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MASTER

EARLY OPERATION OF THE C.E.G.B. NUCLEAR POWER STATIONS

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1. Introduction

When the first two C.E.G.B. nuclear power stations commenced generation in June 1962, the objectives which the operators had before them were, in order of priority

(1) to demonstrate both the designed nuclear safety of the stations and the operators' ability to exercise full control;

(2) to demonstrate the reliability of nuclear generation;

(3) to achieve the design output of the station.

The first of these objectives was paramount. The staffs at both stations were carefully selected and trained [1, 2] for nuclear operation and during the first winter at power (1962/63) demonstrated their ability to operate safely under both normal and quite abnormal conditions: the latter, caused by severe weather conditions, included periods of extreme instability of the electrical network voltage. The second objective, the demonstration of the reliability of nuclear generation, has been made clear during the winters of 1962/63 and 1963/64; the performance statistics for these periods are recorded in Table I.

The performance during the whole period since start-up of each station, July 1962 - February 1964, is presented in Table II in terms of the utilisation factor which is defined as

$$\frac{\text{Units sent out} \times 100}{\text{Design sent out capacity} \times \text{Time}} \%$$

*U.K. Central Electricity Generating Board.

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TABLE I

Performance during Peak Loading of C.E.G.B. System

		Berkeley		Bradwell	
		Nov.-Feb. 1962/63	Nov.-Feb. 1963/64	Nov.-Feb. 1962/63	Nov.-Feb. 1963/64
Performance					
Design S.O. Capacity	MW	275	275	300	300
Maximum S.O. Capacity achieved	MW	231	241	278	311
Units sent out	$kWhx10^6$	528	557	552	807
Utilisation factor	%	67	70	64	93
Limitations on Output					
Restricted permissible nuclear fuel element temp.	MW	16	-	22	-
Excessive steam pressure drop in H.P.& L.P.Superheaters	MW	28	-	-	-
Turbine restriction	MW	-	34	-	-
On power dates		R1 June 1962 R2 Oct. 1962		R1 June 1962 R2 Nov. 1962	

TABLE II

Analysis of Performance from Start-up to February 1964

	Berkeley %		Bradwell %	
UTILISATION FACTOR		52		60
UTILISATION LOSSES				
(a) Output Restrictions				
(i) Nuclear fuel temperature		4.8		5.8
(ii) Non nuclear pressure drop in Superheaters		8.0		0
(b) Plant Non-Availability				
(i) Nuclear				
Reactor Trips	0.4		0.4	
Spurious Reactor Trips	1.1		0.6	
Flux Scan Tube failure	0		1.8	
Absorber, fuel, etc. movements off load	2.6		2.1	
Fuel failures	0.7	4.8	0.4	5.3
(ii) Non nuclear				
Modification of S'heaters	9.6		0	
Turbines, Boilers, etc.	6.3	15.9	7.0	7.0
(c) Planned Maintenance		3.6		9.0
(d) External Causes		0.2		0.3
(e) All other causes (load changing, start-up, fuel integrity tests, etc.)		10.7		12.6
		100%		100%

2. Generation Costs

The cost of generation per unit sent out, presented in Table III, has been assessed assuming that a fuel target irradiation of 3000 MWD/Te will be achieved.

TABLE III

Period July 1962 - February 1964 inclusive

Costs of Generation (mills/kWh)	Berkeley	Bradwell
Capital charges	9.7	9.0
Fuel replacement cost, other works costs, insurance and indirect costs	4.4	3.5
	14.1	12.5

Assumed lifetime load factor 75%
Assumed useful life 20 years
Works costs have been adjusted to a 75% lifetime load factor
Capital charges based on an annuity over useful life at interest rate of 7½% p.a.

The incentive under present conditions in the U.K. to maintain both maximum power and maximum availability of nuclear stations using natural uranium is made clear by the replacement generation cost per day for Bradwell, which was £27,000 in January 1963 and £13,000 in July 1963. (The replacement cost is the incremental fuel cost per day of the next available station(s) in the order of merit needed to replace Bradwell's 300 MW.)

