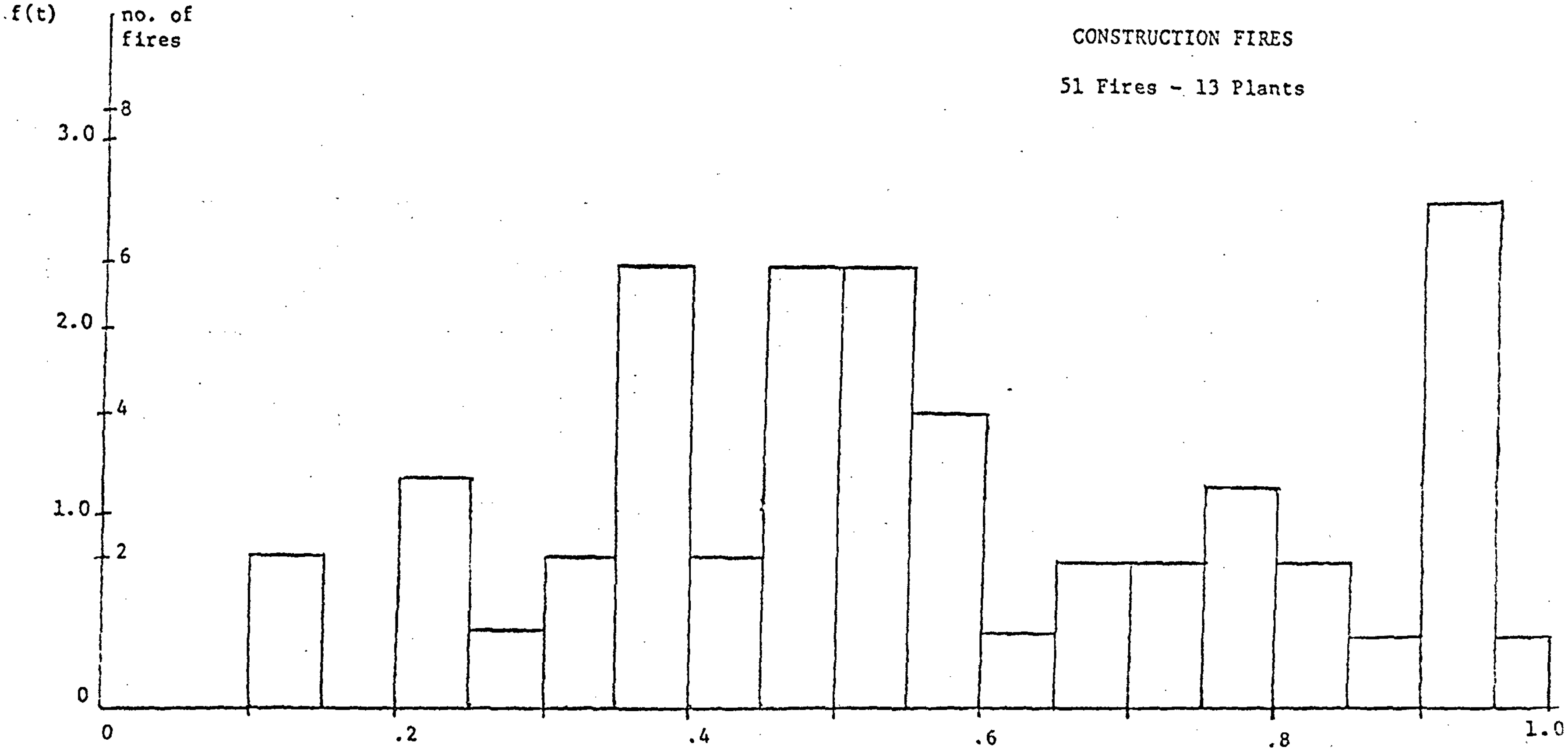
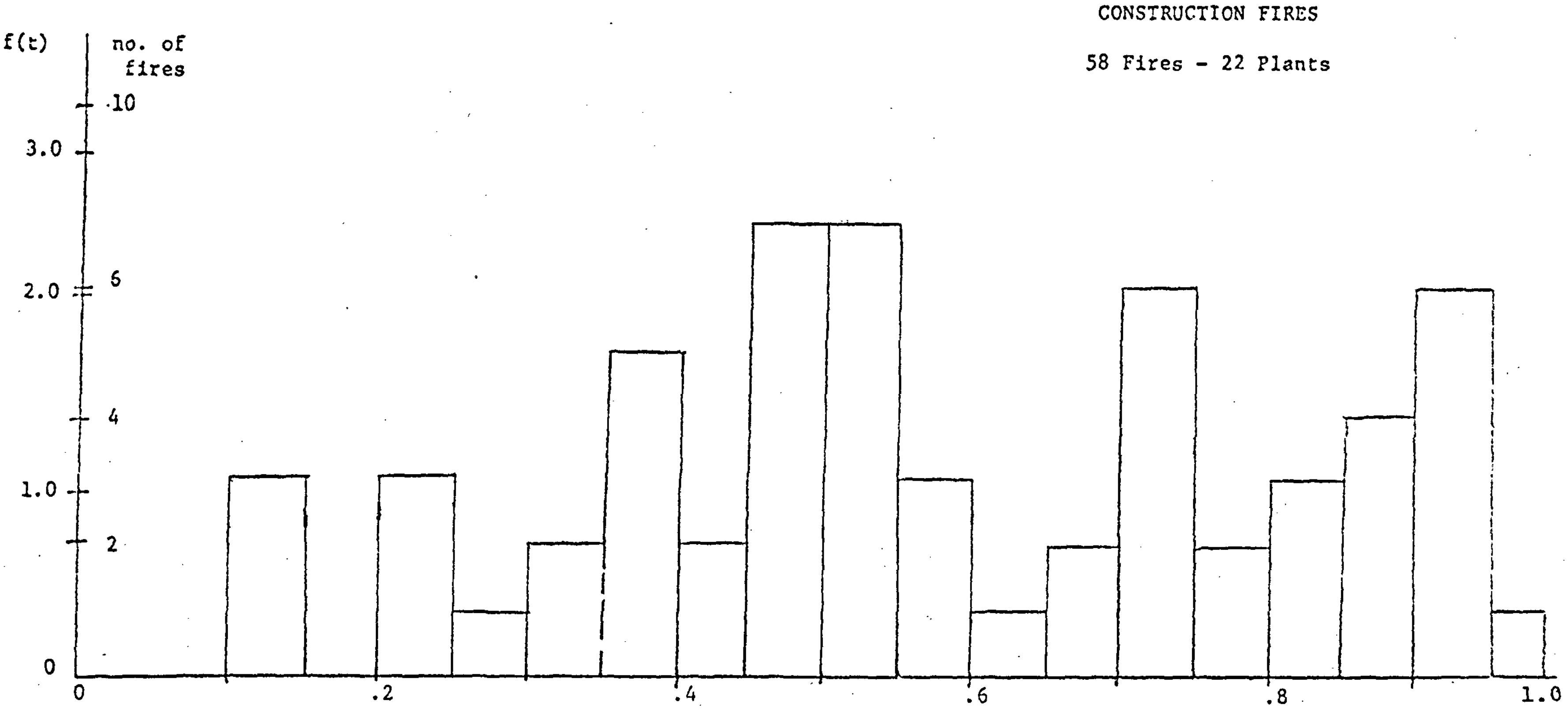


Figure B.9 Construction Fires - Group 1



NORMALIZED TIME SCALE

Figure B.10 Construction Fires - Group 3



CONSTRUCTION FIRES

58 Fires - 22 Plants

NORMALIZED TIME SCALE

Figure B.11 Construction Fires - Group 5

TABLE B.3

TEST FOR EQUAL OCCURRENCE RATE; CONSTRUCTION FIRES

Group	Number of Plants	Number of Time Intervals	Number of Fires Reported	χ^2_{90}	χ^2_{90}(obs.)
1	6	6	31	7.779	4.419
2	13	6	51	7.779	5.588
3	13	18	51	23.542	26.294
4	22	6	58	7.779	7.586
5	22	18	58	23.542	24.551
6	6	18	31	23.542	21.839

B.4.2 Time Dependence of Fires During the Operational Phase

A total of 24 safety related fires were reported during the operational phase of 17 nuclear power plants in the period from March 1968 to June 1978.(4) The time histories of these 24 fires were analyzed in order to obtain estimates of occurrence rates and expected number of fires versus time.

For this time-dependence analysis, the fire occurrences are modeled as a non-homogeneous Poisson process with Weibull occurrence rate.(3) For the Weibull model, the expected number of fires, $y(t)$, occurring in time t, the age of the plant from first commercial operation is:

$$y(t) = \lambda t^{\beta} \qquad \text{B.4.1}$$

The occurrence rate, $u(t)$, for the non-homogeneous Poisson process is then:

$$u(t) = \frac{dy}{dt} = \lambda \beta t^{\beta-1} \qquad \text{B.4.2}$$

and the probability $F(t)$ that a fire will occur in time t is:

$$F(t) = 1 - \exp[-\lambda t^{\beta}] \qquad \text{B.4.3}$$

Maximum likelihood estimates of the parameters λ and β were obtained following the procedures presented by Crow.(3)

For a particular plant q, we assume fires have been recorded from age S_q to age T_q, $q=1,\ldots K$ where K is the total number of plants in the record. The number of fires in each plant is denoted by N_q with X_{iq} equal to the age of the plant at the i^{th} fire occurrence, $i=1,\ldots, N_q$.

From Crow, the maximum likelihood (ML) estimates of λ and β are:

$$\hat{\lambda} = \frac{\sum_{q=1}^{K} N_q}{\sum_{q=1}^{K} \left(T_q^{\hat{\beta}} - S_q^{\hat{\beta}}\right)} \qquad \text{B.4.4}$$

$$\hat{\beta} = \frac{\sum_{q=1}^{K} N_q}{\hat{\lambda} \sum_{q=1}^{K} \left(T_q^{\hat{\beta}} \log T_q^{\hat{\beta}} - S_q \log S_q \right) - \sum_{q=1}^{K} \sum_{i=1}^{N_q} \log X_{iq}} , \qquad \text{B.4.5}$$

and in general $\hat{\lambda}$ and $\hat{\beta}$ must be found by iteration. The above equations are valid for the time truncated case in which S_q and T_q are not related to the failure times X_{iq}.

For the fire occurrence data, $S_q = 0$ and $\hat{\beta}$ becomes:

$$\hat{\beta} = \frac{\sum_{q=1}^{K} N_q}{\hat{\lambda} \sum_{q=1}^{K} T_q^{\hat{\beta}} \log T_q - \sum_{q=1}^{K} \sum_{i=1}^{N_q} \log X_{iq}} \qquad \text{B.4.6}$$

To obtain an initial value of β to start the iteration implied by Eqs. (4) and (6), Crow's expression for $\tilde{\beta}$, the conditional maximum likelihood estimate of β is used:

$$\tilde{\beta} = \frac{\sum_{q=1}^{K} N_q}{\sum_{q=1}^{K} \sum_{i=1}^{N_q} \log \left(\frac{T_q}{X_{iq}} \right)} \qquad \text{B.4.7}$$

Equations (4), with $S_q = 0$, and (5) are then used in the iteration process to find $\hat{\lambda}$ and $\hat{\beta}$.

The data were separated into three groups in order to reduce the effect of differences in reporting from plant to plant. This procedure leads to different best estimates and associated upper and lower bounds on λ and β. Group 1 consists of four plants having more than 1 fire occurrence, Group 2 of 13 plants with one occurrence each and Group 3 includes all 17 plants. The estimates obtained for λ and β are presented in Table B.4 with the occurrence rates and expected number

Table B.4

Estimate of λ and β

Group	$\hat{\lambda}$	$\hat{\beta}$	$\hat{\lambda}\hat{\beta}\, t^{\hat{\beta}-1}$	$\hat{\lambda} t^{\hat{\beta}}$
1	.1587	.7172	$.1138\ t^{-.2828}$	$.1587\ t^{.7172}$
2	.1155	.5309	$.0613\ t^{-.4691}$	$.1155\ t^{.5309}$
3	.1284	.5920	$.0760\ t^{-.408}$	$.1284\ t^{.592}$

* Time t in months

Table B.5

Values of C_M^2 Statistic* For Several Plant Groups

Group	C_M^2(Calculated)	C_M^2 5% Significance Level	C_M^2 10% Significance Level
1	0.214	0.216	0.166
2	0.041	0.218	0.168
3	.155	.216	0.169
4	.142	.212	0.167
5	.127	.206	0.163

* Crow

of fires for each group.

To test the assumption that the times of fires follow the non-homogeneous Weibull model, the statistic (3) C_M^2 is used:

$$C_M^2 = \frac{1}{12M} + \sum_{j=1}^{M} \left(Z_j^{\bar{\beta}} - \frac{2j-1}{2M} \right)^2 \qquad \text{B.4.8}$$

where an unbiased estimate of β is:

$$\bar{\beta} = \frac{M-1}{M} \tilde{\beta} \qquad \text{B.4.9}$$

$$\tilde{\beta} = \frac{M}{\sum_{q=1}^{K} \sum_{i=1}^{M_q} \log\left(\frac{T_q}{X_{iq}}\right)} \qquad \text{B.4.10}$$

$M_q = N_q$ since the data are time truncated,

$$M = \sum_{q=1}^{K} M_q \qquad \text{B.4.11}$$

$$Z_j = X_{iq}^{*} = \frac{X_{iq}}{T_q} \text{ ordered from smallest to largest.} \qquad \text{B.4.12}$$

Critical values are available for various M values and levels of significance; the test utilizing C_M^2 is a modified Cramer-Smirnov Test[3] and is discussed in Crow[3]. In order to not reject the hypothesis of a non-homogeneous Weibull model, C_M^2 must be less than the critical values given in Table B.5 for each selected grouping. The value of C_M^2 equal to 0.214 for Group 1, is barely rejectable at the 5% significance level. The hypothesis of the Weibull model being applicable would thus not be rejected at the 5% level but would be rejected at the 10% level. For Group 1, the Weibull model does not give as close a fit as some other models might, but it is still judged not to be inadequate for risk analyses purposes. Comparisons of groups 2 and 3 show that they are not rejectable at the 10% level of significance. Plots of predicted y(t) versus observed y(t) are given in Figures B.13-B.15. The observed y(t), $y_{obs}(t)$ is calculated as:

$$y_{obs}(t) = \frac{\sum_{q=1}^{K} N_q(t)}{K} \qquad \text{B.4.13}$$

where:

$N_q(t)$ = number of observed fires in plant q at time t

To test the hypothesis that the shape factors are the same for each member of the group, i.e. that $\beta_1 = \beta_2 = \ldots \beta_K$, Crow recommends the statistic:

$$L = \sum_{q=1}^{K} M_q \log (\tilde{\beta}_q) - M \log (\beta^*) \qquad \text{B.4.14}$$

where

$$M = \sum_{q=1}^{K} M_q \qquad \text{B.4.15}$$

$$(\beta^*)^{-1} = \sum_{q=1}^{K} M_q \tilde{\beta}_q^{-1}/M \qquad \text{B.4.16}$$

Critical values are found by noting that:

$$D = \frac{2L}{a}, \qquad \text{B.4.17}$$

where

$$a = 1 + \frac{1}{6(K-1)} \sum_{q=1}^{K} \frac{1}{M_q} - \frac{1}{M}, \qquad \text{B.4.18}$$

is approximately distributed as a chi-square random variable with K-1 degrees of freedom. The hypothesis is rejected if L, or equivalently D, is too large.

Table B.6 gives one-sided χ^2 values for three groups. Critical values for 5% and 10% significance levels are also shown. Examination of Table B.6 shows

Table B.6

D Statistic For β_q Comparisons

Group	D	5%	10%
1	0.317	$x^2 < 7.815$	$x^2 < 6.251$
2	9.113	$x^2 < 18.549$	$x^2 < 21.026$
3	10.326	$x^2 < 23.542$	$x^2 < 26.296$

that the hypothesis of equal shape factors is not rejected at the 10% (and hence 5%) significance levels. The individual plants within the groups are thus fairly homogeneous.

Confidence bounds(3) on $\hat{\beta}$ and $\hat{\lambda}$ were also calculated, using the chi-square method to first find the upper and lower bounds on β and then those for λ. The chi-square and w statistics were used to calculate the confidence bounds on β and then those on λ.

For the chi-square method,

$$\chi^2 = \frac{2M\beta}{\tilde{\beta}} \qquad \text{B.4.18}$$

is distributed as a chi-square random variable with 2M degrees of freedom. The $(1-\alpha)\cdot 100$ percent lower and upper confidence bounds on β, are thus:

$$\beta_{\ell b} = \tilde{\beta}\,\frac{\chi^2(\frac{\alpha}{2}, 2M)}{2M} \qquad \text{B.4.19}$$

$$\beta_{ub} = \tilde{\beta}\,\frac{\chi^2(1-\frac{\alpha}{2}, 2M)}{2M} \qquad \text{B.4.20}$$

The statistic w when

$$w = \sqrt{M}\,\left(\frac{\beta}{\tilde{\beta}} - 1\right) \qquad \text{B.4.21}$$

is approximately distributed as a standard normal variable. Thus alternate confidence bounds on β are:

$$\beta_{\ell b} = \tilde{\beta}\left[1 + \frac{z_{\alpha/2}}{\sqrt{M}}\right] \qquad \text{B.4.22}$$

$$\beta_{ub} = \hat{\beta} \left[1 + \frac{Z_{(1-\alpha/2)}}{\sqrt{M}} \right] \qquad \text{B.4.23}$$

where the Z_α is the standard normal percentile at level α. The confidence bounds on λ are obtained using the lower and upper bounds on β:

$$\lambda_{\ell b} = \frac{\chi^2(\frac{\gamma}{2}, 2N)}{2 \sum_{q=1}^{K} T_q^{\beta_{ub}}} \qquad \text{B.4.24}$$

$$\lambda_{ub} = \frac{\chi^2(1-\frac{\gamma}{2}, 2N+2)}{2 \sum_{q=1}^{K} T_q^{\beta_{\ell b}}} \qquad \text{B.4.25}$$

The confidence for both intervals $(\beta_{\ell b}, \beta_{ub})$ and $(\lambda_{\ell b}, \lambda_{ub})$ covering the true values β and λ respectively is at least $1-\alpha-\gamma$. In Eqs. (24) and (25), the values of β_{ub} and $\beta_{\ell b}$ can be those obtained from the chi-square statistic or the w statistic.

The confidence bounds for λ and β were calculated using Equations (22) and (23), then (24) and (25). The results are presented in Table B.7 for three groups of plants representing a maximum range of characteristics.

The parameters λ and β and their confidence bounds for Group 3 may be used as best estimates for risk evaluations while those for Group 1 would be also useful for sensitivity evaluations. The expected number of fires, y(t), for Groups 1-3 are compared in Figures 12 through 14, respectively, to the observed number of fires. The expected number of fires, y(t), the observed number and the upper and lower bounds for y(t) are shown in Figure B.15 for Group 3. For reasons of clarity, only the expected y(t) is shown for Groups 1 and 2; note that

Table B.7

Confidence Bounds on β and λ

Group	$\beta_{\ell b}$	β_{ub}	$\lambda_{\ell b}$	λ_{ub}
1	0.4806	1.3215	0.007285	0.6826
2	0.3497	0.8842	0.01543	0.3890
3	0.4755	0.9359	0.02093	0.2921

these lie well within the bounds of Group 3. The occurrence rate u(t) is shown in Figure B.16 for Group 1-3 including the upper and lower bounds on Group 3. The negative slope in this log-log plot indicates that $\beta<1$ or that the occurrence rate decreases with time as plants mature. This decrease in fires can be due to several factors including a decrease in hazardous activities (welding, construction activities), a decrease in human traffic related to non-power production activities and improvements in fire prevention. This decrease in occurrences with plant age can be important in safety and risk evaluation.

