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LMR CENTRIFUGAL PUMP COASTDOWNS*

by

F. E. Dunn and D. J. Malloy
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

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LMR CENTRIFUGAL PUMP COASTDOWNS

F. E. Dunn and D. J. Malloy, Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
312/972-4692

I. INTRODUCTION

Pump behavior during the coast-down resulting from loss of power events and the time at which the rotor locks are important factors in determining the transition from forced to natural circulation in liquid metal reactors (LMRs). This behavior is especially important when designing the current generation of inherently safe reactors[1,2] which will be designed to achieve safe shutdown during unprotected LOF transients without active systems such as pony motors. Until prototype pumps for a new plant are built and tested, it is necessary to extrapolate pump behavior from representative, existing pumps.

A centrifugal pump model which describes the interrelationships of the pump discharge flowrate, pump speed, shaft torque and dynamic head has been implemented based upon existing models. Specifically, the pump model is based upon the dimensionless-homologous pump theory of Wylie and Streeter[3,4]. Given data from a representative pump, homologous theory allows one to predict the transient characteristics of similarly sized pumps. This pump model further draws upon a later development by Marchal, Flesch and Suter[5] which considerably simplifies the homologous treatment.

This homologous pump model has been implemented into both the one-dimensional SASSYS-1 systems analysis code[6] and the three-dimensional COMMIX-1A code.[7] Comparisons have been made both against other pump models (CRBR) and actual pump coastdown data (EBR-II and FFTF). Agreement with this homologous pump model has been excellent. Additionally, these comparisons indicate the validity of applying the medium size pump data of Wylie and Streeter to a range of typical LMR centrifugal pumps.

II. SUMMARY OF THE PUMP MODEL

A brief review of the more familiar form of homologous pump theory is presented below. Dimensionless-homologous pump theory and data has been developed for many years. The original pump test data of Hollander is presented by Knapp in 1937 (Ref. 8) and subsequently utilized by Stepanoff[9] and Donsky[10] (among others) in 1956 and 1961 respectively. This short summary is provided for completeness; the reader is referred to references 3-5 and 8-10 for detailed derivations and data.

In the form presented by Wylie and Streeter in 1967 (Ref. 3), dimensionless-homologous turbomachinery theory provided a functional means with which to predict the transient characteristics of a pump. The theory is based upon the fact that the head and torque curves for different pumps (i.e., head vs. discharge flowrate or head vs. speed), have similar shapes given that the pumps are geometrically and dynamically similar. This similarity condition is satisfied when the specific speeds of the pumps of interest are equal or close to one another. The specific speed of a pump is defined as:

$$N_s \equiv \frac{N\sqrt{Q}}{H^{0.75}}, \qquad (1)$$

with

N = rpm,
Q = gpm/(m^3/s),

and

H = feet/(m) for English, i.e. gpm/(metric) units.

The specific speed provides a similarity condition for comparing pump performance, just as the Reynolds number does when, e.g., one is considering comparable pipe flow problems. Homologous pump data is available from Wylie and Streeter[4] for three representative pumps: N_s = 1800, 7600, and 13500 in gpm units. [The FFTF pump has a specific speed of approximately 1400, EBR-II has a value of ~1600 and CRBR's pump has a value of approximately 2100; thus the data at N_s = 1800 appears to be applicable to current LMR pump designs.]

In the dimensionless homologous pump theory of Wylie and Streeter[3,4], as modified by

Marchal, Flesch, and Suter[4], the dimensionless (i.e. divided by their rated values) head ($\bar{H}$) and hydraulic torque ($\bar{T}$) are evaluated as

$$\bar{H} = (\bar{N}^2 + \bar{Q}^2)W_h(x) \qquad (2)$$

and

$$\bar{T} = (\bar{N}^2 + \bar{Q}^2)W_T(x), \qquad (3)$$

where

$$x = \pi + \arctan(\bar{Q}/\bar{N}), \qquad (4)$$

$\bar{N}$ is the dimensionless speed (relative to the rated value), and $\bar{Q}$ is the relative volumetric flow rate. The functions $W_h(x)$ and $W_T(x)$ are the homologous head and torque data as given by Wylie and Streeter[4], i.e. the N_s = 1800 data. For use in the SASSYS-1 code, the homologous pump data values were fit using three-range sixth order polynomial fits, as indicated in Table I. Note that the middle range ($j=2$) corresponds to the region of normal interest with $\bar{N} > 0$ and $\bar{Q} > 0$. This correlation agrees with the Wylie and Streeter curves to within .02 for W_h and within .04 for W_T. Single range representations have been used in COMMIX-1A, which required the application of 8th order polynominal fits. Figures 1 and 2 illustrate the functions $W_h(x)$ and $W_T(x)$ over all four quadrants of pump operation as well as each of the above polynomial fits.