Nuclear generation is moving from the stage where the emphasis and interest is on "nuclear" to the stage where "generation" is recognised to be the true objective. The cost figures quoted above show the incentive to review both the operational limits and operational procedures which are reported below. However, it is appropriate to point out that Table II makes clear that failures in conventional parts of the nuclear power stations have led to losses in utilisation during this early operational stage. Experience with conventional equipment in nuclear enterprises in the U.K. would appear to be very similar to that reported in the U.S.A. by Vice-Admiral H.G.Rickover [3].

3. Operational Experience

3.1. Nuclear Fuel

The magnox canned natural uranium fuel elements manufactured for the C.E.G.B. by the U.K. Atomic Energy Authority have performed very well to date. Post-irradiation examinations carried out in the Board's Berkeley Nuclear Laboratories and in the U.K.A.E.A. laboratories, of fuel with channel average irradiation

up to 550 MWD/Te have not indicated any feature likely to limit irradiation to below a channel average of 3000 MWD/Te. Such an assessment, because of the extrapolation involved, must be treated with caution; however it is in line with the performance predicted from U.K.A.E.A. irradiation trials at Calder Hall and Chapelcross and with out of reactor rig tests. A fuel target irradiation of 2500 MWD/Te was accepted when the reactors were first set to work in 1962 and raised to 3000 MWD/Te in 1963. Confidence is growing that it will be possible to operate this class of fuel to its reactivity limit of about 4,500 MWD/Te. Table IV records the main fuel performance statistics.

TABLE IV

	Berkeley	Bradwell
Number of fuel elements	84,877	41,024
Failed during integrity tests whilst commissioning	5	24
Failed during integrity tests after off-load refuelling	5	0
Slow failure	5	3
Fast failure	1	3
Max. channel average irradiation MWD/Te R1/R2	1008/968	1114/1069

The fuel failures fall into three categories, those detected by integrity tests performed during commissioning and after off-load refuelling periods and those failing during normal operation either as "slow" or as "fast" failures, the latter demand a rapid shut down of the reactor. The fast failure is the most serious type and is generally caused by damage to an end cap weld resulting in a long leak path, enabling carbon dioxide to enter the magnox can and produce a uranium oxide mound which grows until the can ruptures. However no difficulties have been experienced to date in handling failed fuel and no permanent contamination of the reactors has occurred.

The failed cartridge detection system is similar to that installed in the Calder reactors with the important difference at the Berkeley station that data logging and alarm printing equipment is installed. The latter prints out any channel or channel group count which falls outside preset limits for either an absolute value or a differential value between successive counts. The equipment, which comprises mechanical printers, transistorised digital circuits and magnetic drum "memories", after some initial faults, has proved to be extremely reliable. The presentation is good since data is printed out in a format which is convenient to analyse, even for long term changes. The time of an event can

be established easily from the print-outs which enable burst and spurious alarm data to be analysed accurately. This system is a marked improvement on earlier point recorder systems where it was possible to overlook occasional high counts and the differential alarm system has increased alarm sensitivity.

3.2. On-load Refuelling

The on-load refuelling facility is the major difference between the nuclear power stations operated by the C.E.G.B. and the earlier U.K.A.E.A. stations at Calder Hall and Chapelcross. The on-load concept calls for a machine which will operate at reactor pressure, certain parts at reactor temperature and containing adequate provision for thermal cooling and radioactive shielding of the fuel as it is withdrawn from the reactor. The machines have met all of the pressure and radioactive shielding requirements. Much careful proving work accompanied by adjustment and modification has been necessary to ensure the correct positioning and movement of charge chutes through which the fuel is guided to the channel being reloaded and to ensure the correct operation of the grab picking up and putting down the fuel elements. On-load recharging was commenced at Bradwell in mid-April 1963, after a careful proving programme calling for the successful handling both of steel reactivity absorber cartridges (at varying powers up to full power) and fuel elements (with the reactor shut down). Fuel was removed successfully at reactor powers of 100 MW(H) and 300 MW(H) before proceeding to the full power stage, 400 - 500 MW(H). Provided that adequate time, about 30 minutes, was allowed for all parts of the chute to reach thermal equilibrium before chute operation began, the chute performed entirely satisfactorily. The fuel element grabs did not invariably pick up the fuel elements at the first attempt and as a consequence of an unirradiated fuel element being dropped whilst being positioned in the machine storage tube, on-load refuelling operations were suspended from May to November 1963. During this time the grab tolerances were altered to reduce sticking and to provide positive direct indication of the grab jaws' position. Previously indication of jaw position had been given by inference from the electrical current operating the jaw locking bolt.