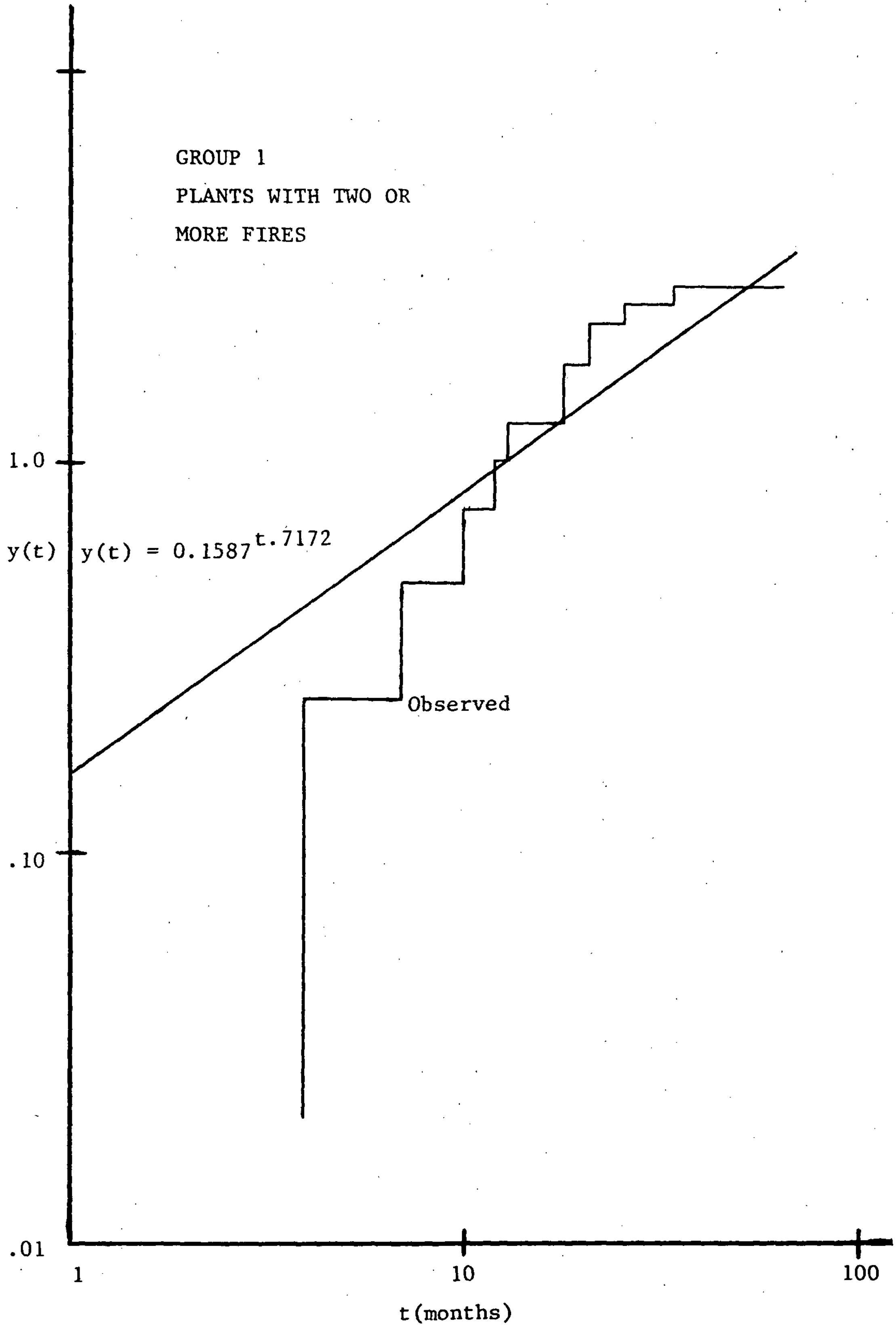


Figure B.12 Time Dependence of Group 1 Plants

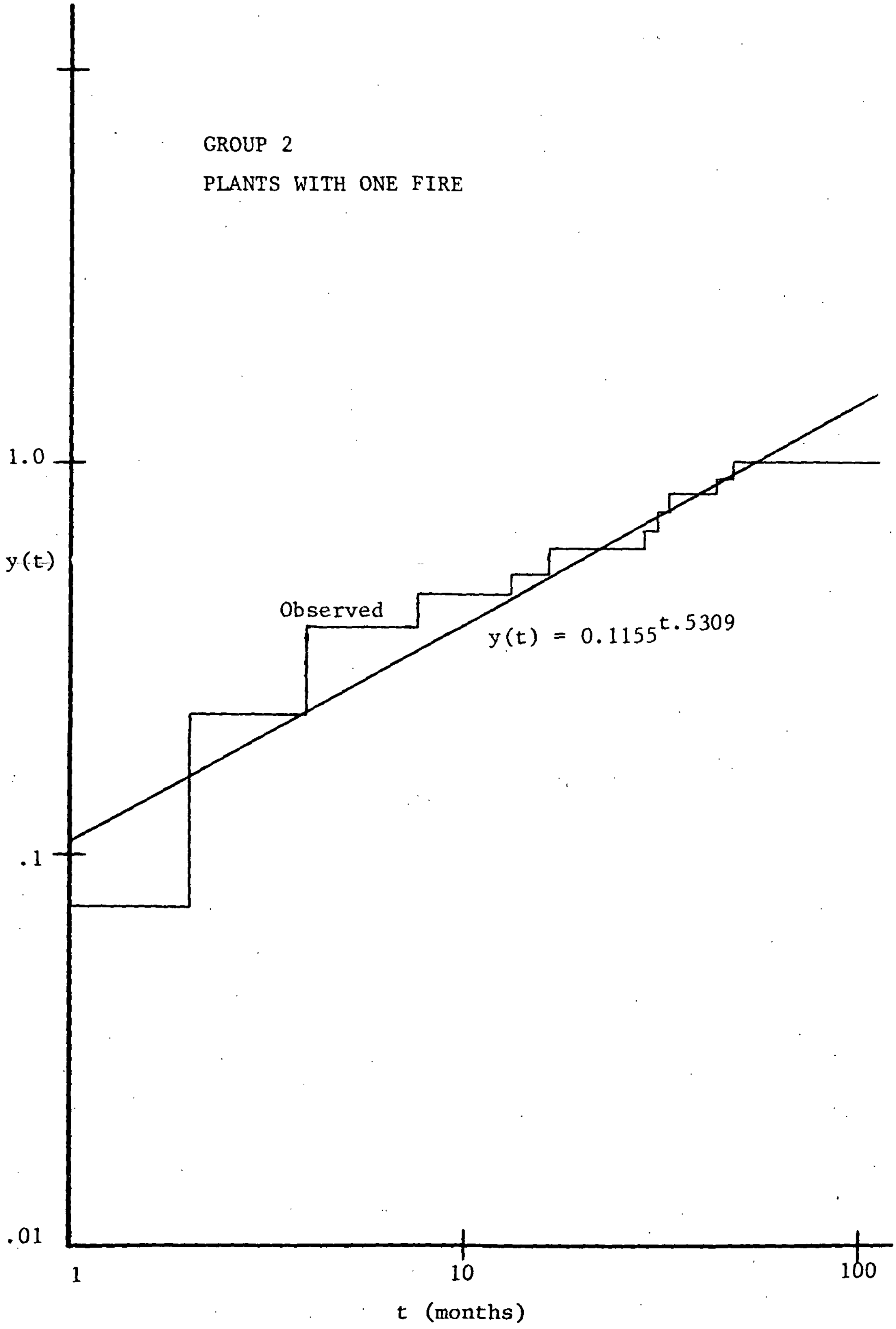


Figure B.13 Time Dependence of Group 2 Plants

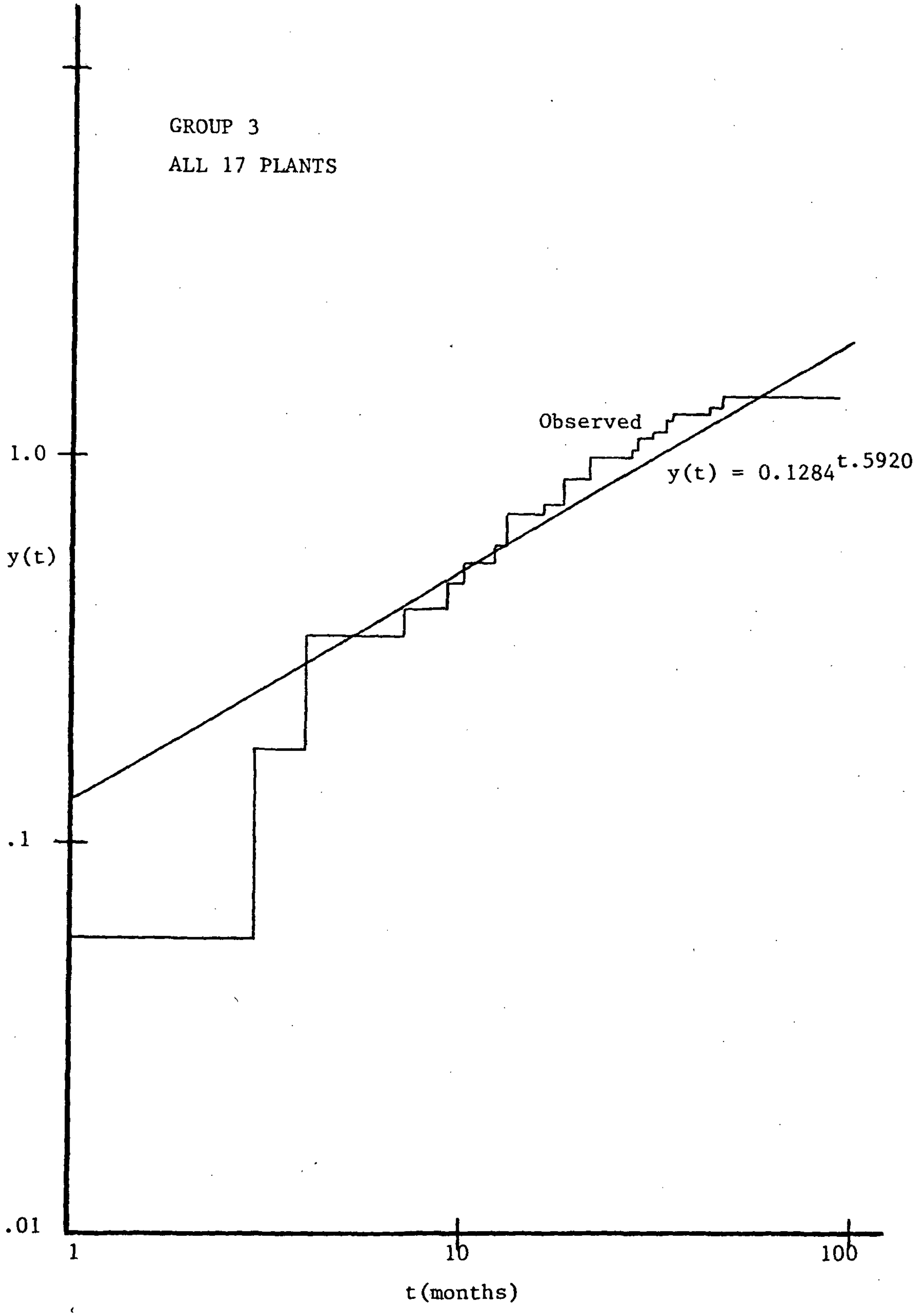


Figure B.14 Time Dependence of Group 3 Plants

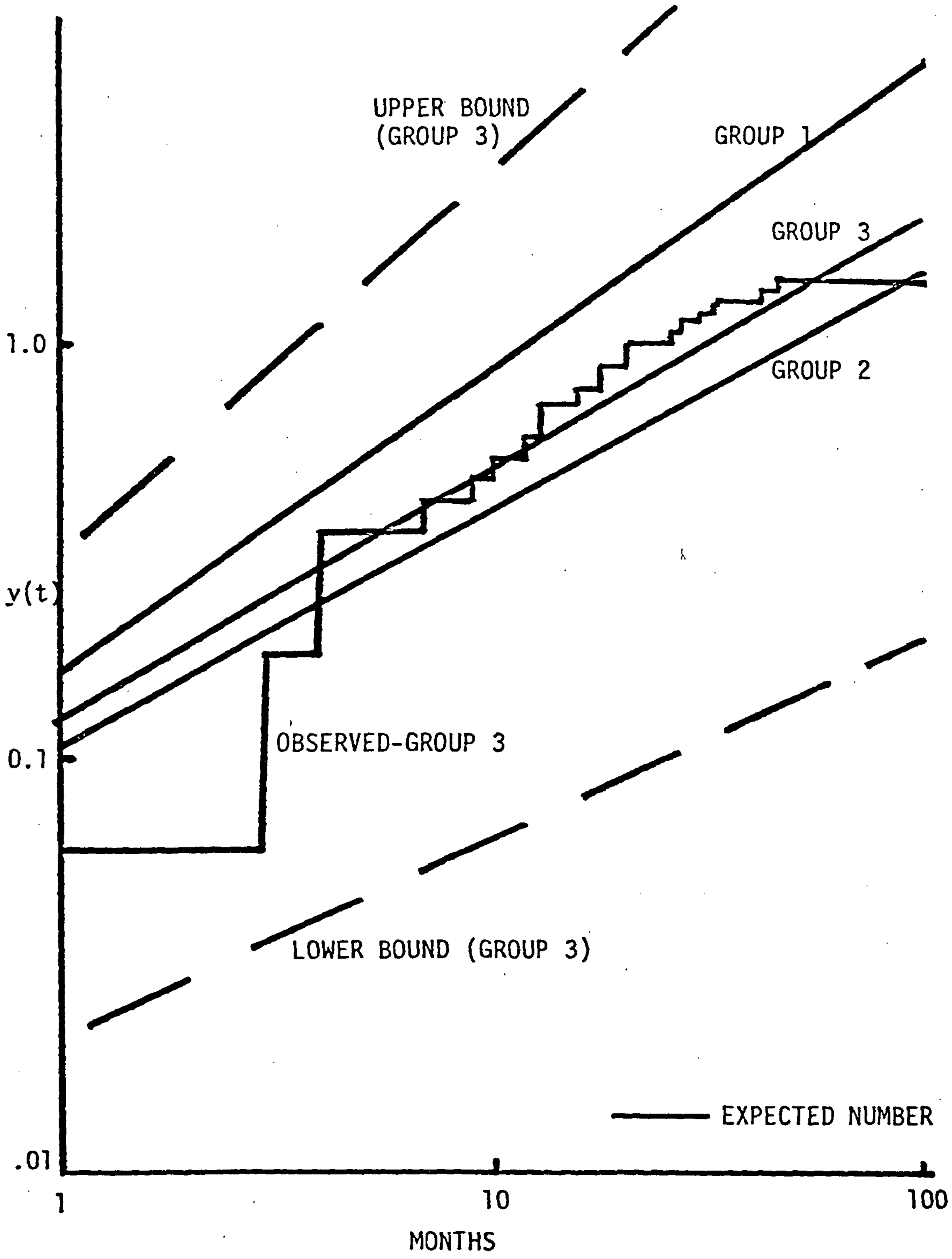


FIGURE B.15 NUMBER OF FIRES y(t) VS. TIME

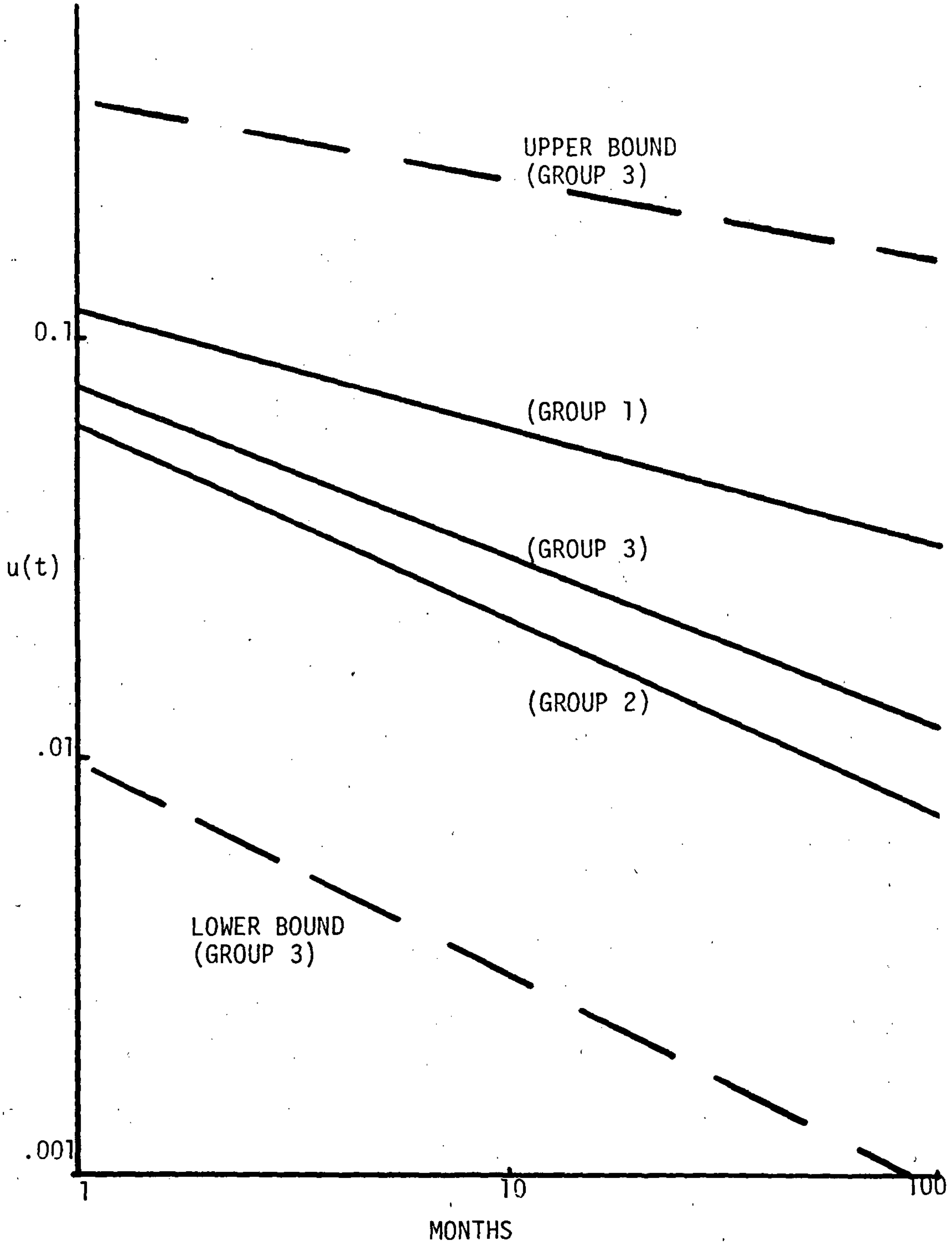


FIGURE B.16 FIRE OCCURRENCE RATE VS. TIME

B.5. Bayesian Analysis of Fire Occurrence Rates

A recent paper by Mitra(5) describes a Bayesian prediction model used to re-evaluate the available data on fire occurrences. Mitra assumes that the fire occurrences are random events in time and follow a Poisson process. With this model, the probability of observing exactly y fires over some future time t is:

$$f(y|\lambda,t) = \frac{e^{-\lambda t}(\lambda t)^y}{y!} = \text{likelihood function} \qquad \text{B.5.1}$$

From this prior, $f(y|\lambda,t)$, Mitra obtains a posterior distribution $f(\lambda|x,t_o)$:

$$f(\lambda|x,t_o) = \frac{t_o}{\Gamma(x+1)}[\lambda t_o]^x \; \exp(-\lambda t_o) \qquad \text{B.5.2}$$

With these two distributions, Mitra then obtains a Bayesian predictive density function:

$$f(y|x,t_o,t) = \int_0^\infty f(y|\lambda,t)f(\lambda|x,t_o)d\lambda \qquad \text{B.5.3}$$

$$f(y|x,t_o,t) = \frac{\Gamma(x+y+1)}{\Gamma(x+1)\Gamma(y+1)}\left(\frac{t_o}{t_o+t}\right)^{x+1}\left(1-\frac{t_o}{t_o+t}\right)^y \qquad \text{B.5.4}$$

A classical predictive density function is then obtained by substituting the posterior distribution in Equation (3) as a delta function $\delta(\lambda-\hat{\lambda})$ with $\hat{\lambda} = x/t_o$. This results in:

$$f(y|x,t_o,t) = \frac{\left(\frac{xt}{t_o}\right)^y \exp[-\frac{x}{t_o}t]}{y!} \qquad \text{B.5.6}$$

Mitra applied these relations to a population of 15 fires and obtained a predictive distribution peaking at about 4-5 fires for a plant lifetime t of 40 years for both the classical and Bayesian estimates.

We have applied these relations to our population of 24 safety related or potentially safety related fires. The results are shown in Figure B,17 where CHP refers to the classical homogeneous Poisson case and BHP denotes the Bayesian homogeneous Poisson case. Note that the peaks for both curves occur at 11 fires for a 40 year plant lifetime. However, if one uses the non-homogeneous Poisson (NHP) model which predicts y fires in time t:

$$f(y|\lambda,\beta,t) = \frac{e^{-\lambda t^{\beta}}(\lambda t^{\beta})^{y}}{y!} \qquad \text{B,5,7}$$

the peak occurs near y = 4 to 5 fires, about a factor of 2.5 below the homogeneous Poisson model predictions. As Mitra points out, the Bayesian result approaches the classical result as the number of events increases. We can thus say that a Bayesian predictive density function incorporating the non-homogeneous Poisson model would also peak at 4 fires.

In summary, the use of Bayesian techniques to compensate for a scarcity of data is indeed worthwhile. As can be seen from our fire data (and from other applications of Bayesian methods), the likelihood distribution (NHP in our case) can make a critical difference in the outcome.

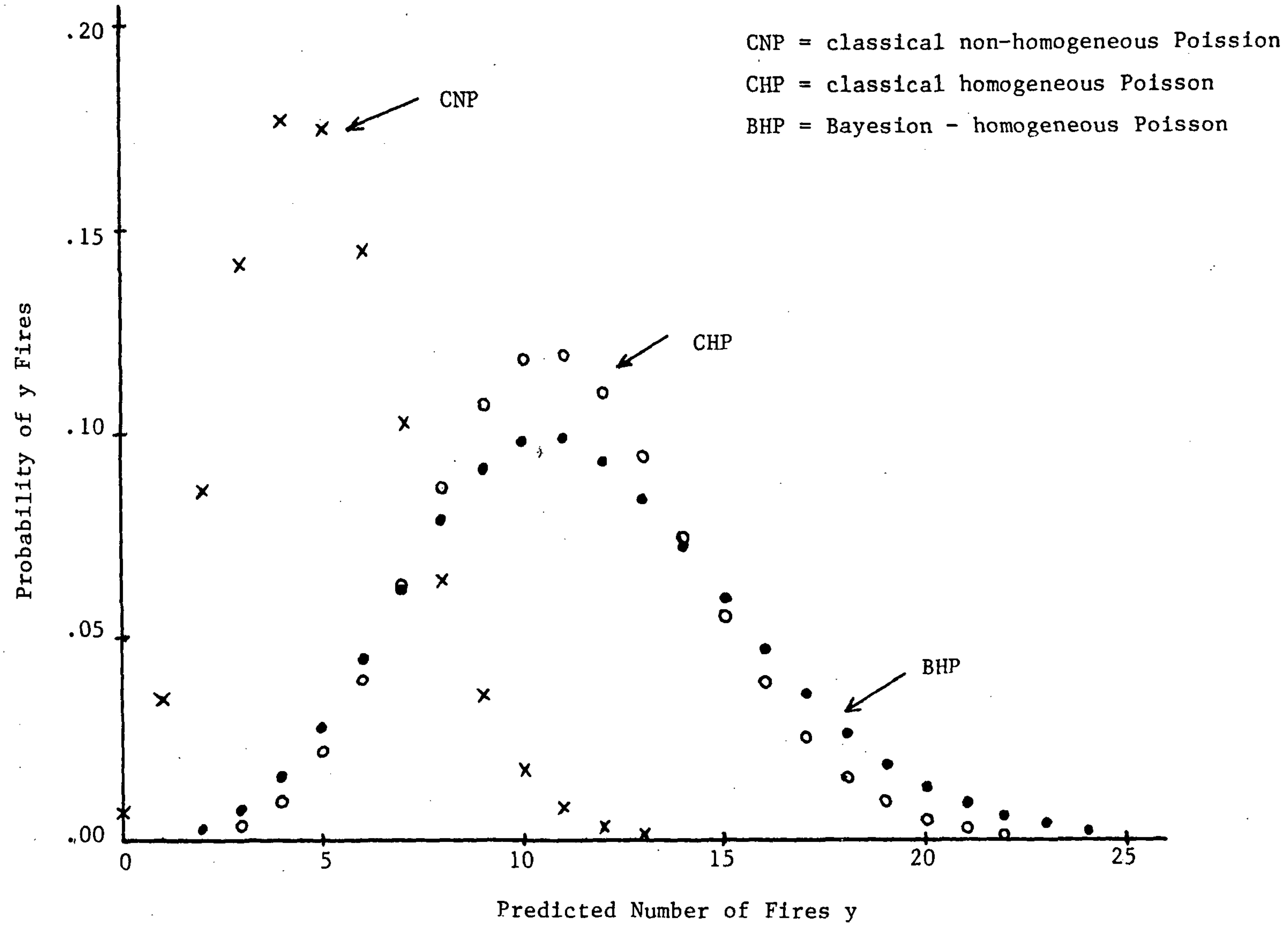


Figure B.17 Predictive Probability Distributions

B.6. Event Tree Development For Detailed Scenarios

B.6.1. General Approach

A generalized event tree for a postulated fire event is shown in Figure B.18. The branching points A - F indicate an idealized time sequence of events following the initial fire. The overall probabilities for each path are indicated on the right hand side at the end of each path. By using event trees of this general type and adapting them to suit the specific area in question, possible sequences of fires and related system failures can be mapped out.

The following comments apply with respect to making the event trees specific to a particular area in a plant:

1. Detection - would have to be expanded to include human and/or automatic detection, however appropriate to the area. One possible event tree expansion of this detection phase is shown in Figure B.19. The time sequence is drawn corresponding to the possibility of human detection occurring before automatic detection. It might also be drawn such that the first stage branches on automatic detection.
2. Safety Effect - This category includes all types of fire damage, allowing for a waste paper basket fire or a diesel generator fire. If safety components are involved, then their relation to scram and shutdown functions must be followed in a separate development.

A logic diagram and its Boolean equivalent are useful in determining the effect of the loss of any component (i.e. pump, cable, control unit). The Boolean expression is the expression for successful operation, in this case. For example, the simple system in Figure B.20.a, must supply water. The equivalent logic diagram in Figure B.20.b, can be expressed as a Boolean:

$$S = W \cdot V_1 \cdot (B_1 \cdot P_1 \cdot V_2 + B_2 \cdot P_2 \cdot V_3)V_4 \qquad \text{B.6.1}$$

where the cables have been included in the notation for electrical support

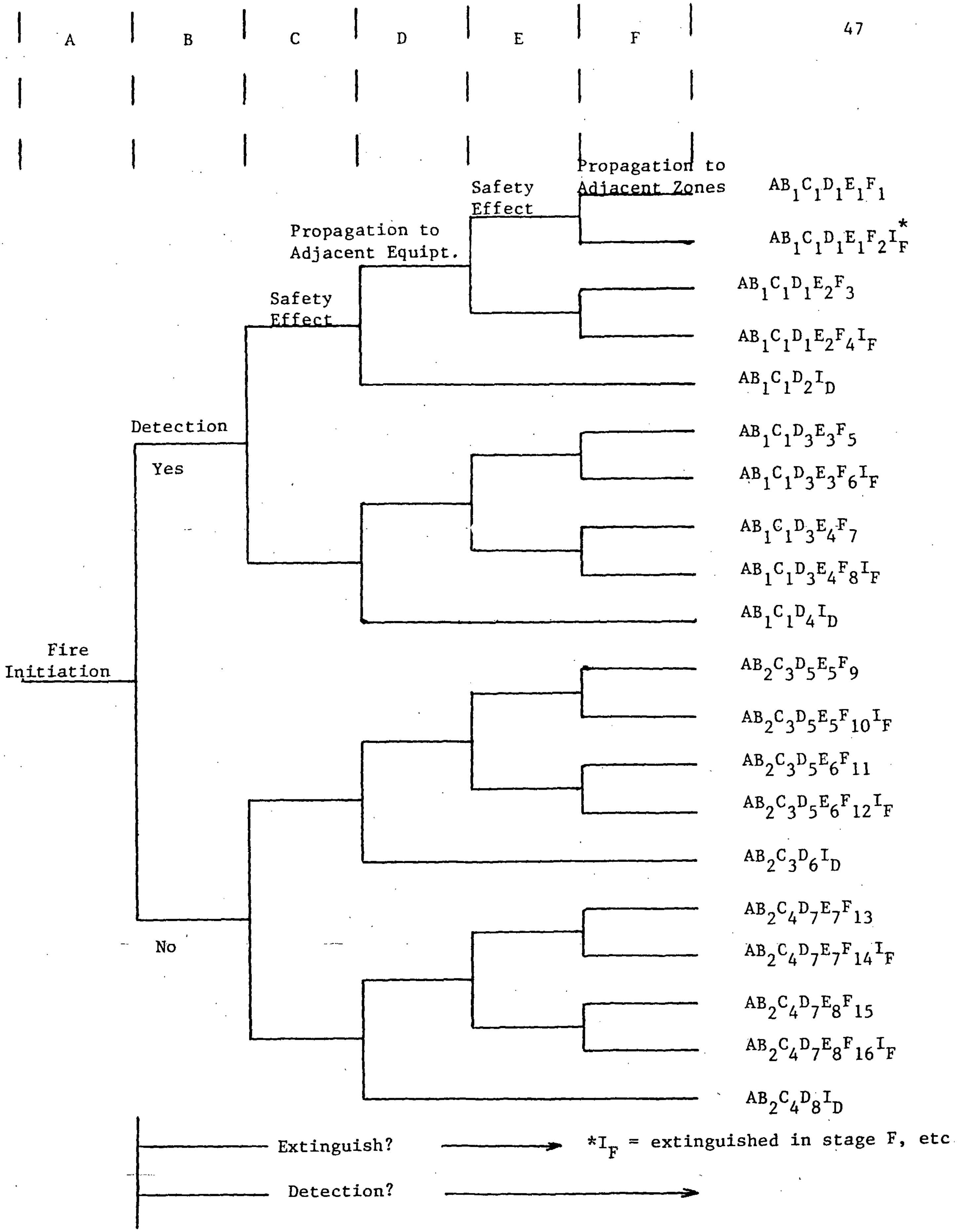


Figure B.18 Event Tree for Generalized Area

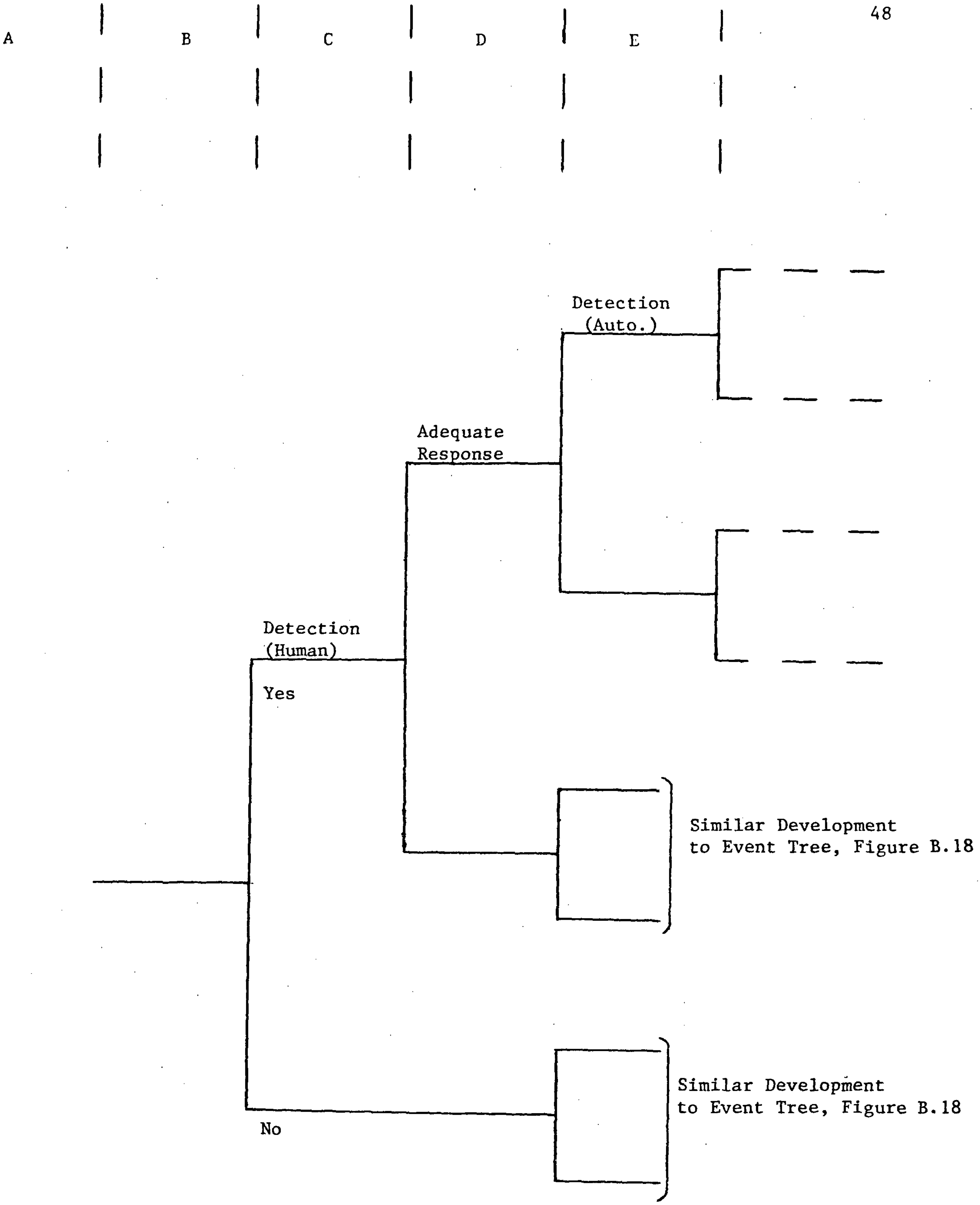


Figure B.19 Partial Event Tree for Area with Human and Automatic Response Available