The equation used for rotor speed, N(rpm), is

$$\frac{2\pi}{60} I_p \frac{dN}{dt} = T_m - T_R \bar{T} - T_R \bar{T}_\ell, \qquad (5)$$

where I_p is pump moment of inertia, T_m is the motor torque, T_R is the rated hydraulic torque, and $\bar{T}_\ell$ is the normalized loss torque which represents the bearing friction, viscous losses, fluid/rotor interaction and windage, normalized to Tr. At normal operating speeds the loss torque is small compared with the hydraulic torque; but at low speeds the loss torque dominates. Thus, the loss torque largely determines the shape of the flow coastdown tail and the time of rotor lock-up. Based on measurements on the CRBR prototype pumps, Severson[11] created a correlation for $\bar{T}_\ell$ of the form:

$$\bar{T}_\ell = \begin{cases} .01 - 73.13\,\bar{N}^2 & \text{if } .01 > \bar{N}, \\ .00268 + .07\,\bar{N}^2 & \text{if } .268 > \bar{N} > .01, \\ .00383 + .01071\,\bar{N} + .01406\,\bar{N}^2 & \text{if } \bar{N} > .268. \end{cases} \qquad (6)$$

For expediency, the above functional dependency will be applied to each of three pumps in this work.

III. MODEL APPLICATIONS

III.A Applicability of Data for N_s = 1800 (gpm)

The Wylie and Streeter head and torque data[4] are given for pump specific speeds of N_s = 1800, 7600, and 13500 (gpm units). The data of N_s = 1800 was chosen as being representative of typical medium sized LMR pumps. The applicability of these data is briefly discussed here.

Table I. Coefficients for Fits to Wylie and Streeter Pump Head and Torque Curves

$$W_h(x) = \sum_{i=0}^{6} a_{hji}\, x^i \qquad W_T(x) = \sum_{i=0}^{6} a_{Tji}\, x^i$$

	j=1, π>x>0		j=2, 3π/2 > x > π		j=3, 2π > x > 3π/2	
i	a_h	a_T	a_h	a_T	a_h	a_T
0	.63380980	-.68436766	431.96699	-1154.9471	-6171.9821	-379.8[illegible]80
1	.46015764	2.7759909	-576.61438	1858.4915	-4958.9692	726.14514
2	-2.4004049	-5.3988010	301.00029	-1237.6683	1406.3329	-496.2509
3	3.17937240	6.8541205	-75.465856	436.01653	-126.17344	167.64136
4	-1.7730449	-4.0757860	8.6754986	-85.573772	-13.217121	-30.366923
5	.46235776	1.0813311	-.26062352	8.8627717	3.2450530	2.8311896
6	-.04624640	-.10475812	-.01596287	-.37830487	-.16925040	-.10681625

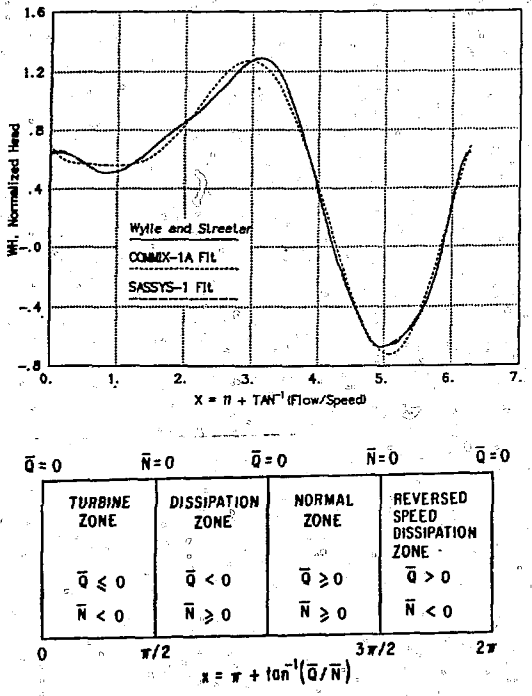

Fig. 1. Dynamic Head, Data and Fits

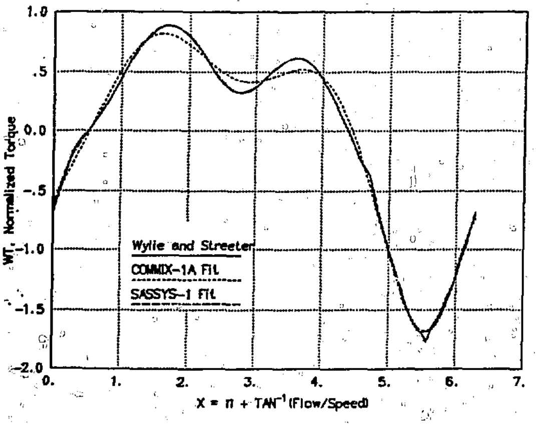

Fig. 2. Hydraulic Torque, Data and Fits

The Wylie and Streeter data span a range of ΔN_s = 12,000 with the data sets separated by ΔN_s = 6000. By inference, a change in the pump specific speed of several thousand is deemed substantial and will lead to changes in the characteristic pump response. Conversely, a change of only several hundred in N_s is deemed to be minor: substantive changes to the pump's characteristic response will probably not occur. This point is also made by Donsky[10] and is implicit to the data reported by Stepanoff.[9] To illustrate this subjective argument, the specific speeds of several LMR pumps are given below in Table II.