Particular attention was paid to the weight-sensing device incorporated in the discharge machine to indicate if two fuel elements were being raised at the same time. There was no evidence of any sticking occurring between the cup and cone of adjacent fuel elements. During refuelling the channel gas sample signal is continuously monitored and has been observed to decrease and increase during the unloading and loading of each fuel element. It is hoped that an indication of fuel abnormality may be obtained from such signals during refuelling. To date

no such abnormal signal has been observed but neither has any fuel loaded on-load failed. The fuel, graphite and outlet gas temperatures and the reactivity control have all proved satisfactory during on-load refuelling. Since November 1963 the rate of on-load refuelling has steadily improved; the rate necessary to maintain the equilibrium fuel cycle, 60 channels per month, has been achieved. During February 1964, 72 and 92 channels were refuelled in Reactors 1 and 2 respectively.

At Berkeley the refuelling equipment was extensively tested off-load during the summer of 1963, whilst the reactors were shut down for boiler superheater modifications, some 530 channels being refuelled. On-load refuelling was commenced towards the end of January 1964, at 300 MW(H); one channel was removed successfully but either a positioning error and/or positioning indication error led to a fuel element from the second channel being trapped and the graphite support struts associated with the fuel element (Berkeley is the only station with this design of magnox fuel) were broken. The recovery of the pieces of graphite from the reactor necessitated a reactor shut-down. By mid-March 1964 a further 10 channels had been refuelled on-load successfully.

All those concerned with on-load refuelling have achieved a major success in making the on-load concept a reality.

3.3. Reactor Incidents

Two incidents have occurred during this initial operational phase, one at each station, which are worthy of comment.

During the return to service of No.2 Reactor at Berkeley in March 1963, a power excursion occurred when a faulty auxiliary contactor switch spring caused the gas circulator speed to rise although the control switch was in the "off" position. The speed of the gas circulators increased from 1000 to 3000 r.p.m. in $1\frac{1}{2}$ minutes causing a power increase from 170 MW(H) to 290 MW(H) at which stage the neutron flux protection initiated a reactor scram. The fuel element temperatures fell from 380°C to 335°C during the incident immediately prior to the scram. It is worth noting that during reactor start-up the operators continuously reset the trip levels of the excess neutron flux protection equipment and consequently during this incident may have raised the power at which the trip occurred by some 20 - 25 MW(H). Modification to prevent recurrence has been made to the switch.

In May 1963 at Bradwell a 3 cm. diameter tube used to guide a neutron flux plotting wire from the top of the reactor pressure vessel into the graphite core became detached from the standpipe assembly. The defect was observed when a standpipe assembly, which includes a standpipe shield plug, was being replaced

after a routine neutron absorber change. The assembly could not be correctly positioned and a controlled reactor shut-down was initiated. Inspection of the standpipe assembly revealed that some 6 metres of the 3 cm. tube was missing within the reactor. By using a CO_2 cooled TV camera the missing tube was located in two pieces, a short straight piece about 1 metre long, together with the longer piece lying on top of the reactor core. Special grabs were made to retrieve the sections of pipe and after the pipe had been successfully grappled, lifting was done by pile cap crane through a weighing machine. The latter ensured that the lifting force was known and that further damage would not be caused by continuing to lift the tubing if it became entangled with gas sampling pipework within the reactor. In withdrawing the two pieces of tube some 25 cms. broke off the longer piece and fell back into the reactor. Search in fuel element channels by TV camera located this piece which was withdrawn by a remotely driven clamping tool attached to the bottom of the TV camera. The incident was caused by the failure of one or more of the three welds attaching the tube to the standpipe assembly. The detached tube was then able to be broken into pieces as the standpipe assembly was withdrawn through the standpipe. An improved attachment was designed and all flux plotting guide tubes were modified. As a result of this recovery exercise which caused the loss of 18 days generation, renewed attention is being paid to in-reactor illumination. Radiation and contamination controls supervised by the Station Health Physicist ensured freedom from over exposure and from the spread of radio-active contamination.