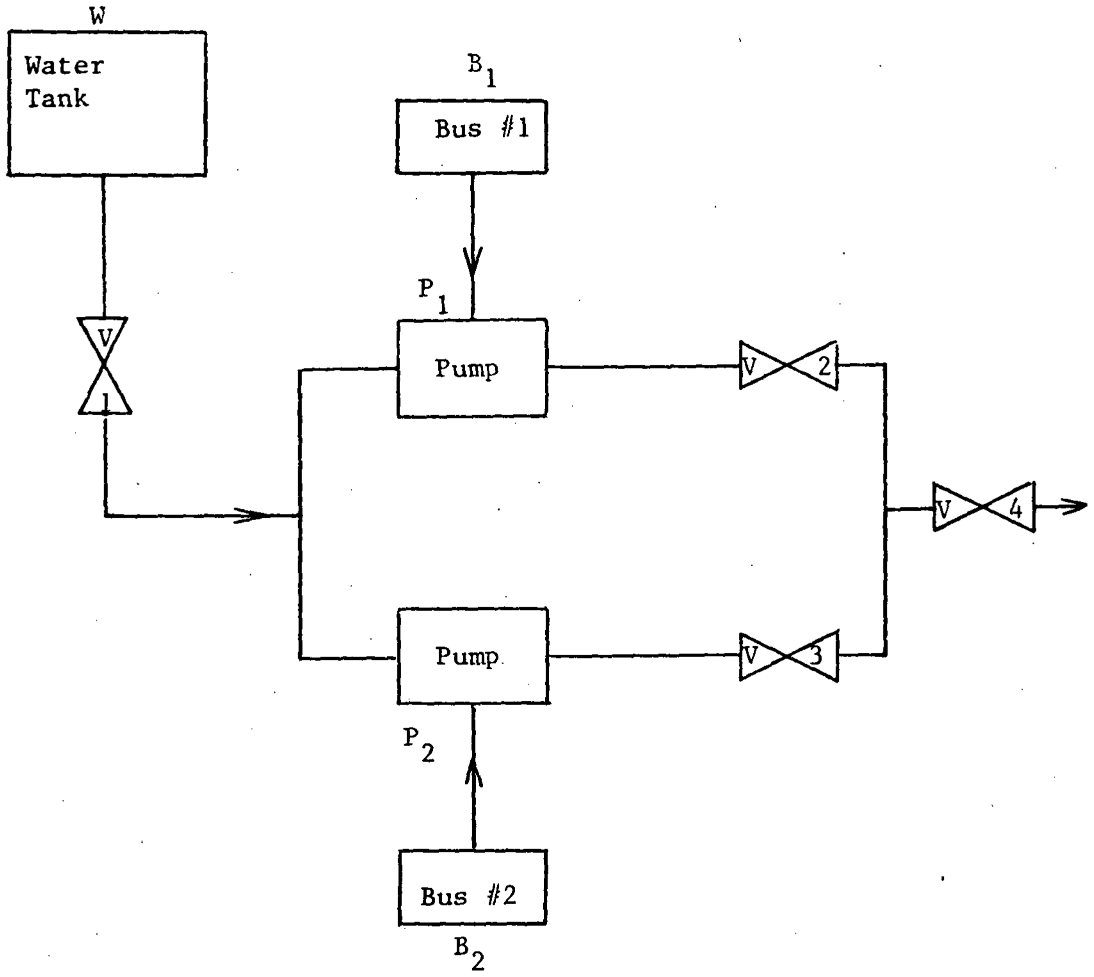


Figure B.20a – System Diagram

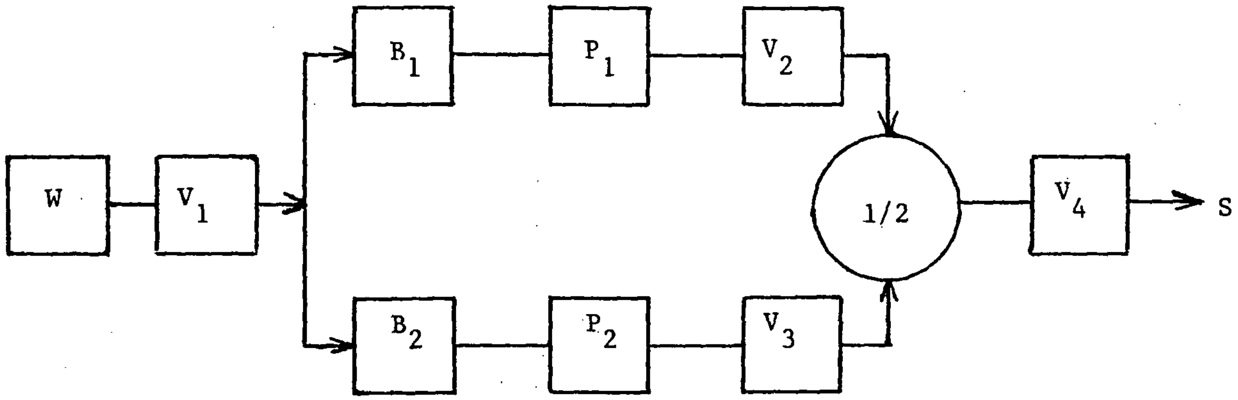


Figure B.20b – Logic Diagram

systems B_1 and B_2.

If an event tree indicates potential loss of Bus # 1 by a cable fire, for example, then B_1 is set = 0 and S becomes:

$$S_{fire} = W \cdot V_1 \cdot (0 \cdot P_1 \cdot V_2 + B_2 \cdot P_2 \cdot V_3) V_4 \qquad \text{B.6.2}$$

$$S_{fire} = W \cdot V_1 \cdot B_2 \cdot P_2 \cdot V_3 \cdot V_4 \qquad \text{B.6.3}$$

indicating that the system is still functioning.

If the event tree follows the sequence through to loss of both Bus #1 and Bus #2, with an associated small probability expected, then $B_1 = B_2 = 0$ and the Boolean statement becomes:

$$S = W \cdot V_1 (0 \cdot P_1 \cdot V_2 + 0 \cdot P_2 \cdot V_3) V_4 \qquad \text{B.6.4}$$

$$S = 0 \text{ (system failure)} \qquad \text{B.6.5}$$

The Boolean statements have been obtained for all the safety systems in this BWR plant, in the process of developing priority ranking of zones (Section B.2).

3. Propagation to Adjacent Equipment - This allows for the possibility of the fire spreading to one or more combustible items, including safety components, in the same area. This will be highly dependent on the area in question.

4. Safety Effect - This is similar to 2. above.

5. Propagation to Adjacent Zones - This will also be very dependent on the area examined and, hopefully, would have a low probability.

6. The time sequence could vary greatly, depending on the nature of the postulated fire. This variability would be due to the initial combustible, its distance to adjacent combustibles, and its distance to fire detectors. For example, stages B and C could occur simultaneously. Stages E and F might correspond to the cable fire at Browns Ferry.

7. In the case of "no detection", B_2, the fire might be self-annunciating during stages C - F (as has actually happened), causing system malfunction and an associated alarm at the reactor control panel.

8. The possibility of extinguishment at any stage A - F should be included. This probability would be time-dependent due to the initial growth of a fire, its period of maximum intensity and then a fall-off in temperature. Extinguishment at D, would end that part of the sequence. However, D_1 implies that a safety related effect has already occurred and this branch must be followed to its logical end.

The event tree approach offers a coherent means to follow scenarios. This process identifies the variables involved and the branching probabilities required in addition to the qualitative nature of the scenario under study. It is expected that the latter part will provide useful information for future designs or modifications.

B.6.2. Specific Application

As implied in the previous section, the event tree must be tailored to the specific fire zone under consideration, as was true for the application of event trees for postulated events in WASH-1400. The most efficient policy, then, is to use the priority ranking of fire zones from Section B.2 as a guide to the order of investigation.

Example - Switchgear Room

Figure B.21 shows one layout for a switchgear area. The event postulated corresponds to an actual occurrence. This fire took place in cable trays, due to an over-current and a subsequent cable insulation fire. The duration was 52 minutes; detection occurred by one operator observing erratic readings on control panel indicators and another observation of smoke from the switchgear room ventilators. Extinguishment by CO_2 and dry chemicals failed, water fog hose lines finally were successful. Figure B.22 shows an event tree for this occurrence.

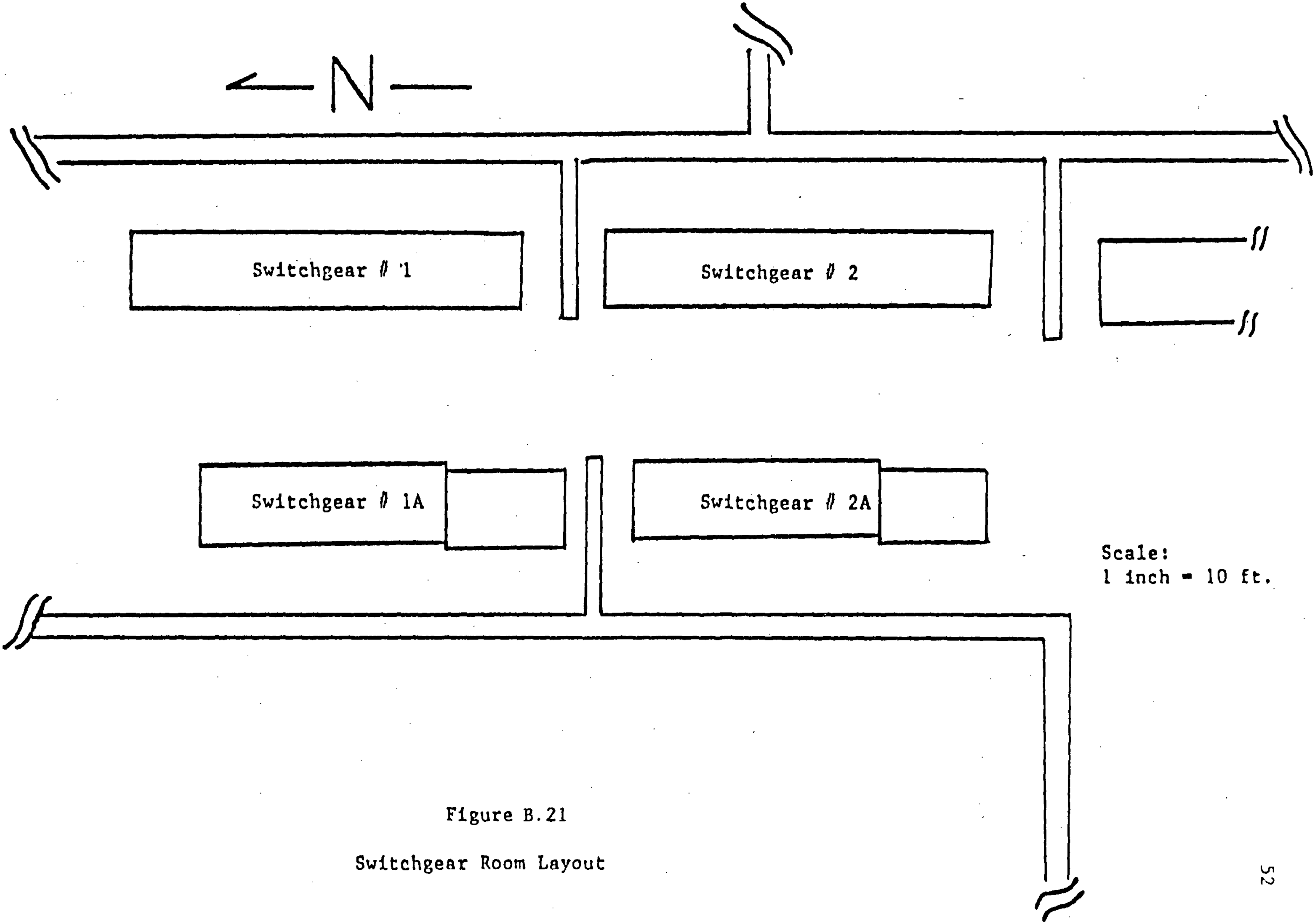


Figure B.21

Switchgear Room Layout

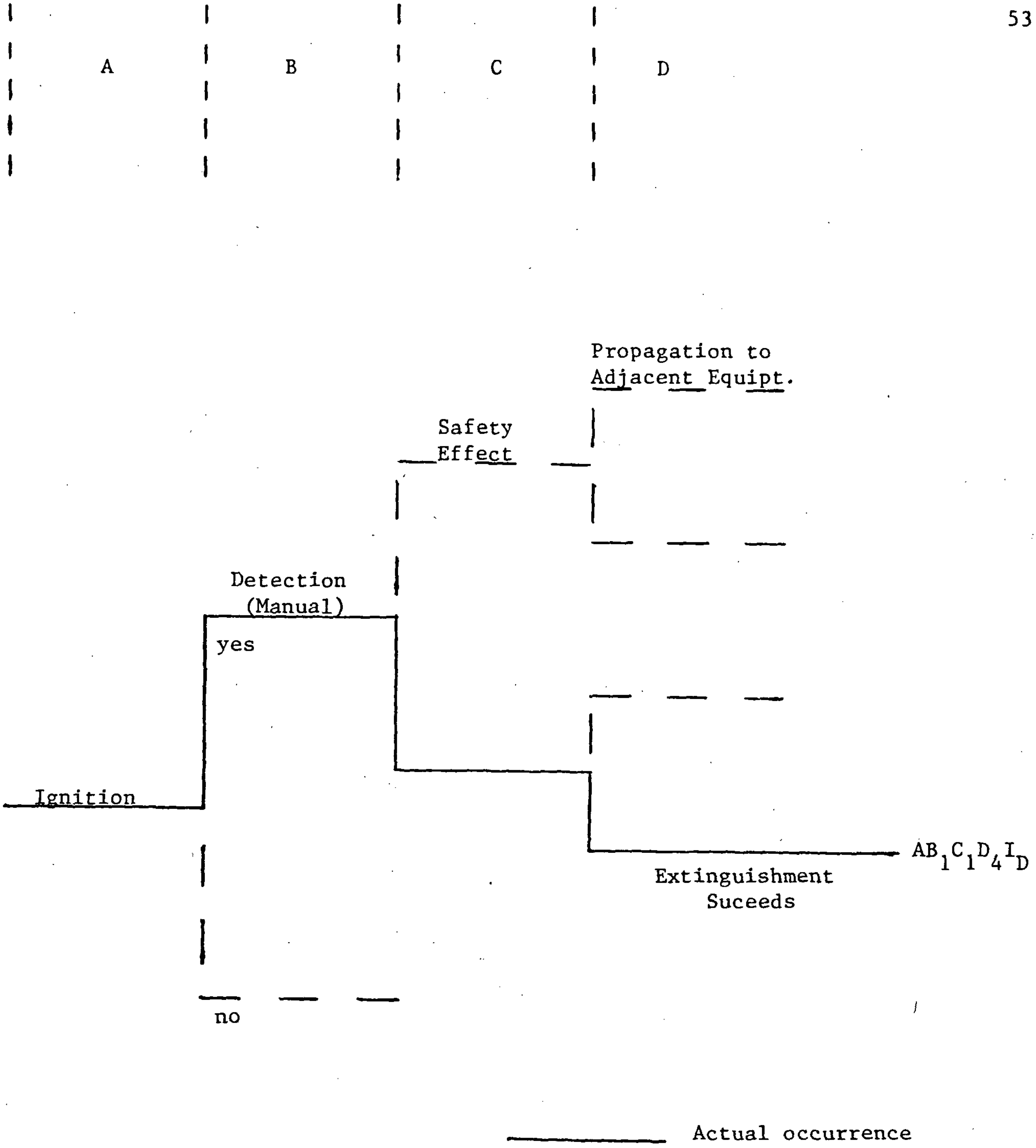


Figure B.22 Event Tree for Observed Fire in Switchgear Room

B.6.3. Overall Methodology

Figure B.23 presents the principal features of a systematic evaluation leading to estimates of loss of safety related components. The particular losses postulated must then be followed to determine their effect on safety functions such as loss of shutdown capability and loss of cooling.

The work outlined appears to be a major effort. However, by setting up an overall framework (Figure B.23), determining priorities of areas to be examined, examining scenarios in these areas by means of event trees, identifying safety-related component losses and the effect of these losses on the required safety functions, a complete problem can be reduced to a finite number of possibilities. This entire process identifies:

(1) information (probabilities) required for its numerical evaluation

(2) the priority of these needs.

(3) what kind of practical measures can be implemented at once, for example, further separation of redundant equipment, fire detector location, type of extinguishment apparatus, etc.

The methods of Pinkel(6) and Harmathy(7) appear to be useful in estimating the probability that the initial fire will (1) spread to other combustibles in the area and (2) cause high temperature-induced damage by heat transfer processes. Although these methods are approximate, it should be possible to use probabilistic methods to arrive at upper and lower bounds on the heat flux from the initial fire at various points in the room. If better methods to calculate the spatial distribution of heat fluxes and temperatures, their results can be easily incorporated into the event tree scheme.

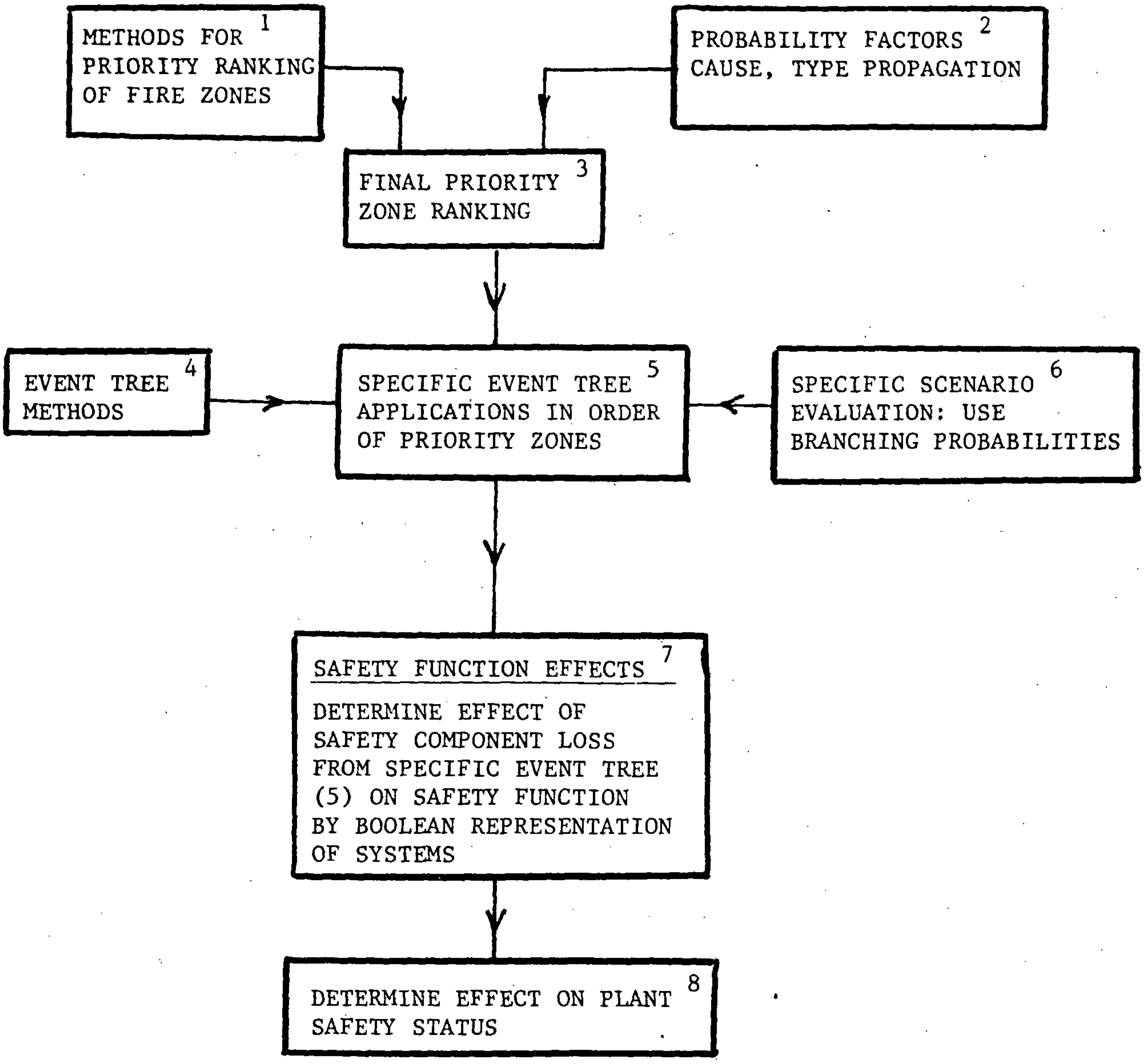


Figure B.23 Effect of Fire on Plant Safety by Priority Ranking, Probability Factors and Event Trees

C. Fire Histories and Available Data

C.1. Fire Records

Data for the fire data base were drawn primarily from insurance firms, namely: American Nuclear Insurers (ANI) main source, Nuclear Mutual Liability (NML), and the Tennessee Valley Authority (TVA) which is self-insured. Additional events were obtained from tne NRC's Licensee Event Report's (LER's) and from summaries in "Nuclear Operating Experience".

The data are stored on disc in the main computer at Rensselaer. Access to the data is provided through a computer code developed at Rensselaer in a preceding stage of this research program. The data can be tabulated with respect to varying parameters such as: facility type, mode of operation, location of fire, type of fire, and means of detection and extinguishment. In addition, narratives of varying lengths describing each incident are contained in the data bank.

Currently, the data base contains 235 events from numerous facilities, including: research and educational reactors, commercial boiling water and pressurized water reactors, (BWR's and PWR's), high-temperature gas cooled reactors (HTGR's), experimental fast breeder reactors (FBR's), enrichment facilities, and fuel fabrication plants. One hundred fifty (150) of these occurred during construction or steady-state operation in BWR's or PWR's.

C.2. Fire Data Base

The data encompass all phases of commercial operation for the power plants from construction to testing and operations, and hot, cold, and refueling shutdowns. Many types of reactors are represented including: research and educational, commercial Boiling Water Reactors (BWR's) and Pressurized Water Reactors (PWR's), as well as High Temperature Gas Cooled Reactors (HTGR's) and experimental Fast Breeder Reactors (FBR's).

One hundred eighty-two (182) of these events occurred at BWR and PWR plants. Fifty (50) of these (182) occurred while the plants were in the operation phase (BWR:25, PWR:25). The complete breakdown of events by facility type is given in Table C.1.

C.3 Data Retrieval and Updating

(2,8)

The fire data are retrieved from the fire data base by a computerized search. It is possible to tabulate the data by several parameters simultaneously to assemble the relevant incidents for a given set of parameters. Examples are searching for all operational fires in BWR's and PWR's, all construction events, all events where a safety loss occurred, etc.

Two output options are available: listing of pertinent events or sorted events. As the data base continues to expand, size and economic limitations suggest the use of a totalized run. It is necessary, therefore, to ensure that the content of the fire data is adequately identified by the output parameter.

It has been necessary in some cases to tabulate the data manually, because several parameter dependencies desired could not be tabulated automatically, e.g. relative to quality assurance activities, standards and regulations, "serious" fires, contributing and mitigating factors.