3.4. Gas Circulators

The types of gas circulators at Berkeley and Bradwell differ from those at Calder Hall, which are of the centrifugal type running at about 1000 r.p.m. with a Ward Leonard speed control. Berkeley and Bradwell use induction motor drives at speeds close to 3000 r.p.m. and axial blowers.

At Berkeley speed control is effected by adjustment of the scoop setting in the scoop controlled hydraulic coupling between the motor and blower shafts. This equipment and the circulator plant as a whole have proved very satisfactory in service. Some difficulties have, however, been experienced with the performance of the shaft oil seals on the circulators. There is evidence that a small quantity of oil leaks into the seal space and forms a mist which finds its way into the blower casing and hence into the reactor core. Steps are being taken to stop the leakage by better sealing, by providing additional baffling and by creating a controlled positive flow of gas through the blower glands to the outside.

The speed of the circulators at Bradwell is controlled by changing the

frequency of the electrical supply to the A.C. motors, the power for which is generated by three variable frequency auxiliary steam turbo-alternators. This method of speed control has also proved very satisfactory in service. Some difficulties have been encountered with the method of fixing the inlet guide vanes at the entry to the impeller. Initially the guide vanes carried shroud rings which were bolted into the vanes with nuts locked by nylon inserts. During commissioning tests the nuts worked loose and vibration loosened the stator blades. The design of the shroud ring on all circulators was modified to enable them to be fixed directly to the circulator casing instead of to the stator vanes. This alteration appeared to be effective. In December 1963, a circulator on No.1 reactor was shut down following the sound of an impact and the onset of severe vibration. It was discovered that five inlet guide vanes and packing pieces had worked loose and had dropped to the bottom of the casing; one passed through the impeller. Inspection of the circuit showed little damage but the circuit affected is now isolated and the reactor is operating on five coolant circuits. The performance of the other blowers at the station is being closely observed for signs of similar trouble. It has been decided to alter the method of fixing the inlet guide vanes to an integral welded ring, vane and shroud assembly. Modifications to all circulators will be carried out during this summer's shut-down.

3.5. Start-up - Load Following

A cautious approach to start-up at Berkeley and Bradwell has been maintained. The time required to reach near maximum power from the completely shut down zero xenon state is about 30 hours. Three factors dominate this time: the permissible rate of temperature increase, the rate and sequence of withdrawal of the safety, stability and bulk control rods, and the xenon state of the core. At Berkeley the fuel element can temperatures are raised at 1°C per minute and at Bradwell at 4°C per minute. Consideration is being given to a step by step increase of these rates within the Operating Rules, which specify a limit of 10°C per minute. At present it is necessary to operate the safety, stability and bulk control rods in group sequence, the movement of each group having to be completed before the next movement is commenced. This movement of the safety and stability systems takes about nine hours in all. By making these systems move together this time may be approximately halved. It is anticipated that these quite simple alterations will permit a start-up time from zero xenon of about 17-20 hours. Other more complex changes which may require modifications to the installation are being considered but will require the most detailed safety studies before their adoption.

The C.E.G.B. nuclear power stations, because of their low operating cost, have been used as base load stations, and, as a direct consequence, the number of times when load following has been demanded are few, but on each occasion very satisfactory experience has been obtained. The very large thermal mass of the graphite moderated reactor cores and the large boilers typical of these plants effectively buffer short term changes in electrical load. In general, load following is achieved by adjustment of coolant gas flow whilst the reactor temperatures are maintained very nearly constant by control rod adjustment.