The fire data have been updated so far on two occasions: August 1978 and November 1978. All information available at that time is presently stored in the data base. While tedious, this task is imperative to maintain a current, accurate file of past fire experience in nuclear plants. No future updating is currently being considered, and an information gap is therefore developing. Some system is necessary for the continued recording of fire incidents at a central location for continued verification of judgements made based on past experiences. As the number of plants under construction and operational in the next decade increases, we expect a correlated increase in fire frequency due solely to the

TABLE C.1

FREQUENCY OF FIRE OCCURRENCE BY FACILITY TYPE

FACILITY TYPE	MODE OF OPERATION	EVENTS	% OF TOTAL
Fuel:			
Fabrication		22	9.4
Enrichment		0	0.0
Reprocessing		1	0.4
Transportation		0	0.0
Reactors:			
Research and Educational		27	11.5
Boiling Water			
	Construction	37	15.7
	Pre-Operational Testing	6	2.5
	Operational	25	10.6
	Hot Shutdown	0	0.0
	Cold Shutdown	1	0.4
	Refueling/Extended Outage	3	1.2
Pressurized Water			
	Construction	61	25.9
	Pre-Operational Testing	15	6.4
	Operational	25	10.6
	Hot Shutdown	4	1.7
	Cold Shutdown	4	1.7
	Refueling/Extended Outage	1	0.4

TABLE C.1 (CONT'D)

FACILITY TYPE	MODE OF OPERATION	EVENTS	% OF TOTAL
Heavy Water		0	0.0
High Temperature Gas	Pre-Operational Testing	2	0.8
Fast Breeder	Operational	1	0.4
	Refueling/Extended Outage	1	0.4
	Cold Shutdown	1	0.4

increase in plant population. The implication of the statistics gathered over the next few years may differ significantly from those which have been currently projected.

C.4 Future Data Requirements

As discussed above, it is necessary in the future to maintain a surveillance of existing records of fire occurrence in nuclear plant. Although the RPI-ANI fire data base is believed to be the most complete available, it has become apparent during data analyses that often an insufficient amount of information has been recorded describing a particular incident. Frequently, the primary combustible was unknown or the cause of the fire was not determined. Other reports contained vague or confusing narratives describing the activities which preceded the fire occurrence. Precise time-related data would be very useful if available in the reports to help reconstruct the accident for modelling purposes.

The following list is representative of other questions which often remain unanswered by the fire reports:

1. Where, exactly, did the fire occur?
2. Did the fire propagate through installed fire barriers?
3. Was automatic detection and extinguishment equipment available at the location of the fire?
4. If so, did it function properly, and did it extinguish or control the fire?
5. If not, why not?
6. What, exactly, were the combustibles and ignitor present (amounts, location, geometrical factors, etc.)?
7. What was the cause of the fire?
8. Were there other contributing factors to fire occurrence?
9. Were there mitigating factors to fire propagation?
10. What type of fire pretection equipment were available, and were these what were required?

11. What precautions, or considerations would have prevented the fire?

Two tables follow (Table C.2 and C.3) which list those fire parameters which are presently tabulated, and those which are desirable to tabulate in the future. While all parameters do not apply to every event, any additional information is usually helpful for thorough evaluation of the incident. The inclusion of additional parameters will necessitate the modification or replacement of the computer code presently used to search and tabulate the fire data. In this case, if an expanded, continually updated data base is desired the use of one of the current data base management systems should be considered This would be a more efficient means of up-dating and tabulating desired information.

The implementation of such a system depends on several factors including:

1. compatibility of the data base system with the inherent structure of the data
2. support of a flexible and complete search capability
3. performance (speed of operation), interactive, multiple user use
4. costs incurred from acquisition of hardward and software equipment

Since hardware costs have been decreasing recently, while software costs are rising, it is desirable to utilize simplified application programming which a data base management system provides in conjunction with hardware storage whose redundancy has been minimized.

Perhaps the most important limitation in the present data, also the most difficult to quantify, as the "reliability" with which utilities have reported fires which occurred at their facilities. This is evident by the fact that only 26 BWR and 43 PWR facilities reported fires (10 and 18 respectively, during operations). This can be compared with the most recent survey of nuclear power plants in the U.S. which gave 68 operating plants (1-LGR, 25-BWR, 42-PWR), and 90 plants in various phases of construction for a total of 160 plants operating or under construction. Thus, there are reports of fire occurrence from $\sim$45% of all plants.

TABLE C.2

FIRE PARAMETERS PRESENTLY TABULATED

Facility Type
Operation, Facility ID
Construction, Criticality, Operation, Decommissioning Dates
Mode of Operation or Construction
Insurer
Date of Incident
Time of Incident
Duration of Incident
Components Affected
Systems Affected
Safety or Potential Safety Loss
% Power Degradation
Forced Outage in Days
Direct $ Loss
Type of Fire (A,B,C,D)
Location by Building, Room
Cause of Fire
Detection Means
Extinguished By
Equipment and Agent Used
Availability of Detectors
Initiating components

Description

TABLE C.3

ADDITIONAL FIRE DESCRIPTORS NEEDED

Date pre-operational testing began

Time from fire initiation to detection

Time from fire detection to initiation of suppression

Response time of off-site fire departments

Categorical breakdown of safety system losses

Categorical breakdown of potential safety system losses

Reactor trip

Turbine trip

Forced outage in hours

Location of fire by zones in each major area

Detailed description of combustibles: primary, secondary; their locations, types and quantities.

Availability of personnel in the vicinity of the fire

Availability of personnel trained in fire protection in the vicinity

Frequency of fire watches or rotation patterns

Pattern type

Detailed cause of fire

Primary ignitor source and type

Personnel errors
  - Training history
  - Information
  - Psychological effects
  - Human effects: primary, secondary, tertiary, other

Welding/Cutting
  - Procedures
  - Combustibles

Electrical storm, Earthquake, Tornado

Spontaneous combustion

Suspicious origin

Design errors; categories

Explosions, types

Overheated material

Leaks

Availability/Reliability

TABLE C.3 Contd.

Maintenance factors
  - Calibration
  - Scheduling
  - Repair inadequate
  - Positioning of equipment
  - Procedures

Smoke and heat detectors (present, not present)

Successful (Unsuccessful)
  - Operation; type, locations, distance to fire
  - Adequacy of fire suppression
  - False actuation (notes on frequency)

Auto. extinguish equipment (Present, not present)
  - Types
  - Location
  - Distance to origin of fire
  - Successful (Unsuccessful)

Hose sizes used (and number)

Propagation barriers breached
  - Type
  - Fire rating
  - Rate of flame (fire growth)

Sequence of components affected

Sequence of systems affected

The discrepancy between reporters and non-reporters could be due to several factors, not excluding the possibility that some of the "non-reporters" may have better-than-average fire protection programs. This does not seem likely, however, when one examines the frequency of fire occurrence at "representative" plants. This is particularly true when one considers those fires whose origin appears to be in some type of "random" failure. (e.g. ruptured fuel line, electrical failures, component failures, etc.)

Often, utilities report only those fires whose occurrence demands a response to the NRC (damage to or loss of a safety system) in the form of an LER, or if a loss claim was failed with their insurers (e.g. ANI). Other events may never be recorded. Some of those events reported, which have a relatively insignificant loss (<$5000), are removed from the permanent loss file and discarded. These two factors probably represent the primary sources of error in assuming that the data compiled are representative of the population of all fires which have occurred in nuclear power plants. This is an important consideration, as many fire scenarios which resulted in a small financial or material loss might have led, under different circumstances, to a much more severe result.

The last problem which should be handled better in future data management is that of transcription of information. In certain instances, with present data, a person with considerable fire fighting experience made various estimates based on prior knowledge, particularly with regard to the duration of fires. This was not always the case but occurred enough to influence the data significantly. This was determined by comparing the original loss reports against the transcription prepared for RPI. Another source of error common to any tabulation of data is personal errors in keypunching, interpretation, reading, etc.

D. Analysis of Fire Data

D.1 Qualitative Parameter Identification

Past experience of fires in nuclear power plants is available primarily from the loss files of American Nuclear Insurers. Preliminary scoping studies were conducted on several parameters of interest including: combustibles and ignitor present, location, and cause of fire. Further tabulations were performed on safety system degradation (or loss), detection means, and extinguishing agent and personnel.

Most of the data were validated by comparing the computerized events with the original fire reports. As noted above certain errors in transcribing the data were found to exist, notably, where personal judgement had been used to supplement the limited reported information. This occurred frequently for the fire durations which were given. Another important parameter which was often unavailable was the response time of employees and off-site fire departments.

The most important parameters evaluated were combustibles and location frequencies as well as contributing causes and mitigating factors such as the operation (or failure to operate) of automatic fire protection systems. Factors related to quality assurance activities were also analyzed (see Progress Report May 9, 1978 - July 28, 1978).(1)

These preliminary tabulations enabled the determinations of prominent factors which influence fire occurrence in nuclear plants These factors were then analyzed in greated detail, with the resulting observations contained in the sections which follow.

Evaluation of the "component" probabilities (probability factors) is necessary to extimate the overall probability of some event occurring. The overall probabilities are useful to determine the fire potential for various scenarios and the resulting effect on the safe operation of the nuclear power plant. Areas of general weakness in a fire protection sense, and deficient procedures and regulations are also evident from the probabilities determined.

D.2 Frequency Distributions

The first step in the process of determing probability factors was to tabulate the fire data by several different parameters including: primary combustible, ignitor, location, cause, extinguisher/agent, and means of detection. It became evident that the tabulations would have to be differentiated between the modes of operation of the power plant; construction, operation, testing, cold and hot shutdown, and refueling or extended outage, as the influence of the various parameters varied greatly amongst phases. Similarly, many aspects of the different plant types (BWR,PWR,HTGT,FBR) would influence the tabulation of parameters on a relative scale. The BWR and PWR facilities are similar enough that their data may be lumped together. It is these data that have been emphasized.

Once the data were tabulated, the compiled information was in the form of frequency histograms. These histograms are presented for all phases of operation of BWR's and PWR's.

D.2.1 Construction Phase

The relative magnitudes of occurrence of various primary combustibles during this phase are presented in Figure D.2.1. A primary combustible is defined as that material which is first ignited. The most frequent combustible in construction fires is wood. This category includes not only lumber and assorted construction supplies, but also trailers and frame buildings. The occurrence of wood is twice as frequent as the next largest, insulation. Insulation is often present on exhaust manifolds, around hot pipes, etc. The third largest frequency is for solvents. Used in cleaning, painting, and sundry other operations, their presence is manifest.

These three combustibles: wood, insulation, and solvents account for over 50% of the materials involved in fires during the construction phase of nuclear power plants.

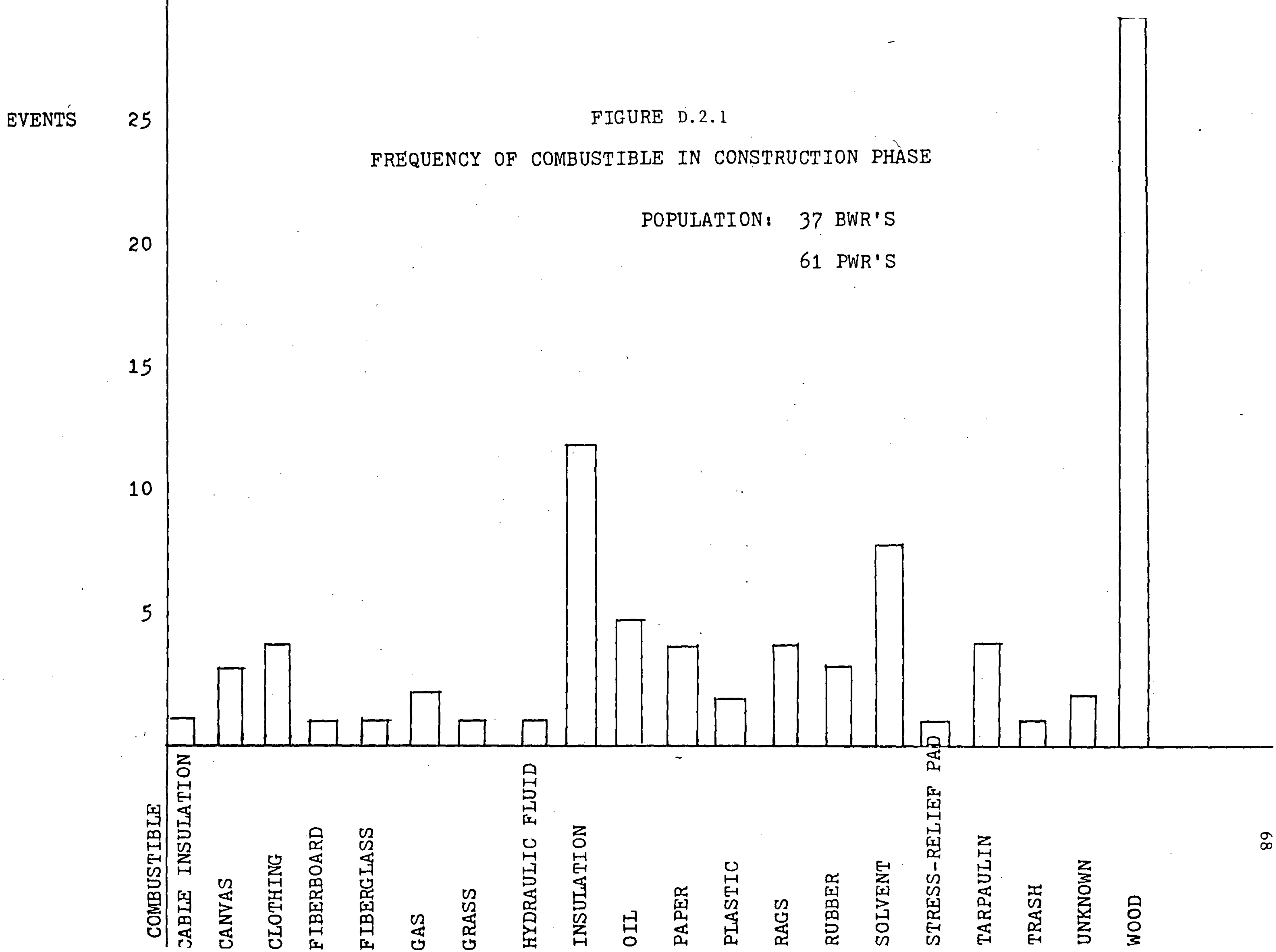


FIGURE D.2.1

FREQUENCY OF COMBUSTIBLE IN CONSTRUCTION PHASE

POPULATION: 37 BWR'S
61 PWR'S

The frequency of various ignitors during construction is illustrated in Figure D.2.2. Two groups are significant:

1. welding and cutting sparks and slag, and electric arcs and shorts
2. electric space heaters and hot surfaces

The predominant ignitor in the construction phase is welding sparks, followed closely by electric shorts of various types. These two ignitors account for over 50% of fires occurring this phase. The second group depicts the significant influence of electric space heaters and hot surfaces (pipes, stacks, lamps, etc.). Together, these two groups represent 75% of the ignitors in the construction phase. An important factor to note is the number of unknown ignitors; that is, when the ignitor could not be determined. This was the case for 10% of the fires reported during the construction phase.

Since the physical characteristics of the plant site are under constant change during construction, it would seem difficult to pinpoint locations of importance with respect to fire occurrence. However, as can be seen from Figure D.2.3, there is a predominant location of fire during construction and it is not specifically in the area of the reactor or auxiliary buildings. Fire occurs four times as frequently in temporary buildings (construction sheds, pipe, welding and electrical shops, and trailers) as in any other location on the site. About 40% of the fires occur in these structures. There are three other main areas, namely: containment, reactor building, and construction yard. These three areas represent about 30% of the fire locations. Together with temporary facilities, they represent 75% of the fire locations for this phase.

Many causes exist for the occurrence of fire. Figure D.2.4 displays those which have influenced fire occurrence during the construction phase. Often, a combination of two or more causes is responsible for the occurrence. All causes present in each event were recorded, so the sum of cause frequencies does not equal the total event population.

FIGURE D.2.2

FREQUENCY OF IGNITOR IN CONSTRUCTION PHASE

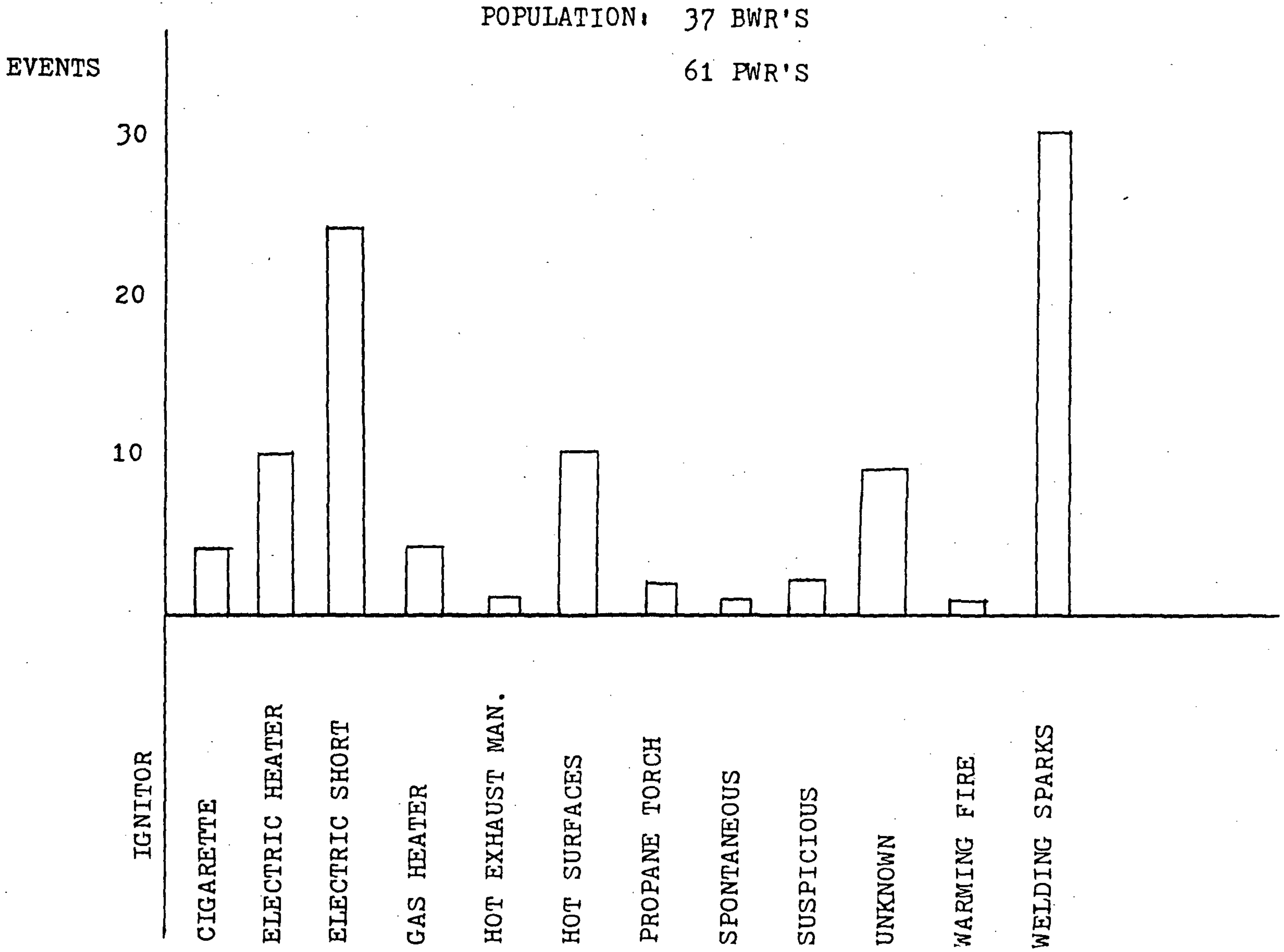


FIGURE D.2.3

FREQUENCY OF LOCATION FOR CONSTRUCTION PHASE

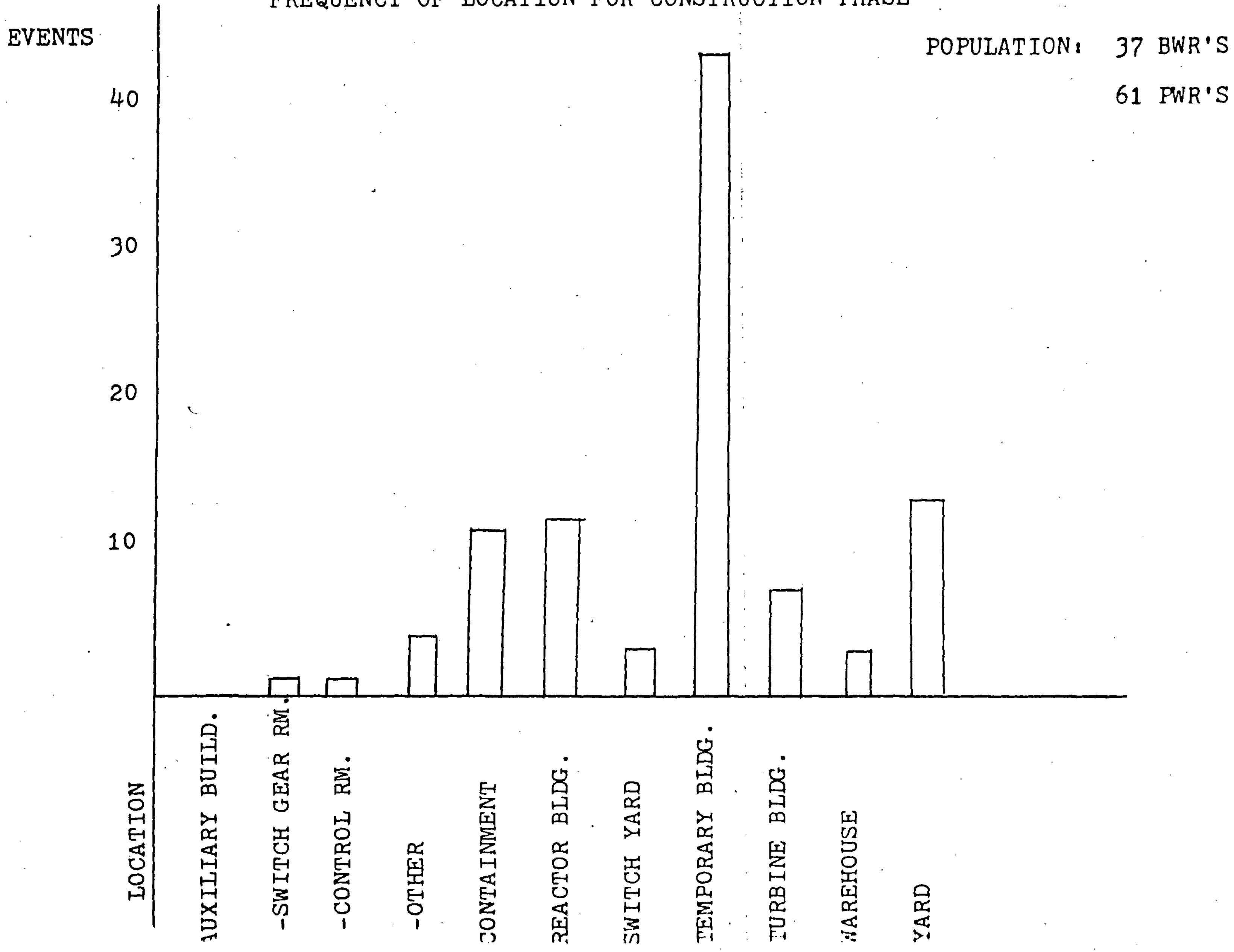
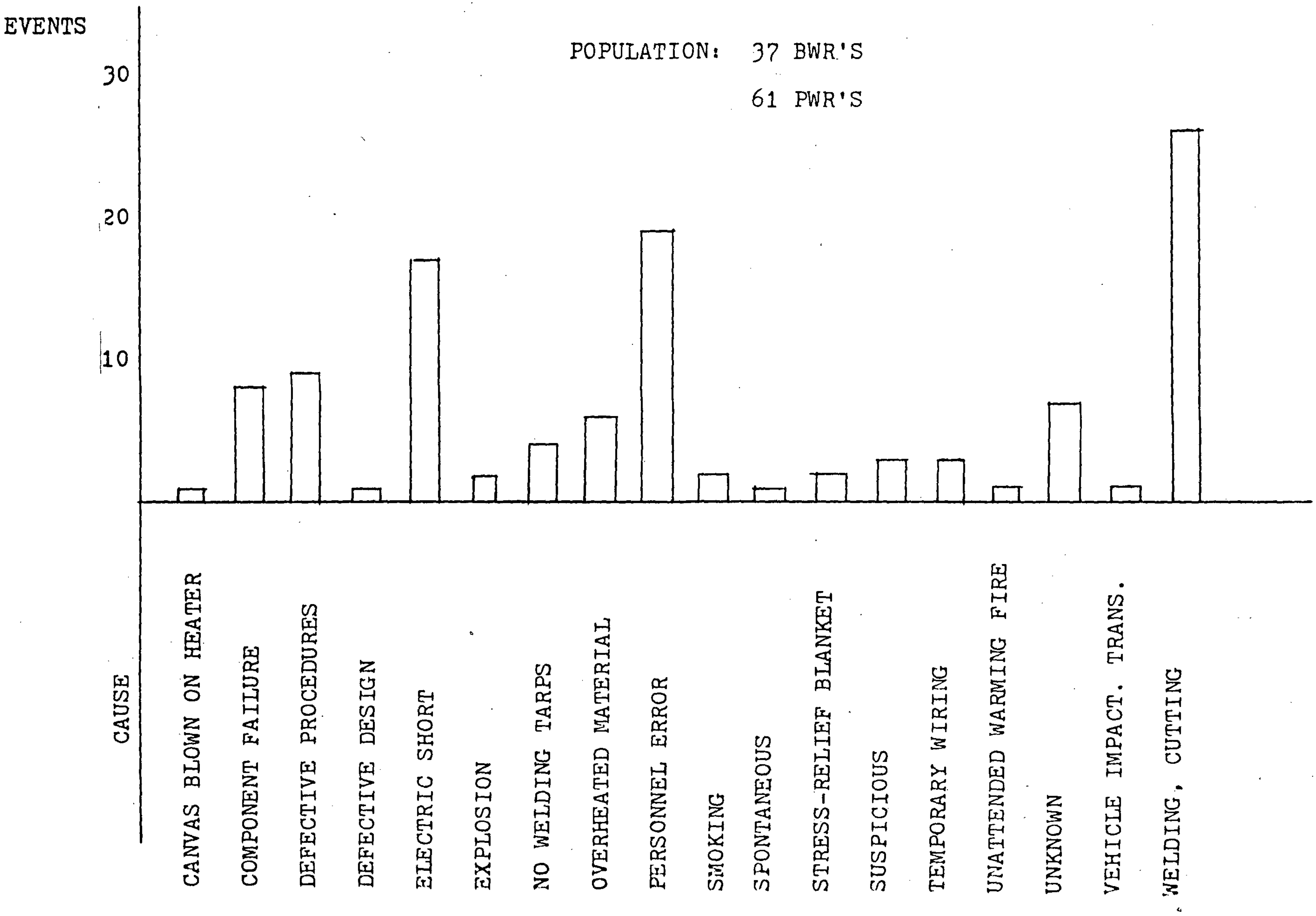


FIGURE D.2.4

FREQUENCY OF CAUSE FOR CONSTRUCTION PHASE


POPULATION: 37 BWR'S
61 PWR'S

The single greatest cause of fire was welding and cutting operations, followed closely by personnel errors and electrical failures of various types. These three causes accounted for 60% of all fires. A second group of significant causes includes: defective procedures and component failure. They contribute 15% of the causes and the two groups combined represent more than 75% of the causes of fire in this phase.