The most noteworthy occasion when appreciable load changes were demanded was during the major system fault on the morning of 26th January 1963, when severe voltage surges were experienced caused by flashover on high tension insulators which had been affected by the severe weather conditions obtaining at that time. Parts of the national grid were disconnected and considerable voltage instability was experienced during which it became necessary to reduce power rapidly at Berkeley. The station output was satisfactorily reduced as shown in the table below.

Berkeley Station 26.1.63		
Time	Units sent out kW.hrs.	Average Output MW.s.o.
06.00 - 06.30	113,900	228
06.30 - 07.00	74,700	149
07.00 - 07.30	59,200	118
07.30 - 08.00	48,300	97

The output of both reactors was satisfactorily halved in the first hour when a most untimely spurious excess flux trip occurred on Reactor 1. However, Reactor 2 continued to run satisfactorily and its output was then raised to compensate for the loss of reactor 1.

4. Operational Limits

Nuclear stations in the U.K. observe operating rules which are formulated by the C.E.G.B. with the aid of U.K.A.E.A. advisers, and are approved by the Ministry of Power's Inspectorate of Nuclear Installations. Subsequent alteration to the operating rules is possible only after sanction by the C.E.G.B. Nuclear Power Station Safety Committee followed by I.N.I. acceptance and Ministerial approval. The rules not only state what limits are to be observed but also, in certain cases, the detailed method by which controls are to be exercised or assessments made. The operating rules are legally imposed restraints and limits; they cannot be altered easily. The permissible fuel element temperature and permissible

graphite temperature rules for Berkeley and Bradwell have both been revised since operation at power commenced.

4.1. Fuel Element Temperature Limitation

The limitations on fuel element can temperatures are determined by the requirement that following a depressurisation accident the probability of one channel of the whole core population igniting shall be less than 1 in 100. A channel fire is taken to arise from the ignition of the magnox cladding of the fuel.

During such an accident the fuel element cans experience a transient rise in temperature the magnitude of which is partly determined by the reactor shut-down rate (fig.1). The second fastest tripping system is taken to provide the initiating trip sequence. A new design of control rod employing a rate of change of pressure sensitive link has been used in the Bradwell and Berkeley reactors, enabling insertion of $-2\frac{1}{2}\%$ to -3% reactivity to be guaranteed in a period of less than two seconds. The consequential reassessment of the Bradwell fuel element temperature transient resulted in a reduction from 120°C for a channel power of 267 kW to a value of 90°C. Similarly, the transient rise for the Berkeley reactors became 110°C for a channel power of 208 kW compared with the previous figure of 140°C.

Experimental work on the ignition temperature of the magnox canning material under the conditions prevailing during the transient has enabled this temperature to be set at 645°C and when allowance is made for possible fin deformation, 640°C is taken to be the maximum permissible temperature during a transient, an increase of 20°C over the previously assumed figure of 620°C.

The channel maximum fuel element can temperature distribution (Tsm) was deduced, leading to the estimated fuel element temperature during the transient (T_T) as shewn in Figs.2a and 2b for Bradwell. An estimate was obtained of the uncertainty in the final fuel element temperature distribution at the peak of the accident transient. The error distribution associated with a typical value of T_T is shewn in Fig.2b. The total reactor risk was obtained for any maximum assessed fuel element temperature (Fig.3 for Bradwell) with a pessimistic allowance for random temperature variations of 15°C.

From this it may be seen that the desired fire risk criterion would be met by a maximum assessed fuel element temperature of 483°C for the Bradwell reactors. A permissible maximum assessed fuel element temperature of 475°C was conservatively adopted, an increase of 25°C over the previous limit. For

Berkeley, the permitted temperature was raised similarly from 437°C to 467°C.

4.2. Graphite Temperature Limitation

The increased fuel element can temperatures required that the permitted temperature of the moderator graphite be reassessed also. The moderator temperature is limited by consideration of the graphite behaviour following a duct rupture accident. Safety studies assume that air will enter the reactor vessel and result in oxidation of the graphite. This reaction is exothermic and its rate increases rapidly with increasing temperature. If the initial moderator temperature is high enough an uncontrollable rise of temperature could occur.