The extinguishment of fires during this phase was most often accomplished by either the local (off-site) fire department, or construction workers. They were twice as frequent as any other means and represented 65% of the events. Plant personnel and the plant fire brigade accounted for an additional 25%. These frequencies are illustrated in Figure D.2.5. This histogram contains the relative means of extinguishment/agent and detection. Again, there are frequently more than one means of extinguishing and agent used. The agent most frequently used was the outside hose (55%). Hand dry chemical, carbon dioxide, and water extinguishers were the next most frequent, each used 15% of the time. The principle means of detection during this phase was the construction worker (45%) with security guards (30%) and plant personnel (15%) following.

There exist many factors which contribute to the occurrence of fire Table D.2.1 presents a list of those factors which have appeared in the incidents examined during the construction phase.

A substantially shorter list can be compiled of those factors which mitigated the growth and spread of fire:

- fire was confined by a hand extinguisher
- fusible plastic blow-out plugs on gas cylinders released preventing an explosion
- fire of flash type and short duration
- electric fire pump ran automatically
- automatic CO_2 system dumped, smoke-heat detectors function

FIGURE D.2.5

FREQUENCY OF EXTINGUISHER, AGENT, AND DETECTION FOR CONSTRUCTION PHASE

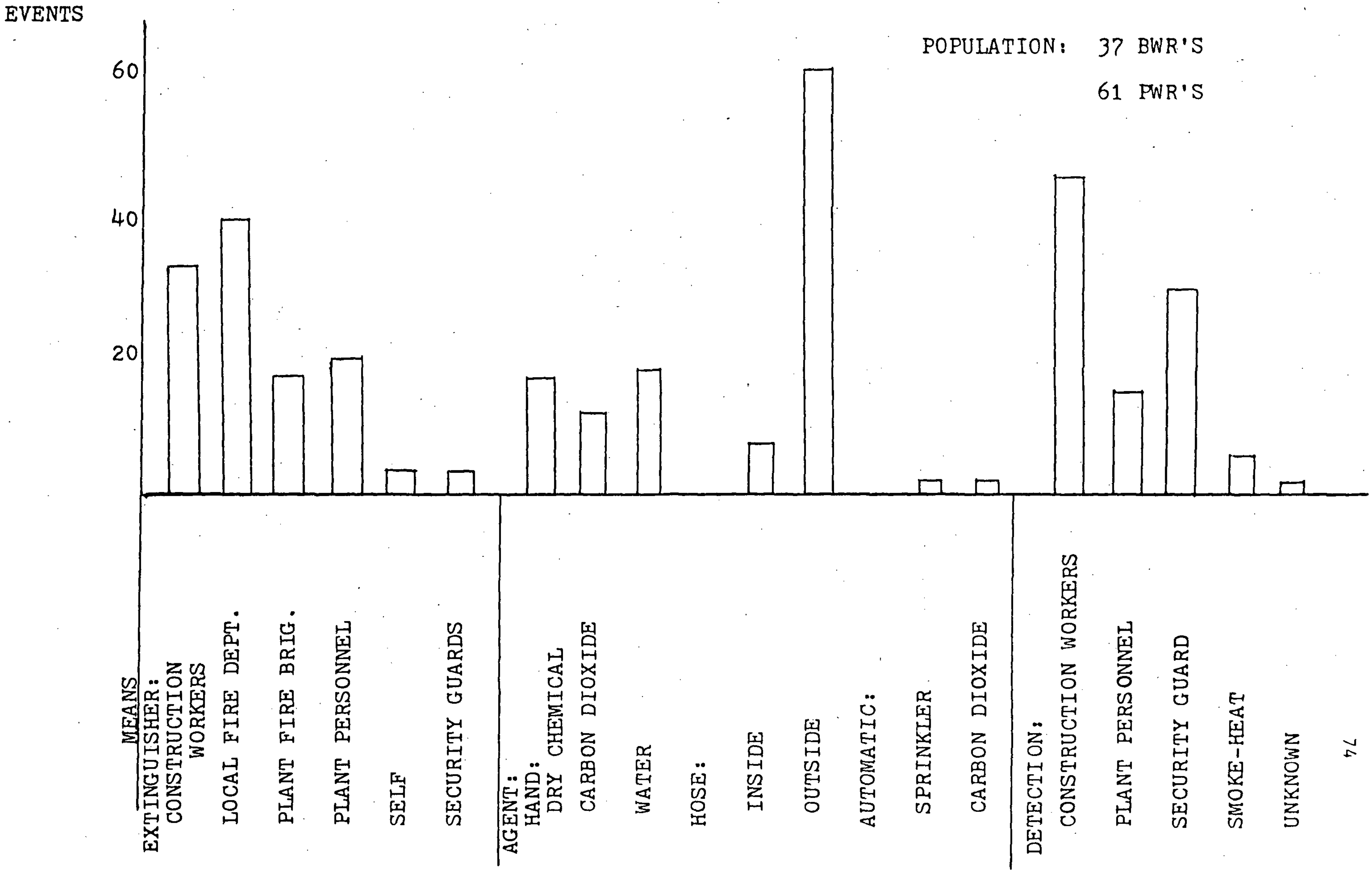


TABLE D.2.1

CONTRIBUTING FACTORS TO FIRE OCCURRENCE DURING CONSTRUCTION PHASE OF COMMERCIAL NUCLEAR PLANTS

- electrical malfunction cleared one of three fuses
- two trailers were positioned close together
- sparks and molten steel burned through a tarpaulin protecting flammable adhesive
- no welding permit system in use
- welding tarps not frequently used, though available
- no sprinkler head in the area fused
- portable heater left turned on
- delay in discovery of fire
- welding above an unprotected cable tray
- overheating of an expansion joint due to welding
- stress-relief operations
- lack of water
- inadequate watchman service
- combustible protective covering
- welding above unprotected flammable adhesive
- Parker Roller bumped into a transformer causing explosion
- temporary wiring
- wood decking and insulation laid on hot steam pipes
- poor maintenance of heater filters
- welding and cutting conducted contrary to standing orders requiring clearance of the area
- difficulty in getting off-site to respond
- fire retardant tarps rigged to protect workers against the weather
- plastic sheeting covered recently installed electrical equipment
- insufficient air circulation to motor windings
- motor failed to trip on receipt of high vibration alarm
- hand extinguisher ineffective
- alarm sounded, but couldn't be heard at the main gate
- off-site assistance did not arrive in time to extinguish blaze

D.2.2 Pre-Operational Testing Phase

The frequency of occurrence of combustibles in the pre-operational testing phase is shown in Figure D.2.6. The dominant combustible is oil, four times as prominent as the next largest. The remainder of the combustible types are relatively evenly distributed. Of special note is the fact that these oil fires have increased in magnitude by a factor of 10 from the construction phase (5% - 50%). The reverse trend is apparent for wood combustibles which have decreased in relative frequency by a factor of six (30% - 5%). The frequency of insulation fires, although decreased in the absolute sense, has remained roughly constant on a percentage basis (10%).

Ignition frequency during this phase is characterized by the Figure D.2.7. Although relatively few events have occurred in this phase, the principle ignitors are hot surfaces and welding sparks (45% and 25%, respectively). A considerable increase in frequency for hot surfaces from 10% to 45% should be noted. The frequency of welding sparks has decreased slightly from 30% to 25%. Similarly, the frequency of electrical short has decreased from 25% to 15%, possibly due to less temporary wiring or electrical equipment being present at the site.

The location of fire for the pre-operational testing phase falls roughly into two groups depicted in Figure D.2.8: reactor building and turbine building, and auxiliary building and containment They represent 50% and 33%, respectively, of the locations of fires which occurred during this phase. These same locations (grouped) represented 20% and 15% of the fire locations for the construction phase. It seems the likelihood for fire in these locations has doubled from the construction to testing phase. Correlated with the end of construction is the lack of any fires in temporary buildings which were the main location for fire during the construction phase.

Figure D.2.9 presents the causes which resulted in fire during the testing phase. The prime factor is component failure composing 15% of the total number of causes. This might be anticipated due to the testing of various equipment

FIGURE D.2.6

FREQUENCY OF COMBUSTIBLE IN PRE-OPERATIONAL TESTING PHASE

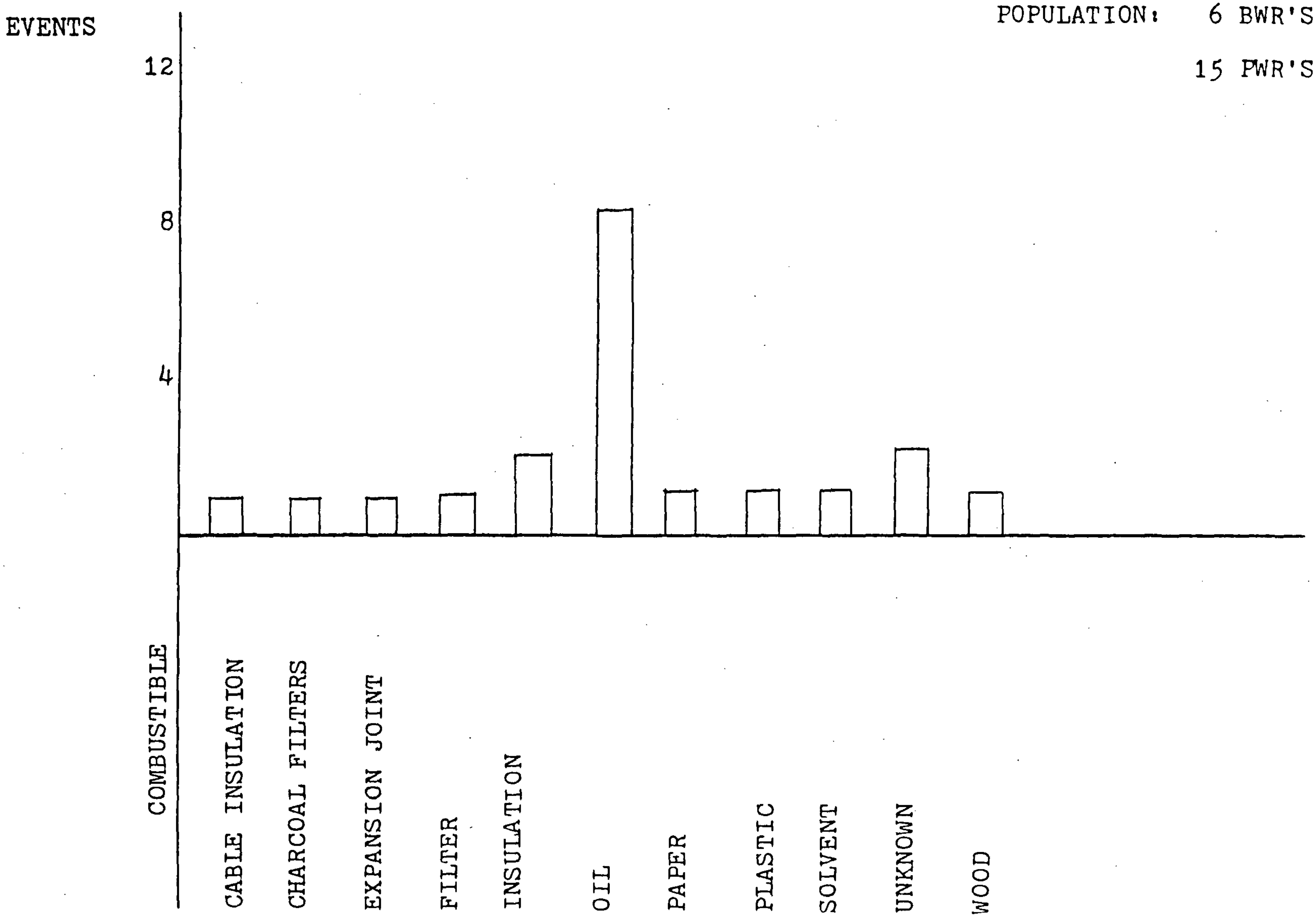


FIGURE D.2.7

FREQUENCY OF IGNITOR IN PRE-OPERATIONAL TESTING PHASE

POPULATON: 6 BWR'S
15 PWR'S

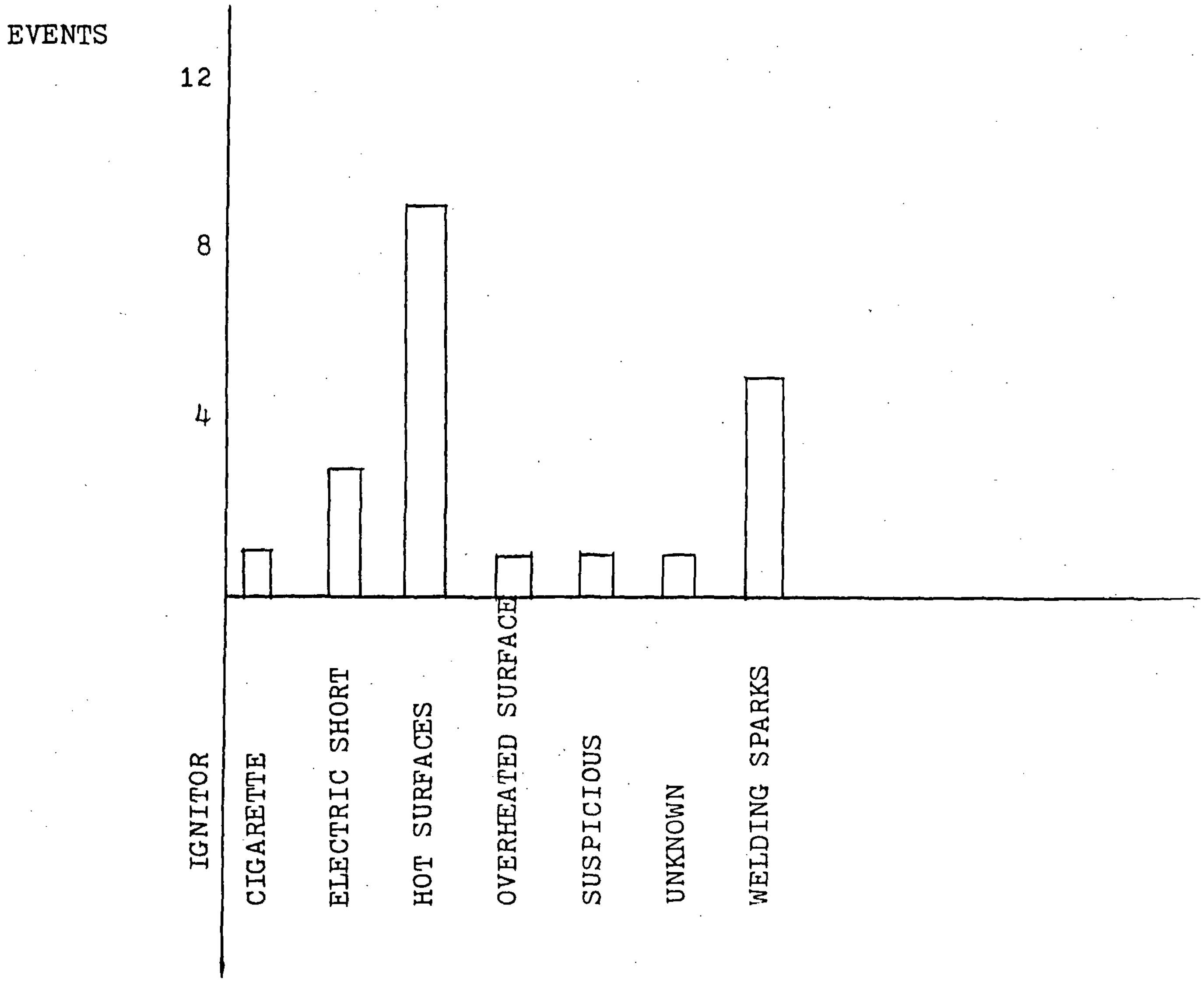


FIGURE D.2.8

FREQUENCY OF LOCATION IN PRE-OPERATIONAL TESTING PHASE

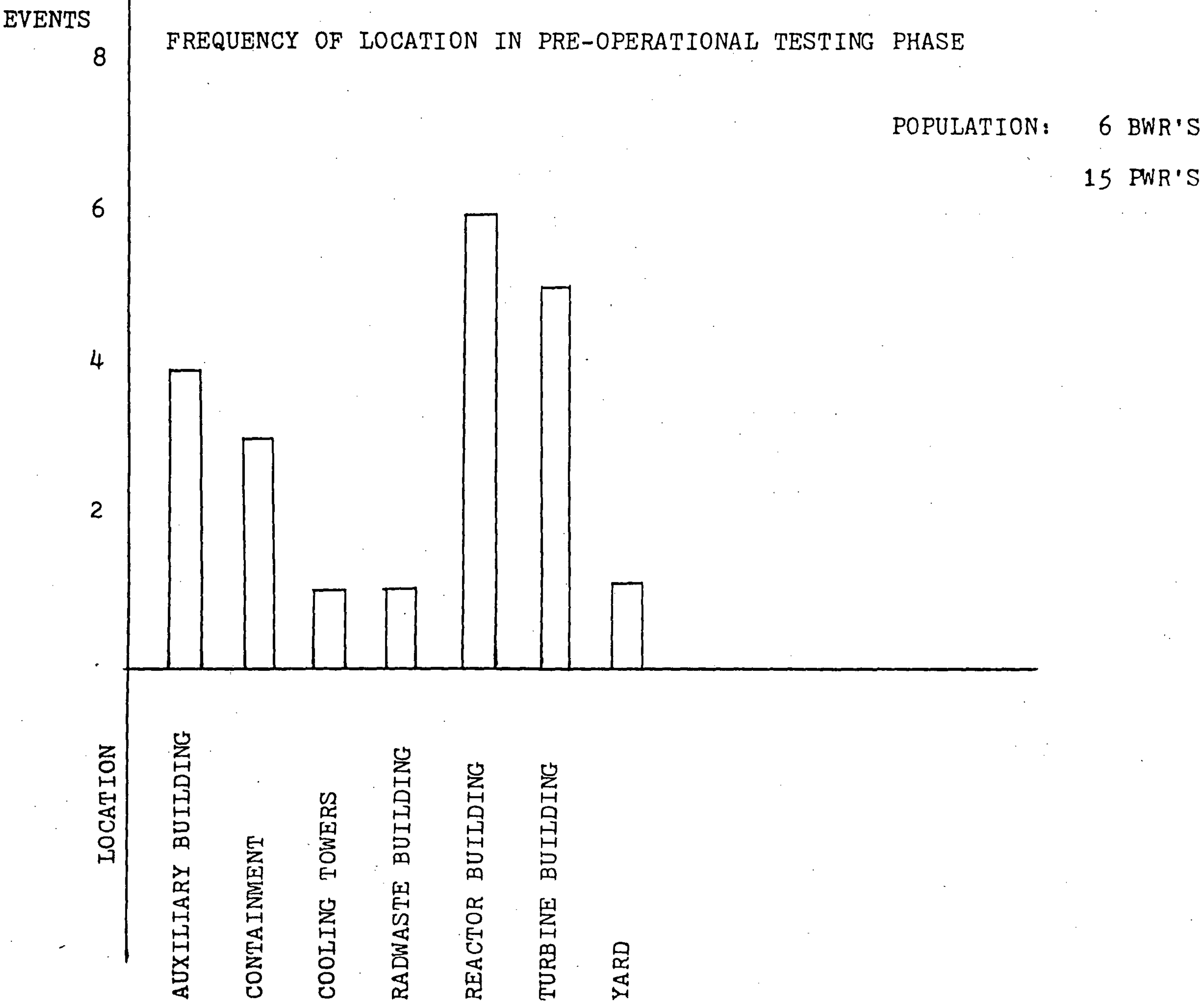


FIGURE D.2.9

FREQUENCY OF CAUSE IN PRE-OPERATIONAL TESTING PHASE

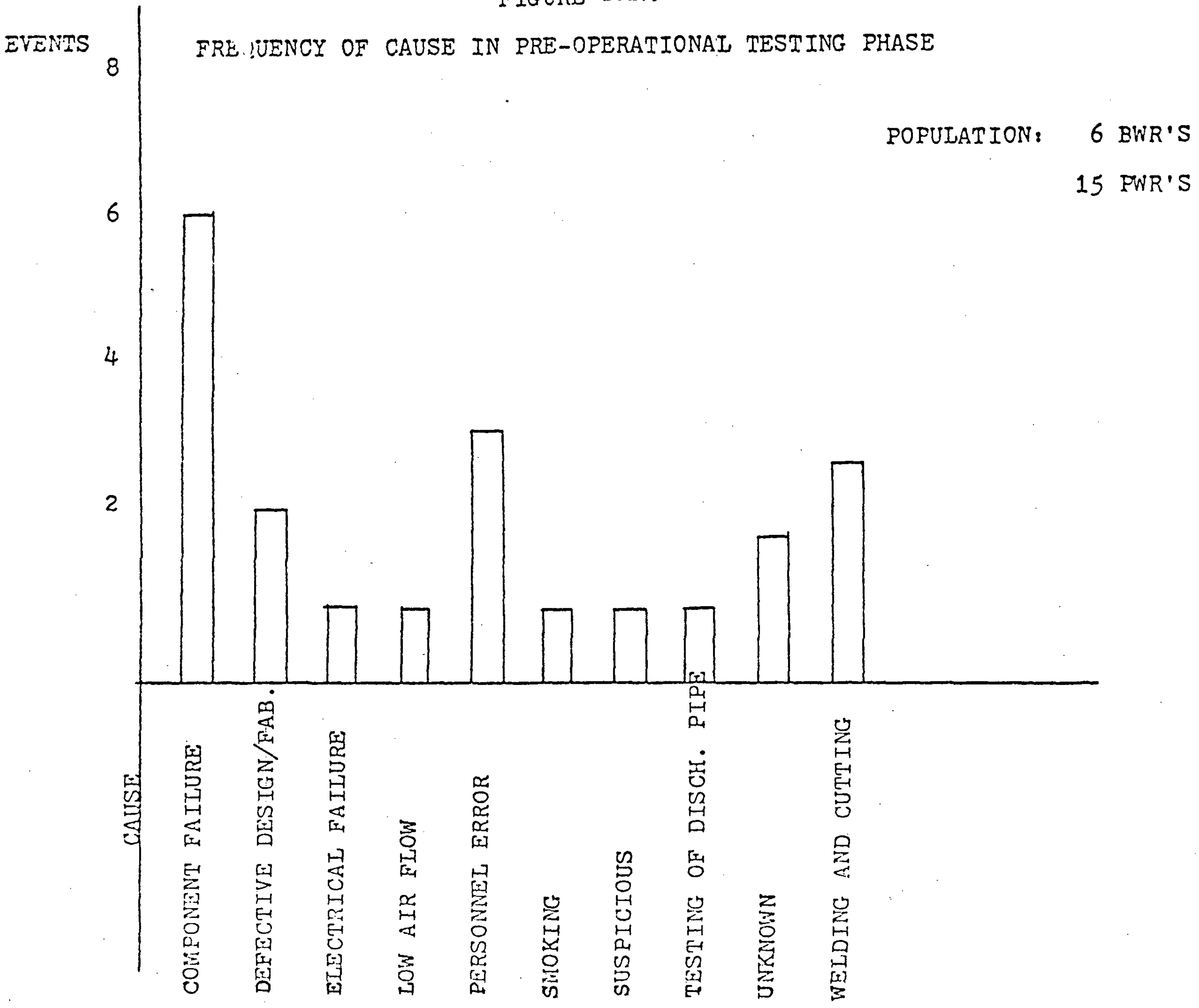
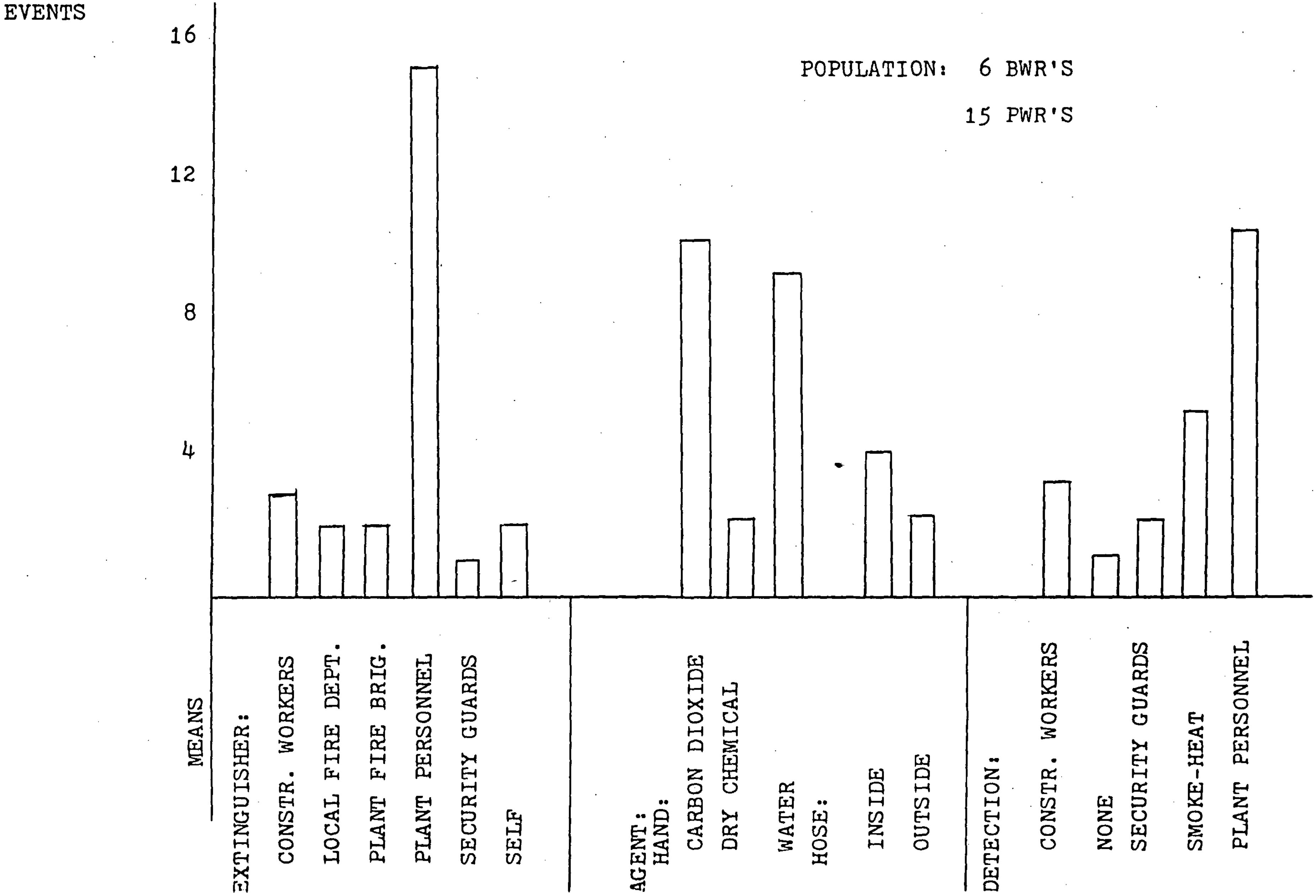


FIGURE D.2.10

FREQUENCY OF EXTINGUISHER, AGENT, AND DETECTION IN PRE-OPERATIONAL TESTING PHASE



and systems during this phase of operation. Personnel error and welding and cutting operations also seem significant, perhaps for the same reason. However, their relative magnitude has decreased to 30%. The magnitude of electric short has also decreased to 5%.

Fire protection effectiveness is demonstrated for this phase by Figure D.2.10 which displays the frequency of extinguisher, agent, and detection method. It is apparent that plant personnel are the most influential in the extinguishment process accounting for 60% of the means as compared with less that 20% for the construction phase. The other means of extinguishment are roughly equivalent in frequency. An interesting note is that the plant fire brigade response frequency has decreased from 15% during construction to 10% during testing; the reverse trend would have seemed more likely.

A dramatic change is present for the agent used to extinguish the fire. Hand extinguishers, particularly CO_2 and water, predominate with 35% and 30% respectively, for this phase. The use of the outside hose, which was prevalent during the construction phase, has decreased to less than 10%. It is important to note that no extinguishment was made with an automatic system of any type.

A shift can be seen in the detection means from the construction worker and security guard (75% in the construction phase) to plant personnel and automatic smoke/heat detectors in the testing phase (75%). It is disturbing to note, however, that a fire went undetected (NONE, Figure D.2.10). The magnitude of automatic detection by smoke-heat detectors increased from 5% during construction to 25% during testing. There appears to be a deficiency in the protection provided by automatic systems since their presence is mandated by design. Although only a quarter as many events were reported during this phase as the construction phase, a few notes can be summarized regarding contributing factors to fire occurrence and propagation during pre-operational testing. These are listed below:

1. no sprinklers available
2. jockey pump on fire protection system lost
3. heavy smoke prevented an attempt to extinguish with an inside hose
4. plant fire brigade arrived 5 minuted after fire was reported
5. automatic sprinkler systems were present, but turned off at the alarm check valve (two leads had fused)

Typical of those factors which helped mitigate the effects of fires were:

1. primarily, the constant personnel monitoring during testing
2. low and high demand fire pumps (electric) operated successfully

D.2.3 Operational Phase

Once the plant reaches the operational phase, many of the transient sources of fire associated with construction should be absent, while the appearance of "new" permanent and transient sources of fire may be expected. When the frequency of combustible, illustrated in Figure D.2.11, is compared with the preceding figures for combustibles, we see that the prominent combustible has shifted from wood for the construction phase, and oil for the pre-operational testing phase to an increasing influence of insulation in fires during the operational phase (20%), The frequency of lube oil fires is still large (20%), although this is relatively less than during the pre-op testing phase (45%). Oil as a general category represents 30% of the primary combustibles for this phase.

The apparent increase in wood fires is actually due to the occurrence of four forest fires off-site. No wood fires were reported on-site during the operating phase. Two combustibles appeared with prominence solely in the operational phase: expansion joints (composite material of wood, paper, plastic) and off-gas. The fires involving off-gas were often initiated by an explosion.

The frequency of various ignitors for fires occurring during this phase is depicted in Figure D.2.12. Predominating are electric short (14%), hot exhaust manifold (20%), hot surfaces (16%), spontaneous (8%), and welding (8%), (unknown 8%)

FIGURE D.2.11

FREQUENCY OF COMBUSTIBLE FOR OPERATIONAL PHASE

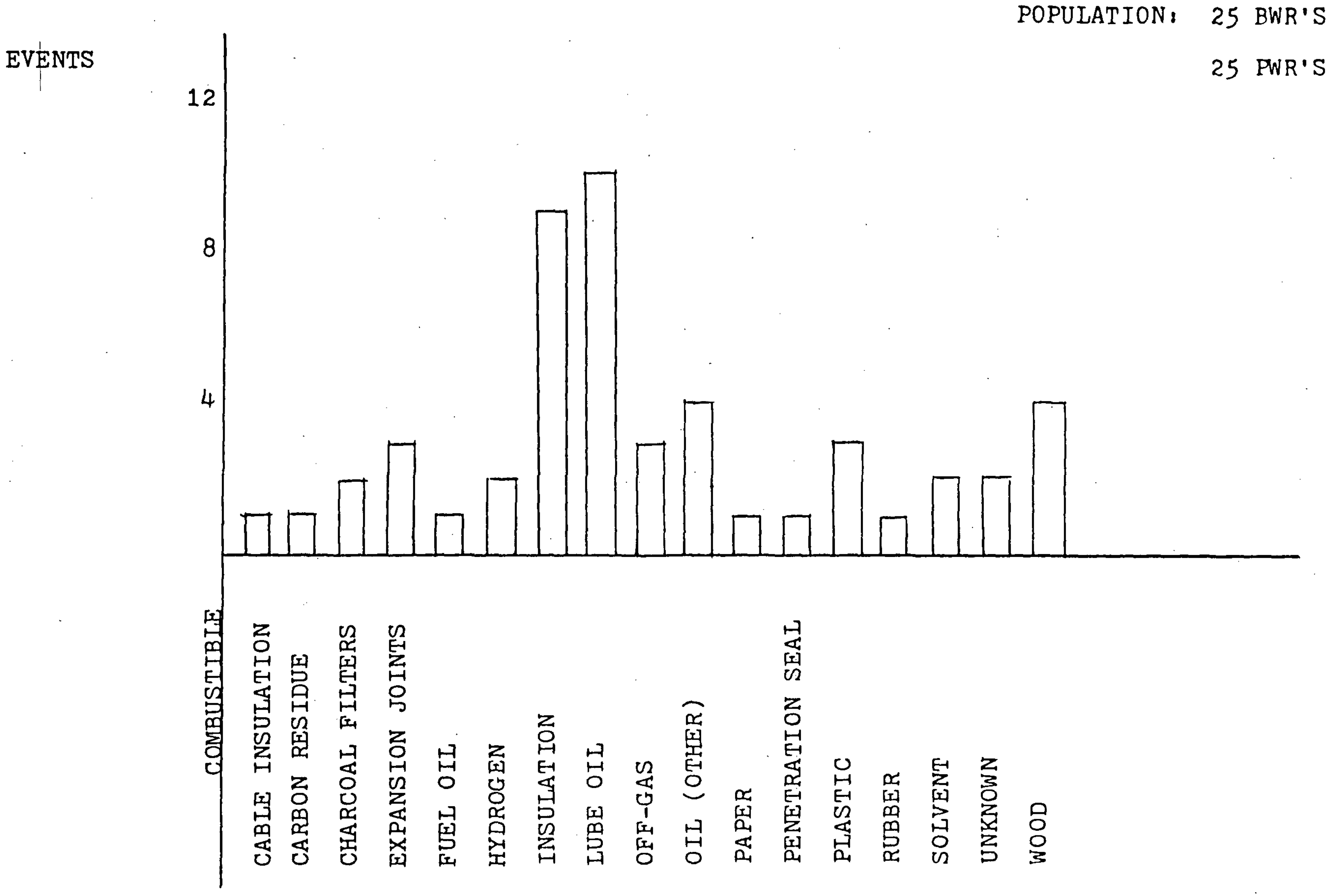
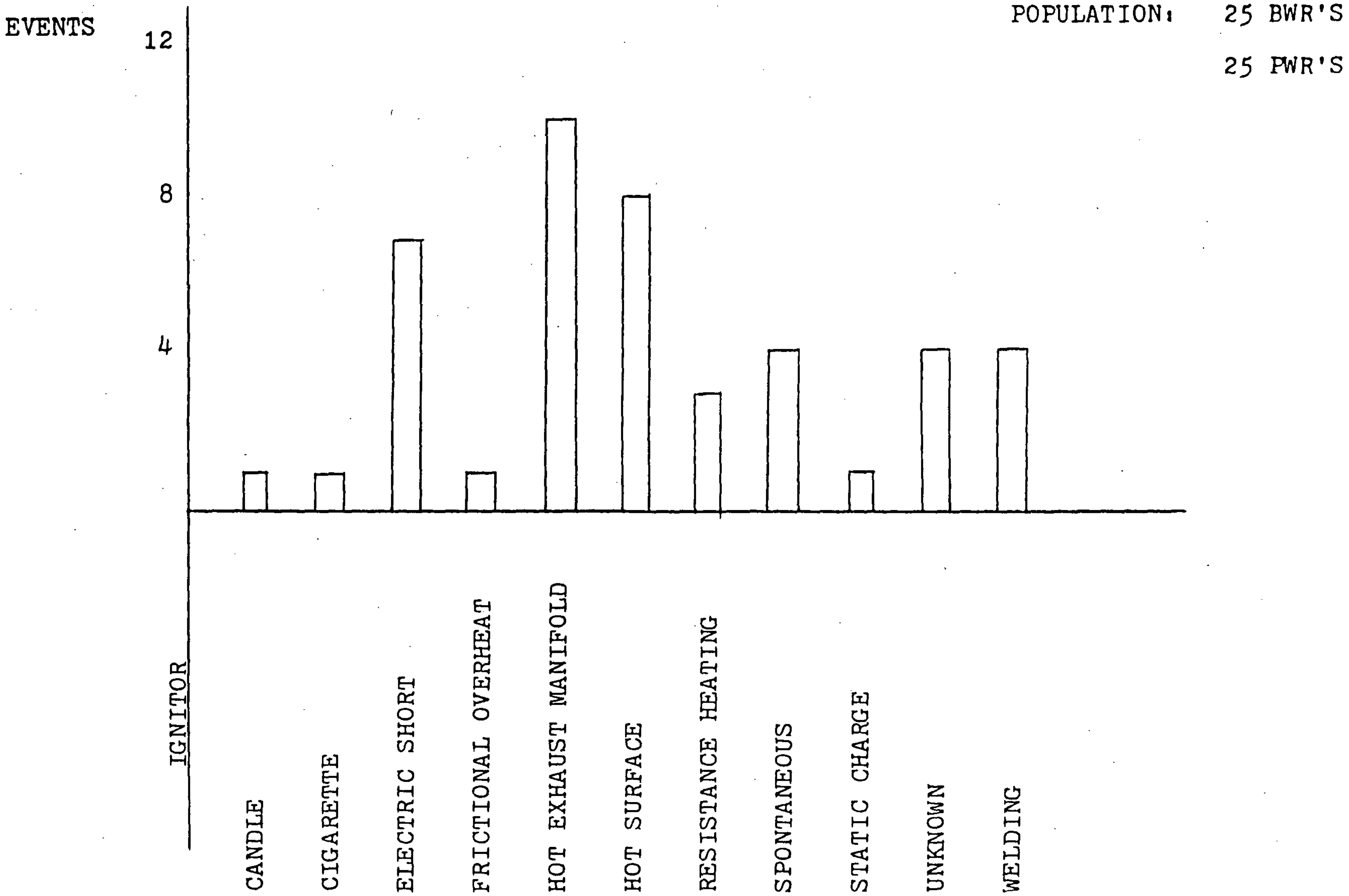


FIGURE D.2.12

FREQUENCY OF IGNITOR FOR OPERATIONAL PHASE



Together, these account for 74% of the events during this phase.

Hot exhaust manifolds ignited no fires during the pre-op testing phase, but were the principle ignition source during the operations phase. The most dramatic change in relative magnitude is for welding and cutting, sparks and slag: construction (30%), pre-op testing (25%), operations (8%). This is the most obvious correlation between the ignition source and phase of work.

Three sources were present solely during the operations phase: frictional overheating, resistance heating, and static discharges. Together these ignition sources comprise 10% of the events during this phase.

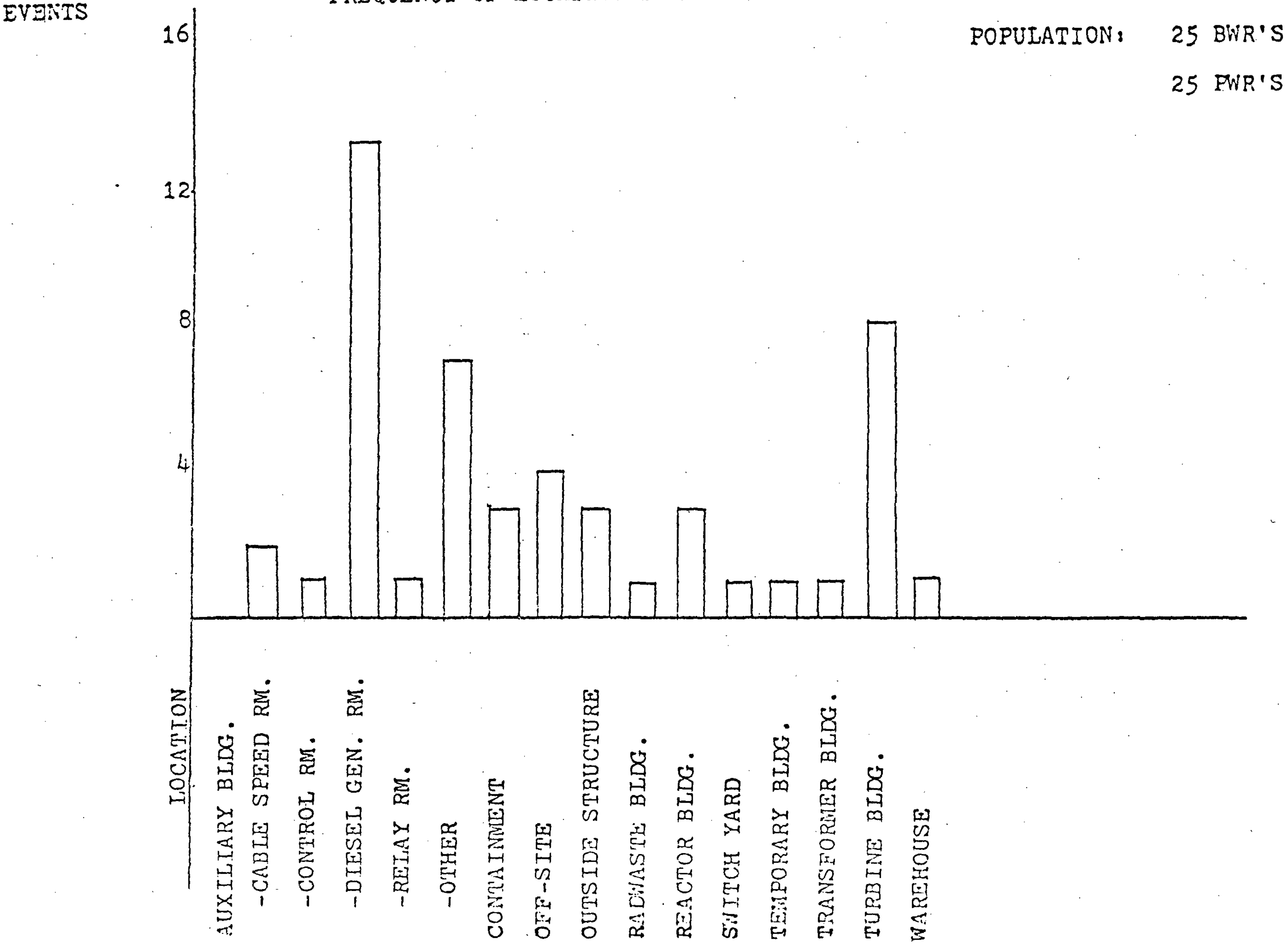
The relative frequency of undertermine (unknown) ignition sources was of the same order for this phase as to the preceding ones: construction (10%), pre-operational testing (5%), and operational (8%). Generally, it appears that the ignition source will be unknown about 10% of the time regardless of phase. However, the influence of forest fires off-site during this phase should be noted; if they are neglected, then no fires of undermined origin occurred during the operations phase.

The auxiliary building is the location of the majority of fires which occurred during the operational phase (48%). The frequency distribution for fire location during operations is shown in Figure D.2.13. The next most frequent location is the turbine building (16%). Other lcations which are significant include off-site forest fires (16%), outside structures (6%), and reactor building (6%). These fire locations account for over 90% of the locations of fire occurring during this phase. Several trends are indicated by these frequencies:

1. importance of the diesel generator room as a location of fires (26%)
2. decrease in the frequency of fires in the reactor building (6%) from the pre-op testing phase (30%)
3. increase in the frequency of fire in the auxiliary building from 20% during construction to 48% during operations
4. slight decrease in the frequency of fires in the turbine building

FIGURE D.2.13

FREQUENCY OF LOCATION FOR OPERATIONAL PHASE



during operations (16%) from the pre-operational phase (20%)

5. increase in the total number of locations of fire occurrence; construction 10, pre-op testing 7, operations 14, indicating a greater distribution of combustible materials over the plant site as constructions progresses and operation begins

Causes of fire during the operational phase are listed in the histogram of Figure D.2.14. The dominant causes are component failure (28%), defective procedures (18%), personnel error (16%), and electric short (12%). These represent 74% of all the causes. Of these causes, only defective procedures changed noticeably in relative magnitude (0% during pre-operational testing to 18% during operations). The remaining causes occurred with roughtly the same frequency as they did during pre-operational testing.

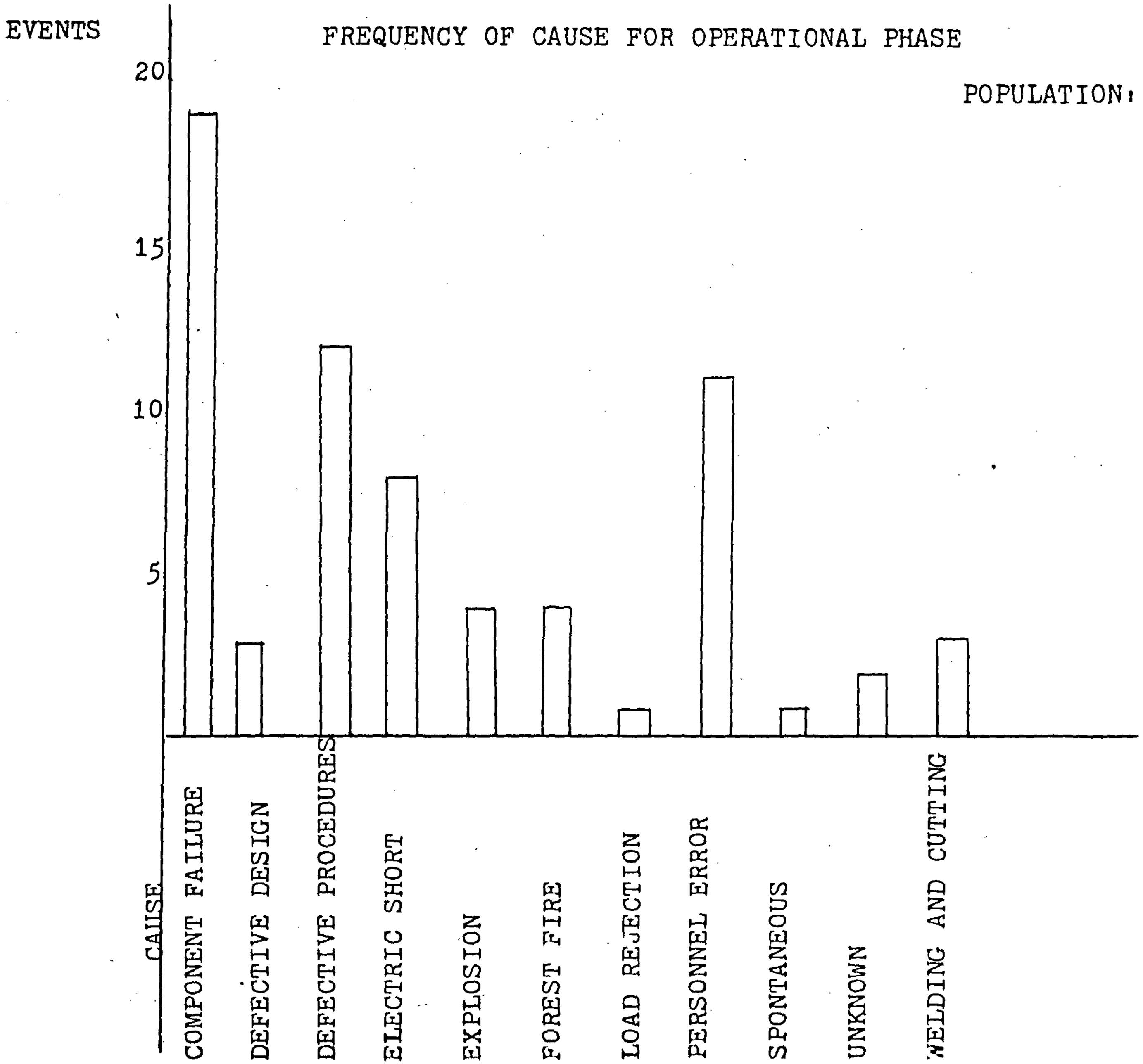
Frequency of extinguisher, agent and detection means are shown in Figure D.2.15. Plant personnel appear to be the dominant factor in extinguishment (54%), with hand carbon dioxide (CO_2) extinguishers as the principal agent (28%). The means of detection is usually plant personnel (62%). This compares with plant personnel responsible for 75% of the extinguishment during the pre-op phase. Throughout the pre-operational and operational phases, hand extinguishers dominated with automatic extinguishing systems activated only 14% for operations and 0% during pre-op testing. Smoke/heat detectors had a low frequency of involvement: 10% during operations, 30% during pre-op phase, and only 6% during construction phase.