A fundamental parameter determining the behaviour of this graphite temperature transient is the air oxidation rate of the graphite. Measured values of this parameter exhibit a large statistical variation. It had previously been the practice to use the largest measured value for inclusion in safety studies. The samples on which the oxidation measurements have been carried out are very much smaller than a moderator brick and it did not, therefore, necessarily indicate that the mean oxidation rate of a complete brick would show the same amount of variation. Whilst large variations of oxidation rate occur within a brick the variation of mean oxidation rate from brick to brick is much less. Statistical analysis of these results enabled a lower value of oxidation rate corrected for the effects of three years' irradiation to be used in computer kinetic studies. At Bradwell the permissible graphite temperature has been increased from 410°C to 427°C.

At Berkeley, chemically active carbon deposits found on graphite core samples and believed to have arisen from the oil ingress referred to in para.3.4, have not permitted a similar increase.

5. Operational Procedure

The incentive for improving availability is great and has led to a reassessment of the time the reactor and its associated turbo-alternators must be off load for maintenance and inspection purposes. It was possible to combine the maintenance period with the period required for off-load refuelling at Calder Hall [4]. The C.E.G.B. reactors however refuel on load and the down time is therefore determined by the maintenance and inspection deemed to be necessary.

5.1. Boiler Tube Failures

Leakage of boiler water into the reactor primary coolant gas circuit has occurred once at Berkeley and on a number of occasions at Bradwell. The infra red gas analysers fitted to each boiler enable the faulty boiler to be

identified, isolated and drained, the reactor remaining on power with the remaining five boilers. In this condition, with the gas side of the faulty boiler still pressurised, the steam and water headers are tested individually for carbon dioxide, the presence of which identifies the faulty section of the boiler. Further exploration with a probe enables the defective tube to be located and it is then plugged. This whole operation takes approximately 20 hours with the techniques which have been developed at Bradwell. However, the Berkeley boiler headers have welded caps and detection and isolation of the one tube leak which has been experienced there took rather longer.

5.2. Control Rod Mechanisms

It is a clear safety requirement to test the insertion characteristics of control rods following a trip signal and, in the case of a reactor refuelling off-load, there is sufficient time for control rods to be tested singly in a specially instrumented rig external to the reactor. In the case of a reactor refuelling on-load, this method may also be used if equipment for removing control rods on load is provided.

At Bradwell there is not an on-load control rod removal facility. To surmount this difficulty a technique has been evolved whereby all the control rods are tripped simultaneously into the reactor when it is being shut down on schedule. A cine film record is taken of the control rod indicators in the control room and from this the necessary information on drop characteristics of each control rod may be obtained.

6. Present Performance

The Bradwell station is now operating at or slightly above the design output of 300 MW s.o. with a margin of 5°C on the new permissible fuel element temperature and a 10°C margin on the new permissible graphite temperature; a maximum of 311 MW s.o. has been achieved.

The Berkeley station is operating at some 241 MW s.o. (cf. design 275 MW s.o.) with the output limited by the turbines. Remedial work will commence after the winter of 1963/64, following which there is little doubt that design output will be achieved.