As with those phases which precede operations, the operational phase events have many underlying contributing factors, some of which are common to the other phases. A sample of some of these which have contributed to events in this phase are listed below:

- no sprinkler protection
- leak testing with an open flame (candle)
- inadequate supervision
- no sprinkler heads functioned

FIGURE D.2.14

FREQUENCY OF CAUSE FOR OPERATIONAL PHASE



POPULATION: 25 BWR'S
25 PWR'S

FIGURE D.2.15

FREQUENCY OF EXTINGUISHER, AGENT, AND DETECTION FOR OPERATIONAL PHASE

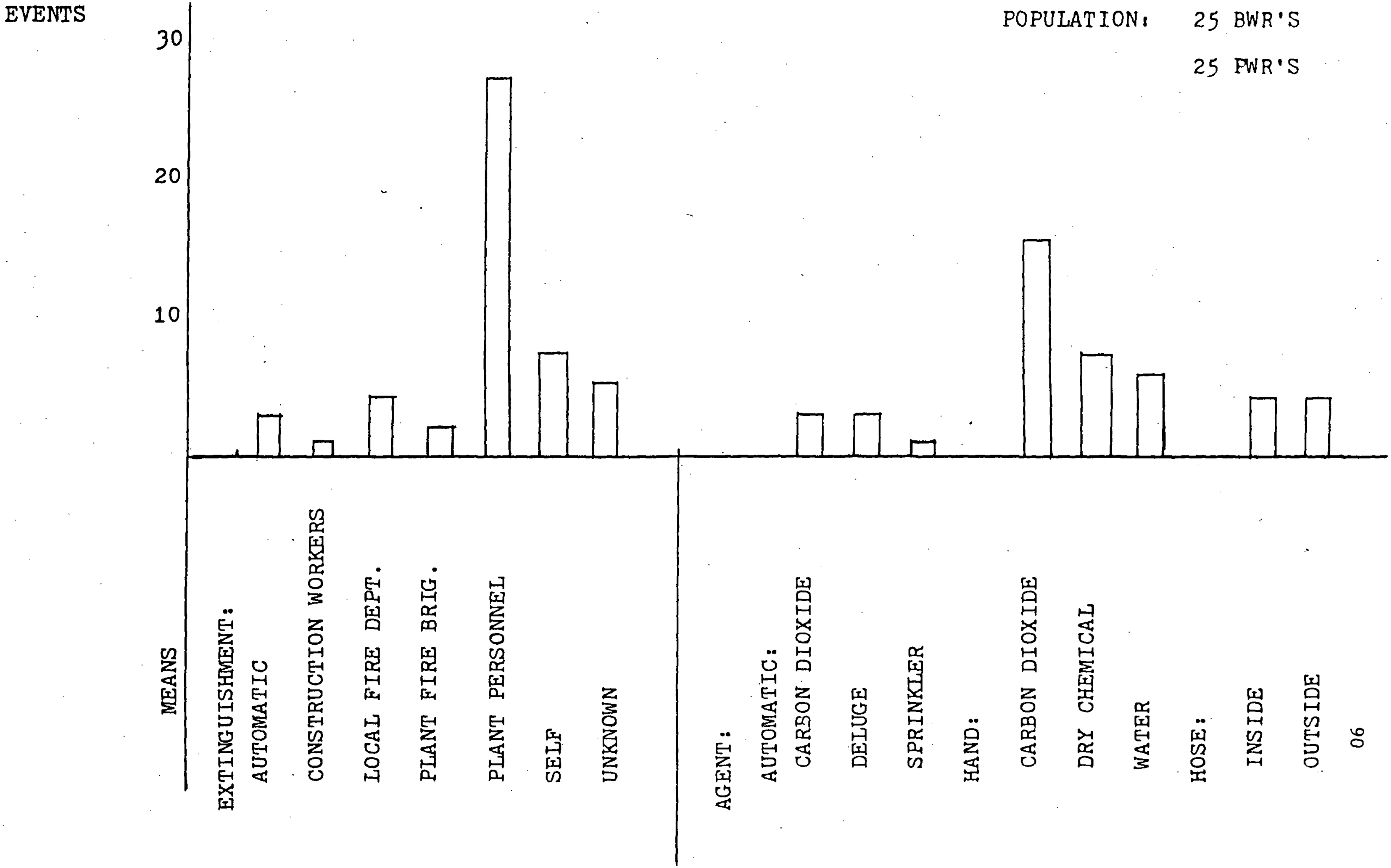
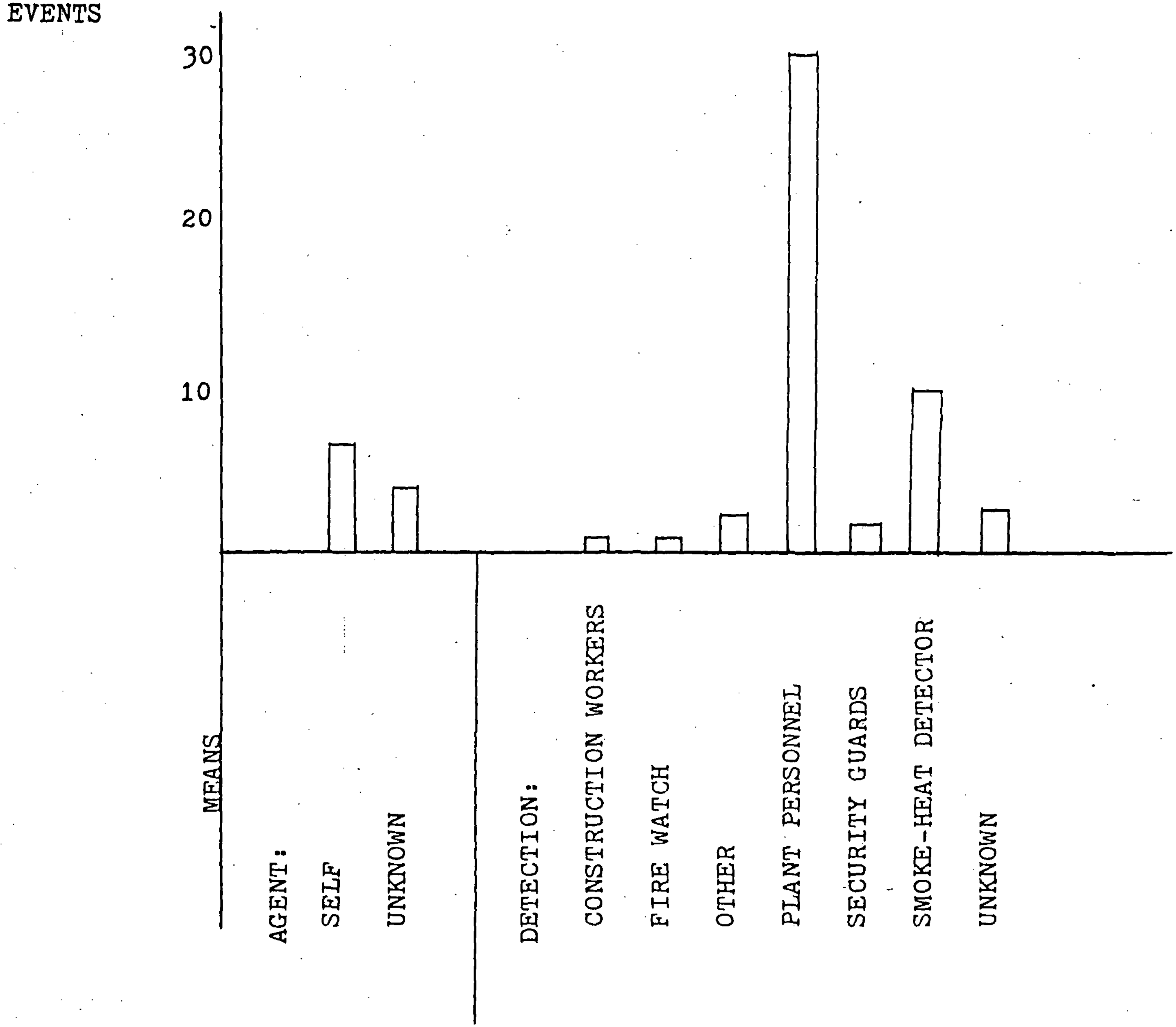


FIGURE D.2.15 (CONT'D)



- low oil indication on computer output 1½ hours prior to fire was not read in the control room
- smoke detectors were available but did not function
- sources of oil leaks not adequately corrected after previous fire of the same type
- off-site forest fires caused arcing to ground and loss of off-site power or transmission
- man-lift left inadvertently next to diesel stack
- carelessness with smoking materials
- hand dry chemical, carbon dioxide unsuccessful
- propagation through a galvanized metal fire strip
- cables overly packed
- diesel generator not sprinkler protected
- accumulation of lube, diesel oil on diesel generator

Similarly, there were various factors which mitigated the propagation or consequences of fire in the operations phase:

- auto deluge operated
- two sprinklers fused and successfully extinguished after hand extinguishers had failed
- the auto deluge system was operated by smoke/heat detectors and extinguished

In seven of the fifty events (14%) the power level of the reactor was degraded by 100% for outages ranging from 87 hours to 550 days.

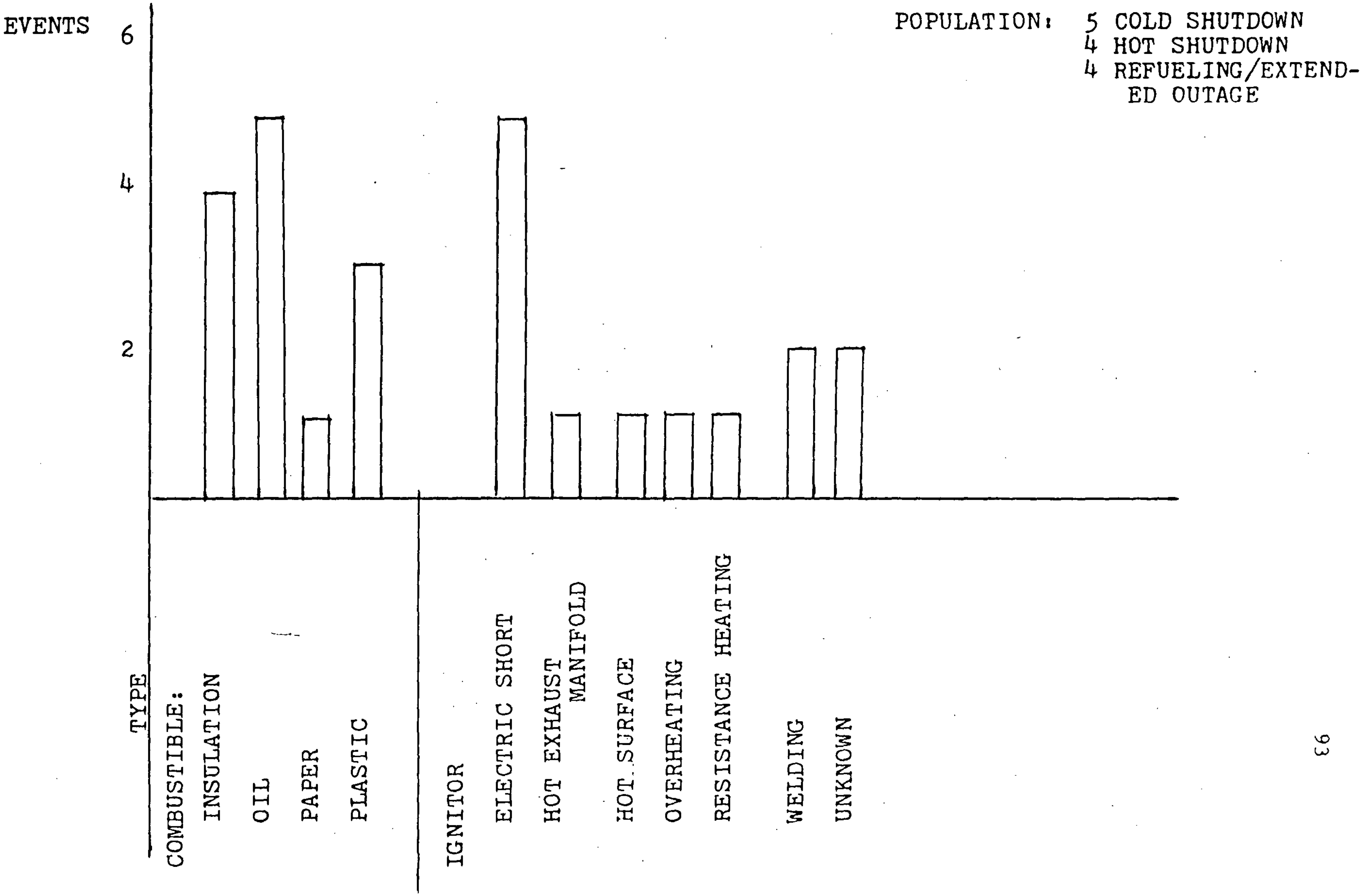
D.2.4 Cold and Hot Shutdown and Refueling/Extended Outages

Cold and hot shutdowns and refueling/extended outages have been lumped together for fire considerations. Figure D.2.16 presents the frequency of combustibles and ignitors during these outages. Insulation and oil are the combustibles. Their magnitudes are proportional to those which occurred during

FIGURE D.2.16

FREQUENCY OF COMBUSTIBLE AND IGNITOR FOR

COLD AND HOT SHUTDOWN AND REFUELING/EXTENDED OUTAGE



the operations phase. Plastic fires are slightly more frequent during the outage period than during operations, perhaps due to the maintenance operations. The predominant ignitor is electric short during the outages. This is a shift from the hot exhaust manifold and hot surfaces which were responsible for many of the fires which occurred in the operations phase.

The locations and cause frequency distributions for the outage phase are presented in Figure D.2.17. As in the operations phase the auxiliary building is the principle location of fire for the outage phase. A decrease in the frequency of fires in the diesel generator room and relay room is noted. All fires were confined to the auxiliary, reactor, and turbine buildings. The cause of fire in this phase is mainly due to component failure, electric failure, and personnel error. The relative frequencies of these causes is similar to that for the operations phase.

The means of extinguishment, detection, and the agent used are tabulated in Figure D.2.18 for this phase. The primary extinguihser is plant personnel - as it has been throughout all the phases of the plant's life. The principal extinguishing means was hand extinguishers of various types. The extinguishing agent was unknown for 2/3 of the events. The primary means of detection was plant personnel, which was also the case during the operations phase.

Some of the contributing and mitigating factors for fires which occurred during these outages are summarized below:

- Contributing Factors
    - fire watch personnel who discovered fire weren't equipped with portable extinguishers
    - alarm for smoke detector noticed only after flames were observed
- Mitigating Factors
    - guard was present at fire location to check people in and out of a "hot" area
    - cable tray had been covered with an asbestos blanket

FIGURE D.2.17

FREQUENCY OF LOCATION AND CAUSE FOR

COLD AND HOT SHUTDOWN AND REFUELING/EXTENDED OUTAGE

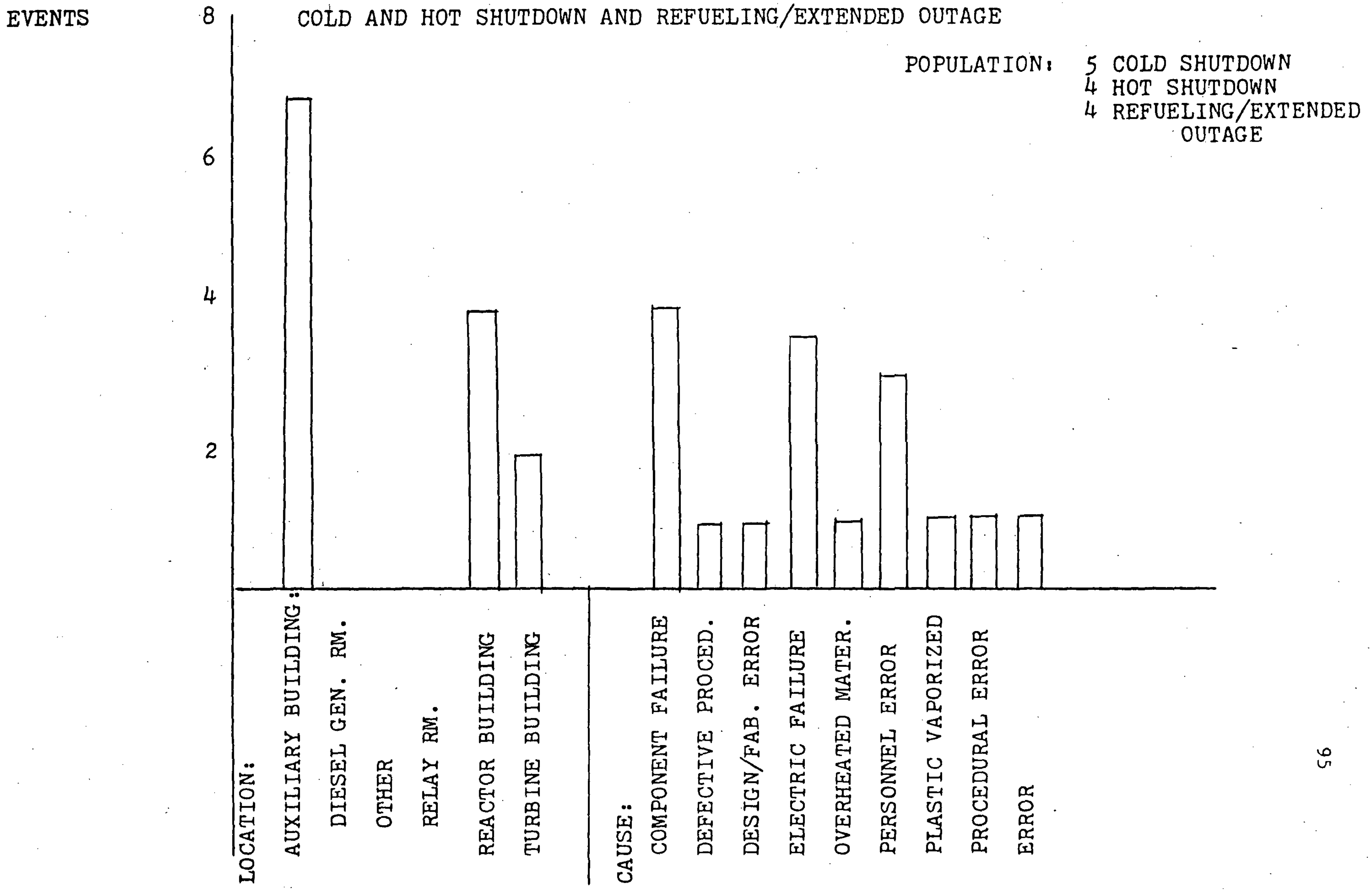
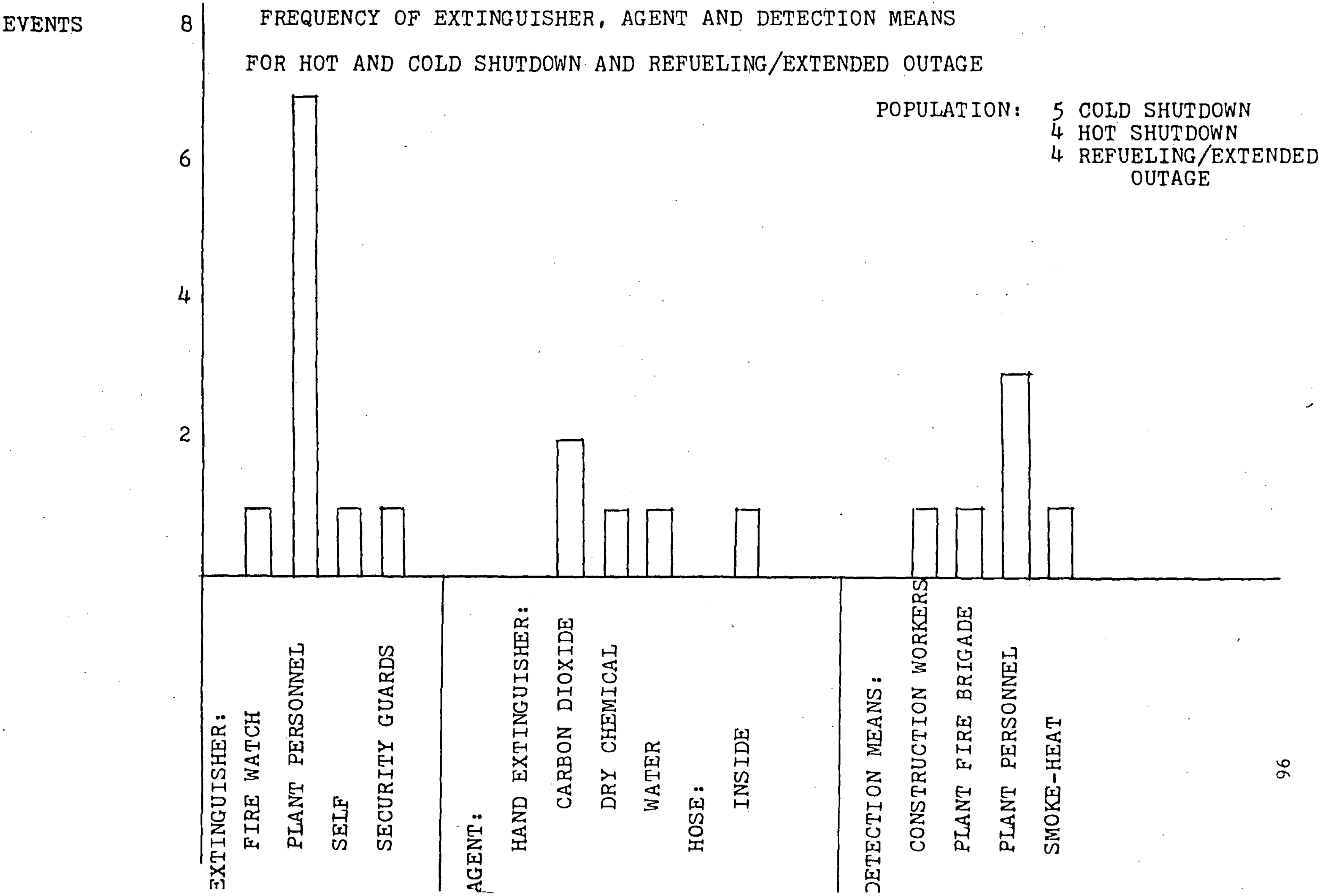


FIGURE D.2.18

FREQUENCY OF EXTINGUISHER, AGENT AND DETECTION MEANS

FOR HOT AND COLD SHUTDOWN AND REFUELING/EXTENDED OUTAGE



D.3 Probability Factors

The preceding section presented a collection of frequency histograms for fire in BWR's and PWR's during their various phases of construction, operation, and shutdown. The presence of predominant combustibles, ignitors, locations, etc., is evident from these figures. It is desirable to further quantify the likelihood for fire occurrence and the resultant effect upon the continued safe operation of the power plant. This likelihood can be treated as a probability or a combination of probability factors. The subject of this section is the evaluation of these component probabilities.

D.3.1 Motivation for Probabilistic Assessment

Since the fire data base is limited with respect to population, "exact" probability estimates are not possible. However, we can compute rough estimates of probability based on the fire data which is accurate to an order of magnitude or better. Once these componente probabilities are determined, they can then be used to estimate further event probabilities.

The ultimate goal is to compute the probability of core meltdown resulting from the occurrence of a fire which disables safety system(s). The following component probabilities must be determined in order to estimate the probability of core meltdown due to fire:

1. Probability of fire occurring denoted: $P(F)$
2. Probability the fire propagates to a zone containing a safety system denoted: $P(PE\text{-}SSZ|F)$
3. Probability safety system i fails or is lost given that a fire has propagated denoted: $P(SSL_i|PR\text{-}SSZ)$
4. Probability of core meltdown given that the i^{th} safety system fails or is lost denoted: $P(CM|SSL_i)$

These component probabilities, if known, could determine an estimate of the probability of core meltdown due to fire $P(CM)$:

$$P(CM) = \sum_i [P(CM|SSL_i) \cdot P(SSL_i|PR\text{-}SSZ) \cdot P(PR\text{-}SSZ|F)\ P(F)]$$

This is a simple expression which ignores common mode effects and does not distinguish between fires which start in some peripheral component of a safety system and those which start somewhere else and propagate to the safety system. A similar expression for the probability of core meltdown given that a fire has occurred is:

$$P(CM\ F) = \sum_i [P(CM|SSL_i) \cdot P(SSL_i|PR\text{-}SSZ) \cdot P(PR\text{-}SSZ|F)]$$

Although these expressions are simple in form, obtaining quantitative values for their components is difficult. The component probabilities calculated from the fire data base can be used in an expression which approximates the above equations.

The probability values determined for the construction phase will not, in most cases, be applicable to the operations phase; hence they must be separated. Several ways present themselves as means of evaluating probabilities: absolute, conditional, and time dependent. Since it is not possible to evaluate absolute expressions, the remaining two types were used. The following sections evaluate the component probability factors previously discussed. Some estimates are presented for the probability of safety system loss and a discussion of means of evaluating the probability of core meltdown follows.

D.3.2 Probability of Fire in Nuclear Power Plants

The time dependence of fires during the construction and operational phases was discussed in section B.4.

An alternate way to display the number of construction fires from date of first construction is shown in Figure D.3.1. (A normalized method was used in section B.4.1.) The increase in number of fires shown here can be correlated directly with an increase in construction materials and personnel followed by a decrease as construction reaches completion. However Figure D.3.1 contains data from many plants of varying construction times, hence this interpretation may be in question (see section B.4.1.)

FIGURE D.3.1

BWR AND PWR TIMES TO FIRE FOR CONSTRUCTION

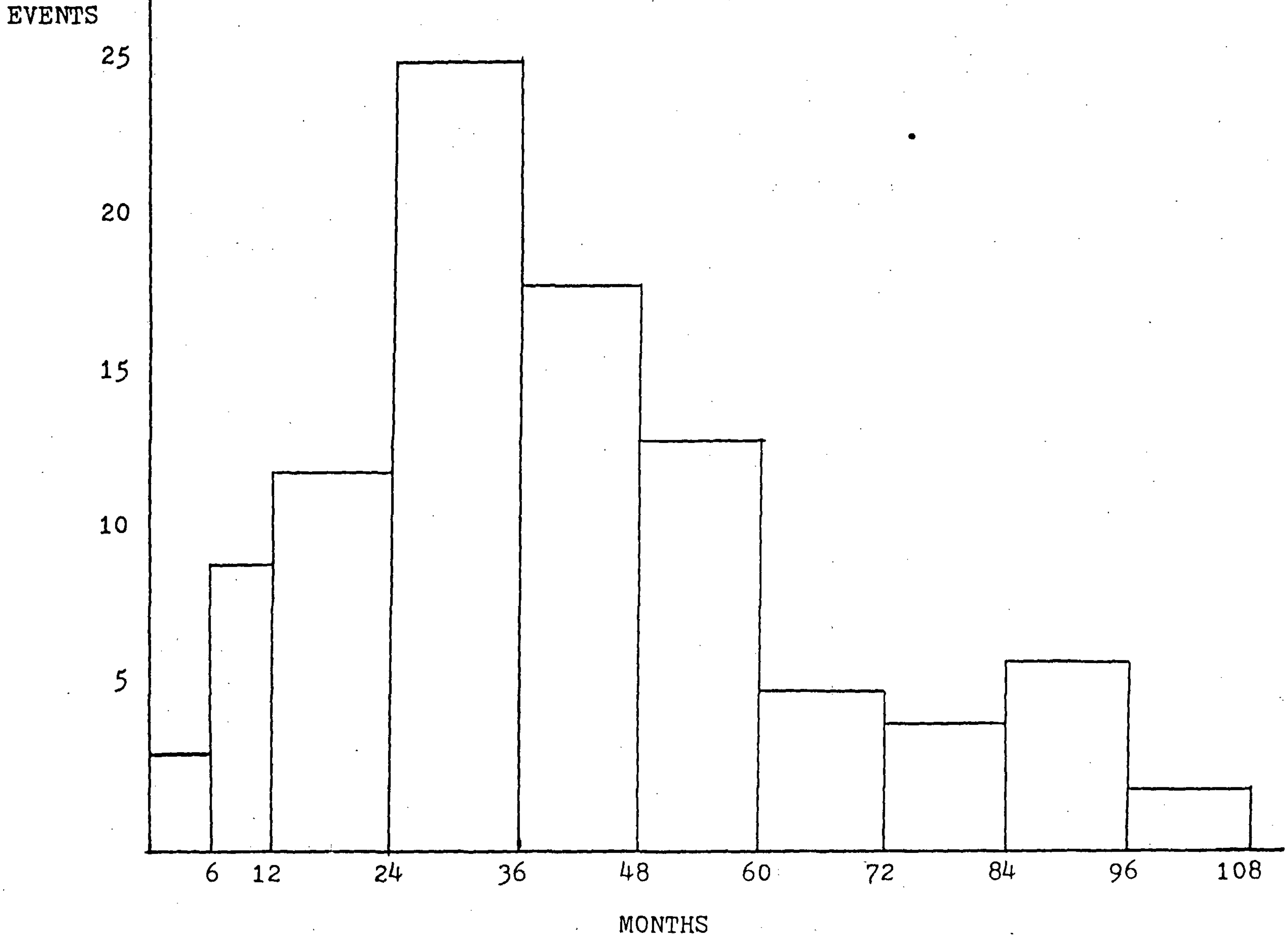
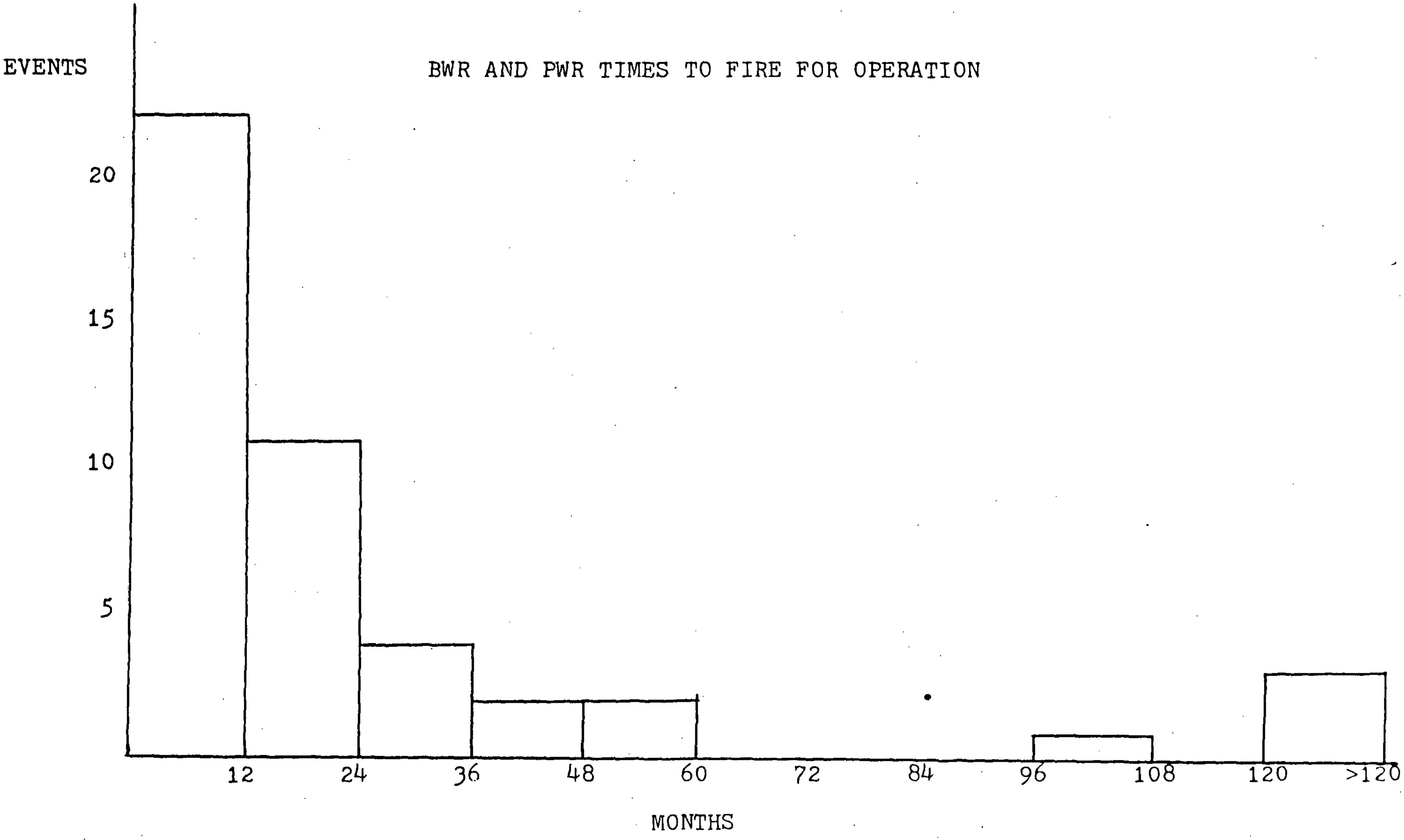


FIGURE D.3.2



BWR AND PWR TIMES TO FIRE FOR OPERATION

The times to fires during operational status is shown in Figure D.3.2. A rapid decrease is seen to occur and other aspects of this time-dependent occurrence rate are discussed in section B.4.2.

D.3.3 Component Probability Factors

Tables D.3.1 through D.3.6 contain the probability factors determined for each of their components from the corresponding histograms presented in section D.2. The data presented in these tables can be used to determine event probabilities.

The probabilities are all conditional on the occurrence of a fire. Listed below are the abbreviations for the probability factors determined in the tables:

- $P(C|F)$: probability of primary combustible given a fire
- $P(I|F)$: " " " ignitor " " "
- $P(L|F)$: " " " location " " "
- $P(CA|F)$: " " " cause " " "
- $P(E|F)$: " " " extinguisher " " "
- $P(A|F)$: " " " agent " " "
- $P(D|F)$: " " " detection means " "

TABLE D.3.1

COMBUSTIBLE DEPENDENCE OF FIRES IN BWR'S AND PWR'S

COMBUSTIBLE	CONSTRUCTION P(C|F)	OPERATIONS P(C|F)
CABLE INSULATION	.01	.02
CANVAS	.03	
CARBON RESIDUE		.02
CHARCOAL FILTERS		.04
CLOTHING	.04	
EXPANSION JOINTS		.06
FIBERBOARD	.01	
FIBERGLASS	.01	
FUEL OIL		.02
GAS	.02	
GRASS	.01	
HYDRAULIC FLUID	.01	
HYDROGEN		.04
INSULATION	.12	.18
LUBE OIL		.20
OFF-GAS		.06
OIL	.05	.08
PAPER	.04	.02
PENETRATION SEAL		.02
PLASTIC	.02	.06
RAGS	.04	

TABLE D.3.1 Contd.

COMBUSTIBLE	CONSTRUCTION $P(C\|F)$	OPERATIONS $P(C\|F)$
RUBBER	.03	.02
SOLVENT	.08	.04
STRESS-RELIEF PAD	.01	
TARPAULIN	.04	
TRASH	.01	
UNKNOWN	.02	.04
WOOD	.28	.08

TABLE D.3.2

IGNITOR DEPENDENCE OF FIRES IN BWR'S AND PWR'S

IGNITOR	CONSTRUCTION (P(|F)	OPERATIONS P(I|F)
CANDLE		.02
CIGARETTE	.04	.02
ELECTRIC HEATER	.10	
ELECTRIC SHORT	.23	.14
FRICTION OVERHEATING		.02
GAS HEATER	.04	
HOT EXHAUST MANIFOLD	.01	.20
HOT SURFACES	.10	.16
PROPANE TORCH	.02	
RESISTANCE HEATING		.06
SPONTANEOUS	.01	.14
STATIC CHARGE		.02
TRANSFORMER EXPLOSION		.02
UNKNOWN	.09	.12
WARMING FIRE	.01	
WELDING	.32	.08

TABLE D.3.3

LOCATION DEPENDENCE OF FIRES IN BWR'S AND PWR'S

LOCATION	CONSTRUCTION P(L|F)	OPERATIONS P(L|F)
AUXILIARY BUILDING		
-CABLE SPEADING RM.		.04
-CONTROL RM.	.01	.02
-DIESEL GENERATOR RM.		.26
-RELAY RM.		.02
-SWITCHGEAR RM.	.01	
-OTHER	.04	.14
CONTAINMENT	.11	.06
OFF-SITE		.08
OUTSIDE STRUCTURES		.06
RADWASTER BUILDING		.02
REACTOR BUILDING	.12	.06
SWITCH YARD	.04	.02
TEMPORARY BUILDING	.44	.02
TRANSFORMER BUILDING		.02
TURBINE BUILDING	.07	.16
WAREHOUSE	.04	.02
YARD	.13	

TABLE D.3.4

CAUSE DEPENDENCE OF FIRES IN BWR'S and PWR'S

CAUSE	CONSTRUCTION $P(CA\|F)$	OPERATION $P(CA\|F)$
CANVAS BLOWN ON HEATER	.01	
COMPONENT FAILURE	.08	.28
DEFECTIVE DESIGN	.01	.04
DEFECTIVE PROCEDURES	.09	.18
ELECTRIC SHORT	.17	.12
EXPLOSION	.02	.05
FOREST FIRE OFF-SITE		.05
LOAD REJECTION		.01
NO WELDING TARPS	.04	
OVERHEATED MATERIAL	.06	
PERSONNEL ERROR	.19	.15
SMOKING	.02	
SPONTANEOUS	.01	.01
STRESS-RELIEF BLANKETS	.02	
SUSPICIOUS	.03	
TEMPORARY WIRING	.03	
UNATTENDED WARMING FIRE	.01	
UNKNOWN	.07	.03
VEHICLE IMPACTING TRANSFORMER	.01	
WELDING AND CUTTING	.28	.04

TABLE D.3.5

EXTINGUISHER AND AGENT DEPENDENCE OF FIRES IN BWR'S AND PWR'S

EXTINGUISHER	CONSTRUCTION $P(E\mid F)$	OPERATIONS $P(E\mid F)$
AUTOMATIC		.06
CONSTRUCTION WORKERS	.29	.02
LOCAL FIRE DEPARTMENT	.35	.08
PLANT FIRE BRIGADE	.14	.04
PLANT PERSONNEL	.15	.56
SECURITY GUARDS	.03	
SELF	.03	.14
UNKNOWN		.10

AGENT	$P(A\mid F)$	$P(A\mid F)$
AUTOMATIC:		
-CARBON DIOXIDE	.01	.06
-DELUGE		.06
-SPRINKLER	.01	.02
HAND:		
-CARBON DIOXIDE	.10	.28
-DRY CHEMICAL	.14	.13
-WATER	.16	.11
HOSE:		
-INSIDE	.05	.07
-OUTSIDE	.53	.07
SELF		.13
UNKNOWN		.07

TABLE D.3.6

DETECTION DEPENDENCE OF FIRES IN BWR'S AND PWR'S

DETECTION MEANS	CONSTRUCTION P(D|F)	OPERATIONS P(D|F)
CONSTRUCTION WORKERS	.48	.02
FIRE WATCH		.02
OTHER		.04
PLANT PERSONNEL	.15	.62
SECURITY GUARDS	.30	.04
SMOKE-HEAT	.05	.20
UNKNOWN	.02	.06

D.3.4 Probability of Fire Propagation

Although in a local sense, the phenomenon of fire propagation is only slightly governed by probabilistic factors, many influence the propagation potential to varying degrees. It is reasonable to assume that probabilistic relations can be determined for the fires which have occurred. The evaluation of this probability can, in turn, be used to evaluate the probability of core meltdown as previously discussed.

Fifty fires have occurred during the operations phase in commercial BWR's and PWR's, five of which propagated from the original location of ignition. We can say that an estimate of the probability of propagation given that a fire has occurred, for this population, is:

$$P(PR|F) = .10$$

D.3.5 Probability of Safety Loss Due to Fire

There are several ways a fire can cause the loss of a safety system. First, the safety system (or component sub-systems) could be directly involved in a fire (cables, relays, etc.). A second means is the propagation of a fire near the safety system (or component) to involve the safety system. Third, the common mode failure of component trains of the safety system by fire could cause a safety loss. The common mode failure probability will not be addressed, but the preceding two are discussed.

It is possible to determine those fires which propagated and caused a safety loss from the fire data. These fires are termed dangerous fires since they endanger the safe operation of the nuclear plant. Two of the five propagating fires caused a safety system loss. A loss of a safety system should be distinguished from a safety loss where the latter implies the endangering of the former. The probability of a safety system loss given that the fire progated can then be expressed:

$$P(SSL|PR) = .4$$

This value can be combined with the probability of propagation given fire occurrence to yield the probability of a safety system loss given a fire (which propagates):

$$\begin{aligned} P(SSL\ F) &= P(SSL|PR) \cdot P(PR|F) \\ &= [.4]\ [.10] \\ &= 4. \cdot .10^{-2} \end{aligned}$$

That is, the probability that a safety loss will occur given that a fire has occurred (and propagates) is approximately $4. \cdot 10^{-2}$.

The probability of safety loss can also be determined directly from the data, for the case where the fire did not propagate, but originated in some cable, component, etc. which degraded a safety system. Nine fires occurred which did not propagate, but did result in a safety system loss. Thus, the probability of safety system loss from non-propagating fire is:

$$P(SSL|NPR) \cong .18$$

The probability of safety system loss due to both propagating and non-propagating fires is the sum of the corresponding probabilities. The probability of safety system loss given fire is then:

$$\begin{aligned} P(SSL|F) &= P(SSL|PR) \cdot P(PR|F) + P(SSL|NPR) \cdot P(NPR|F) \\ &\cong [.4]\ [.10] + [.18]\ [.90] \\ &\cong 4. \cdot 10^{-3} + 1.62 \cdot 10^{-1} \\ &\cong 1.6 \cdot 10^{-1} \end{aligned}$$

D.3.6 Probability of Core Meltdown Due to Fire

Values have been determined for various component probabilities related to fire occurrence, propagation, and effects in previous sections of this report. These numbers could be used in conjunction with known system failure rates and other sources contained in WASH-1400; the Reactor Safety Study. Together, these probabilities may be combined in such a fashion to furnish an estimate of the desired probability of core meltdown due to fire under particular sources.

The probability of core meltdown (given the occurrence of fire) could be determined by numerical methods, e.g. Monte-Carlo. Any results determined by this or any other method must, however, be weighed against the uncertainty which is due to a limited data base and the multitude of propagation paths. The absolute probability of core meltdown due to fire would be a sum of the component probabilities over all the various source (combustible and ignitor), location and safety system combinations which could result in core meltdown. A more simple approach would involve the determination of safety system failure probabilities for those systems located in areas of relatively high fire risk. These probabilities, if then combined with those developed in this report, could provide estimates of the desired probability for specific combinations of source, locations and safety system.

D.4 Confidence Intervals for Factors

The most accurate means of evaluating the confidence in the data values is by computing the confidence in the proportion (factor) for each member of a population. This is relatively easy because most of the data are tabulated in the form of frequency histograms from which the estimating proportion can be read directly.

It is assumed that if it were possible to accumulate many "sets" of fire data from the population of total fires which have occurred, that the proportions would fit a normal distribution regardless of any distributional tendency or dependency of individual factors. The standardized normal distribution can then be used to calculate the confidence in the fire data.

These values are calculated for the location of fire, primary combustible, and ignitor for the operations in Tables D.4.1-4.3. The confidence of $n\hat{p}$, the expected number of fires, is also included. The confidence in the proportion p, is determined for a $100(1-\alpha)\%$ interval by:

TABLE D.4.1

95% CONFIDENCE LIMITS FOR THE PROPORTION OF FIRES IN A LOCATION

Location	$\hat{p}$	$z_{\alpha/2}\left(\frac{pq}{n}\right)^{\frac{1}{2}}$	p Lower	p Upper	np Lower	np Upper
Containment	7.0(-2)	.07615	0	1.5(-1)	0	6.3
Diesel Gen. Rm	3.0(-1)	.41340	0	7.2(-1)	0	31.0
Reactor Bldg.	7.0(-2)	.07615	0	1.5(-1)	0	6.3
Turbine Bldg.	1.6(-1)	.11034	5.2(-2)	2.7(-1)	2.3	11.7
Cable Sp. Rm.	4.7(-2)	.06295	0	1.1(-1)	0	4.7
Temporary Bldg.	2.3(-2)	.04505	0	6.8(-2)	0	2.9
Auxiliary Bldg.	1.4(-1)	.10357	3.6(-2)	2.4(-2)	1.6	10.5
Warehouses	2.3(-2)	.04505	0	6.8(-2)	0	2.9
Off-site	4.7(-2)	.06295	0	1.1(-1)	0	4.7
Control Rm.	2.3(-2)	.04505	0	6.8(-2)	0	2.9
Radwaste Bldg.	2.3(-2)	04505	0	6.8(-2)	0	2.9
Switchyard	2.3.(-2)	.04505	0	6.8(-2)	0	2.9
Relay Room	2.3(-2)	.04505	0	6.8(-2)	0	2.9
Outside Struc.	2.3(-2)	.04505	0	6.8(-2)	0	2.9

TABLE D.4.2

95% CONFIDENCE LIMITS FOR THE PROPORTION OF FIRES BY COMBUSTIBLE

Combustible	p	$z_{\alpha/2}\left(\frac{pq}{n}\right)^{\frac{1}{2}}$	p		np	
			Lower	Upper	Lower	Upper
Solvent	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Insulation	1.9(-1)	1.2(-1)	7.0(-2)	3.0(-1)	3.0	13.0
Plastic	9.3(-2)	8.7(-2)	6.2(-3)	1.8(-1)	2.7(-1)	7.7
Oil	3.5(-1)	1.4	0	1.5	0	65.3
Hydrogen	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Paper, Cardboard	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Unknown	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Expansion Joint	7.0(-2)	7.6(-2)	0	1.5(-1)	0	6.3
Carbon Deposit	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Charcoal Fileter	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Off-Gas	7.0(-2)	6.6(-2)	0	1.5(-1)	0	6.3

TABLE D.4.3

95% CONFIDENCE LIMITS FOR THE PROPORTION OF FIRES BY IGNITOR

Ignitor	p	$z_{\alpha/2}\left(\frac{pq}{n}\right)^{\frac{1}{2}}$	$\hat{p}$		np	
			Lower	Upper	Lower	Upper
Electric Sparks, Arcs	4.7(-2)	6.4(-2)	0	1.1(-1)	0	4.7
Hot Surfaces	1.4(-1)	1.0(-1)	3.6(-2)	2.4(-2)	1.6	10.5
Electric Shorts	1.2(-1)	9.6(-2)	2.0(-2)	2.1(-1)	0.9	9.1
Cigarette	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Heaters	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Resistance Heating	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Spontaneous	1.6(-1)	1.1(-1)	5.2(-2)	2.7(-1)	2.3	11.7
Frictional Heating	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Hot Exhaust Manifold	2.3(-1)	1.2(-2)	1.1(-1)	3.6(-1)	4.6	15.4
Unknown	4.7(-2)	6.3(-2)	0	1.1(-1)	0	4.7
Welding Slag	9.3(-2)	1.8(-1)	6.2(-3)	1.8(-1)	2.7(-1)	7.7
Candle	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9
Static Charges	2.3(-2)	4.5(-2)	0	6.8(-2)	0	2.9

$$p - z_{\alpha/2}\left(\frac{pq}{n}\right)^{\frac{1}{2}} \leq p \leq p + z_{\alpha/2}\left(\frac{pq}{n}\right)^{\frac{1}{2}}$$

The apparent conclusion from these analyses is that the data are accurate to a factor of 3 for those events with small frequency (single events) and increases to a factor of 2 or 1.5 with a larger number events, at a 95% confidence interval.

D.5 Summary of Fire Data Observations

The careful examination of the data presented in the histograms illuminates a clear trend in fire occurrence in commercial nuclear power facilities during the various phases of operation. Fires in temporary buildings and shops ignited by welding sparks predominate in the construction phase. As transient combustibles decrease in quantity, a shift occurs toward fires in the reactor and turbine buildings due to oil fires ignited by hot surfaces for the pre-operational testing phase. A decreasing influence of welding initiated fires is also noted. Further, plant personnel usually extinguished the fires with hand extinguishers rather than off-site fire departments and construction workers with outside hoses during construction.

Fires in the operations phase, like the pre-operational testing phase, are dominated by lube oil and insulation fires, amny on the diesel generator, which were ignited by various hot manifolds and surfaces. Electric shorts present another important means to fire ignition during this phase. The location of fire during operations shifted to the diesel generator room where 25% of all fires during operations occurred. The implications on safety due to the threatening of the diesel generators by fire deserves due consideration. Similarly, fires which occurred in cable trays presented a safety threatening situation. Component failure was also a significant factor in the cause of fires during operation, contributing to 28% of the events. Other important causes included defective procedures, personnel error, and electric shorts. Extinguishment was accomplished by plant personnel, primarily with hand extinguishers. Likewise, 60% of the fires were discovered by plant personnel. This suggests two conclusions: either plant personnel are continually circulating near or in fire-prone areas, or a deficiency in the automatic fire detection and extinguishment systems exists. It would seem that the latter is more likely.

The fire data facilitate a probabilistic analysis of fire based upon historical events. Although the principle factors involved in fire ignition and growth are physical and chemical, probability factors provide information which is useful to determine what is likely to be ignited and its location. The local techniques which have been traditionally applied have little application in predicting fire occurrence in nuclear power plants.

The fire data will not stand alone, however, due to several limitations discussed previously concerning accuracy and reporting. Careful judgement is necessary to hold the fire data in its proper perspective. At its best, the fire data represent a sample of those fires which have occurred, and an indication to those scenarios which may be anticipated in the future.

The most important use of the probabilities determined is for defining important factors to consider for future scenario development. Extended research concerning fire in nuclear plants suggests the development of improved capability for acquiring, storing, sorting, and evaluating fires which have and will, occur in the plants. Such developmental work would be best accomplished by employing one of the data base management systems presently available commercially.

The probability factors can be used correctly only if their respective confidence levels are kept in mind. Although the fire data is at best sparse, the statistical tests upon proportions indicates that the values are accurate to at least a factor of three for infrequent events and perhaps a factor a 1.5 for those more frequent events. This information can be used when evaluating a particular scenario. These confidences are based on the assumption that the proportions are normally distributed.

The sample calculations for statistical confidence can be applied to probability factors in every phase of plant operation. Further work in this area will concentrate upon the incorporation of the determined probability factors into a model for scenario analysis.

E. Summary of Results

The principal results for this contract period are listed below:

1) Identification of important parameters related to fires (Sections C and D).
2) Observed frequencies and conditional probabilities for significant fire parameters, including confidence limits (Section D).
3) Estimates of unreported fires (Appendix A).
4) Time-dependence of construction and operational fires (Sections B.4.1 and B.4.2).
5) Limited scenario development (in Section D, Progress Report 1) based on the techniques of Pinkel and Harmothy, for use in more general model development, item 6 below.
6) Models:
    (a) Three-factor model for preliminary ranking of fire zones (Section B.2), including weighting factors for importance of components in safety systems.
    (b) Model based on observed fire rates and the non-suppression probability (Section B.3).
    (c) Event tree model of typical fire development and its relation to effects on safety systems (Section B.6).
    (d) Identification of other parameters to include in final model (potential release, propagation possibility, susceptibility to fire damage, accessibility) in Section B.3.b.

F. Discussion

The principal results have been described in detail in Sections B-D and summarized in Section E. Estimates of probabilities for the significant fire parameters have been presented for the fires which have actually occurred. Similar estimates can be obtained for other parameters related to fires which have not yet been observed (such as location or component failure induced fires)

Two limited models were developed solely for the purpose of preliminary ranking of fire zones in order of importance for a BWR, to provide a basis for further detailed scenario studies. Factors to be included in more complete models are identified in Section B.3.b. These factors should be incorporated into the limited models to obtain another priority ranking. The use of event trees in tracing postulated fires and identifying critical probability factors was described in Section B.6. These more complete models should now be applied to some of the high priority areas and used to trace out detailed postulated fire sequences in a second phase study for a BWR. A similar analysis should begin for a PWR (SURREY). The results of these detailed studies will be first estimates of the probability of a nuclear accident and will be especially useful for planning a following third phase analyis.

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Appendix A Estimate of the Number of Unreported Fires*

Because of their importance in risk calculations, various estimates of unreported fires* in the operational phase are presented. The last line (#6) of Table 1* presents the number of fires of all kinds actually reported up to June 1978. Using these base numbers, various extrapolations were made in order to arrive at a range, including an upper limit.

Lines 1-3 of Table 1 are extrapolations on the total number of operational plants, referred to certain reference plants as follows:

$$\text{Esitmate} = \left[\frac{\text{No. Reported Fires}}{\text{Plant-months}}\right]_N \text{X} \left[\begin{array}{l}\text{Total Plant-Months}\\ \text{All Operational Plants}\end{array}\right]$$

where:

N = number of reference plants (ie; 4, 6 and all reporting a fire).

The estimates in lines 4 and 5 were based on economic losses. In these cases, an economic threshold for reporting a fire is the criteria for reporting. This may vary somewhat due to plant-to-plant differences in coverage. Line 5 is preferred since this extrapolation is based on five reference plants covered by American Nuclear Insurers, for which all fires are required, in principle, to be reported.

The estimates presented here refer to all types of fires in all locations, internal and external to the plant. Note that the three upper estimates range from 298-467, with a geometric average of 362 fires to June 1978.

*Taken from Progress Report 5/9/78-7/28/78, Contract NRC-04-78-220, by R.W. Hockenbury and M.L. Yeater

TABLE 1

ESTIMATES AND TIME CHARACTERISTICS OF COMMERCIAL NUCLEAR PLANTS

OPERATIONS PHASE*-JUNE, 1978

	ESTIMATE	BWR	PWR	HTGR	FBR	TOTAL**
1.	Total Number of Fires (based on 4 reference plants)	205	244	10	8	467
2.	Total Number of Fires (based on 6 reference plants)	111	135	6	3	298
3.	Total Number of Fires (based solely on plants reporting fires)	21	22	2	0	88
4.	Total Number of Fires (Assuming all major (economic loss) fires reported, based solely on plants reporting fires)	14	11	2		70
5.	Total Number of Fires (Assuming all major (economic) fires reported but based on 5 reference plants)	130	158	7	4	342
6.	Actual Number Reported	20	21	0	2	43

* Time period covers the operational phase for all commercial reactors up to June 1978.

** Reported + Unreported

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Approximately 235 Fire Events have been examined, classified and analyzed for various probability factors related to fires in nuclear facilities. The fire incident data bank is computerized, thus making the information readily accessible for simple sorting. The observed fire events have been used to aid in the construction of preliminary models for estimating the risk due to fires in nuclear power plants. Various aspects of the models are presented, including features to incorporate in second-phase modeling efforts.

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