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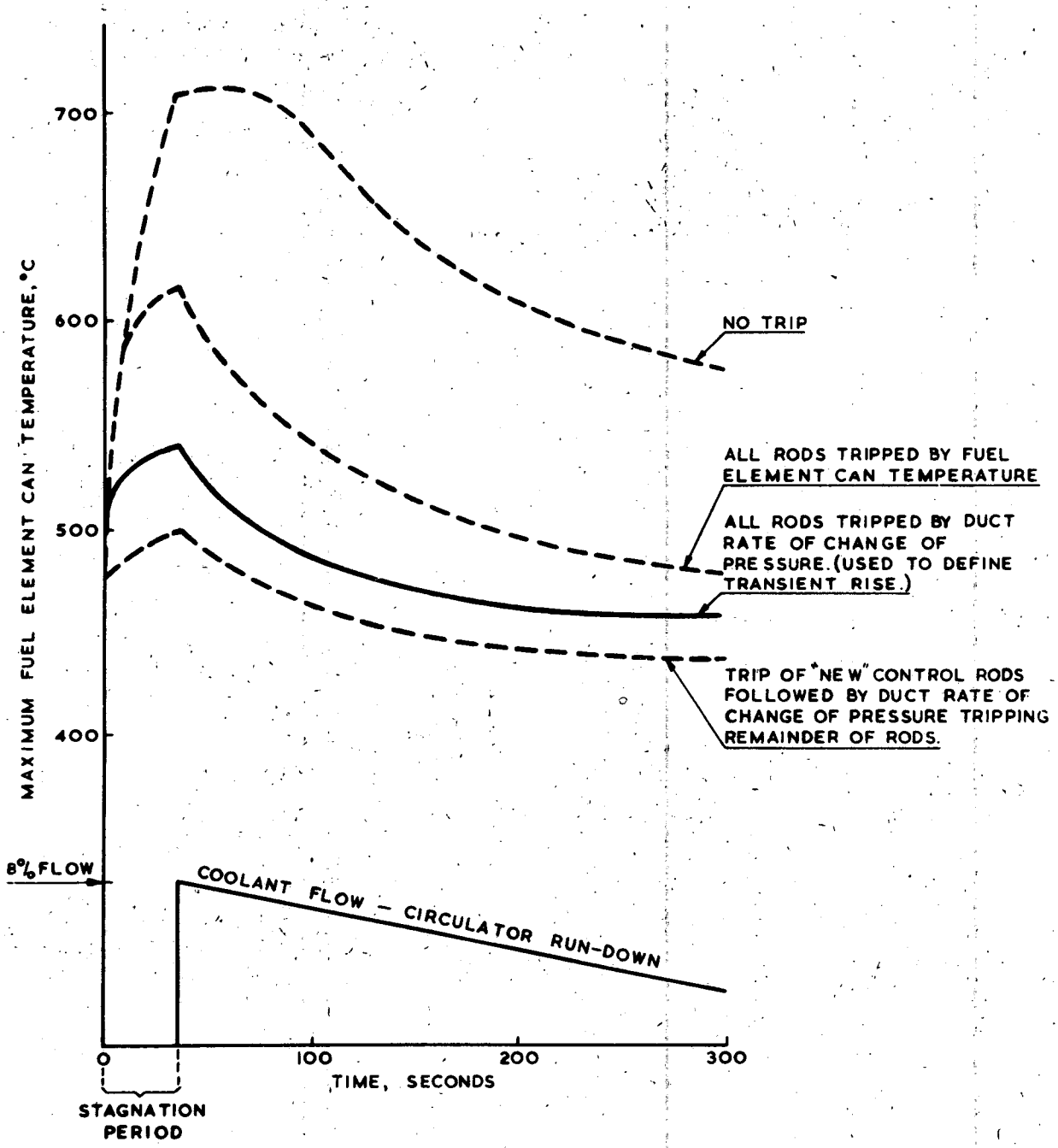

FIG. 1. FUEL ELEMENT CAN TEMPERATURE IMMEDIATELY FOLLOWING BURST BOTTOM DUCT ACCIDENT.
(ZERO IRRADIATION OF CORE: FULL POWER PRIOR TO ACCIDENT.)

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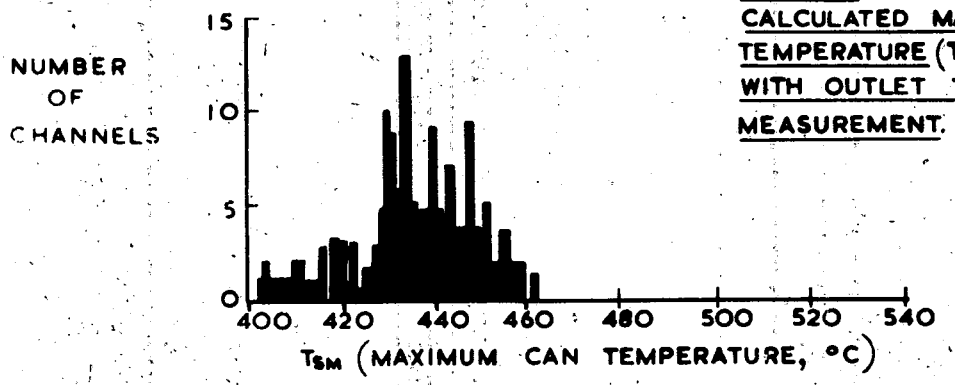

FIG. 2 A
CALCULATED MAXIMUM CAN TEMPERATURE (T_{SM}) IN CHANNELS WITH OUTLET TEMPERATURE MEASUREMENT.

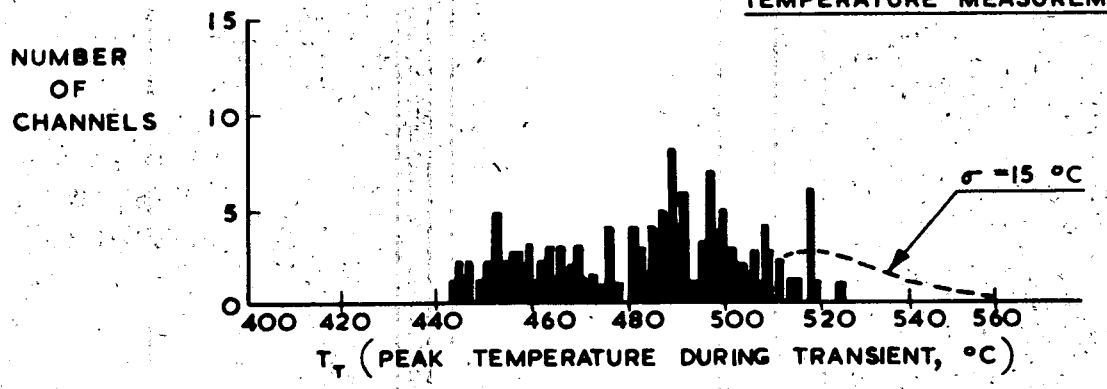

FIG. 2 B
TRANSIENT PEAK TEMPERATURES (T_T) IN CHANNELS WITH OUTLET TEMPERATURE MEASUREMENT.

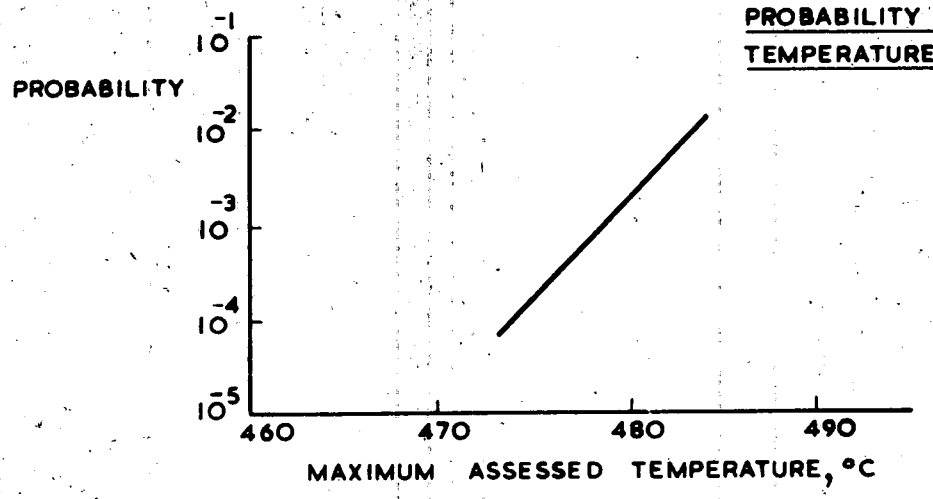

FIG. 3
PROBABILITY OF A CAN TEMPERATURE EXCEEDING 640 °C

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