As can be seen, specific speed variations of several hundred are evident among the pumps. In fact, the FFTF pump listing illustrates how relatively small changes to the rated parameters can alter N_s by approximately 150. Given this, one can easily justify the use of the homologous data at N_s = 1800 gpm for pumps in the range of, e.g., N_s = 1400 → 2200. Verification of this subjective decision is seen in the following section which compare the homologous pump model results utilizing N_s = 1800 gpm data with both the EBR- II (N_s = 1600) and FFTF (N_s = 1200) pump coastdowns.

III.B Comparison with Other Calculations

The application of the homologous pump theory is relatively straightforward, as is the pump equation of motion. This basic methodology and pump data have been utilized previously with good success.[12] An initial benchmark of this homologous pump model was to duplicate the results from the homologous pump model calculation of Ref. 12. This was done and essentially verified that the homologous methodology was correctly installed in the current model. As a further step toward model verification, the CRBR primary pump coastdown was computed and compared with the calculations resulting from the Westinghouse pump model.

III.B.1 Comparison with the Westinghouse Pump Model Calculation of the CRBR Coastdown

The Westinghouse pump model solves the pump equation of motion in a manner essentially identical to the current homologous pump model. The head and torque data, however, were developed directly from prototypic test results rather than utilizing representative pump data. Although the Westinghouse data is represented in a similar functional fashion as the Wylie and Streeter data fits (e.g. H = f (Q/N), T = f (Q/N)), the Westinghouse correlations are specific to the CRBR primary pump. A comparison of the CRBR pump coastdowns resulting from both the current homologous model and the Westinghouse model will therefore serve to quantify the impact of the head and torque differences between the two models. In addition the comparison will serve to demonstrate the applicability

Table II. Specific Speeds of Various LMR Pumps

$$N_s \equiv N\sqrt{Q}/H^{3/4}$$

	N_s		Rated Conditions		
			N_R	Q_R	H_R
	SI	English	(rpm)	(gpm)	(ft)
Wylie and Streeter Medium Sized Pump	34.86	1800	-	-	-
EBR-II	31.01	1602	870	4670	124
FFTF: Steady State Test	21.45	1108	1010	13444	500
FFTF: Rated	24.48	1264	1110	14500	500
SNR-300: Primary	28.62	1478	960	23335	459
SNR-300: Secondary	34.32	1772	960	20254	328
Phenix	38.53	1989	800	16731	194
CRBR	40.08	2069	1116	33700	458

of generalized head and torque data to a pump whose specific speed is somewhat different: N_s = 2069 for CRBR vs. N_s = 1800 for the Wylie and Streeter medium sized homologous pump data.

A coastdown calculation was performed with the homologous pump model utilizing the CRBR pump parameters listed in Table III (the rated frictional torque is denoted $T_{f,R}$). The results, along with those from the Westinghouse calculation, are presented in Figure 3. The global characteristic response is essentially the same between the two models. The homologous pump speeds are seen to be consistently higher than those from Westinghouse, but not by an excessively large degree. For the first portion of the transient (i.e. the first minute), the homologous model values are ~13% higher. The homologous pump model effectively stretches out the transient with respect to the Westinghouse results; rotor lock occurs at 130 s and 143 s for the Westinghouse and homologous models, respectively. Global response, however, is well predicted overall.

Given that the global pump response is accurate, it is expected that the homologous calculation can be easily adjusted, if desired, to produce a more exact agreement with the Westinghouse calculation. To illustrate this capability, the pump's moment of inertia (I_p) was reduced from the nominal 1182 kg.m^2 to 1071 kg.m^2. The homologous pump model calculation was repeated with only this change; the results are also shown in Fig. 3. It is seen that this slight change in I_p reduces the homologous results such that they agree very well with the

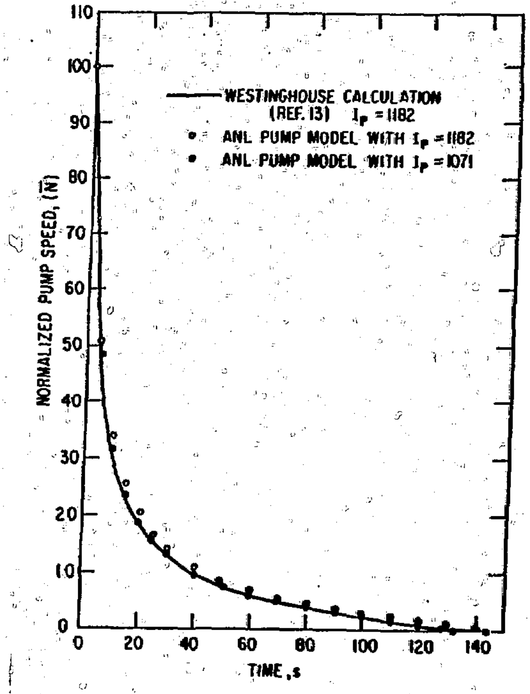

Fig. 3. **Comparison of the Homologous and Westinghouse Pump Model Calculations of CRBR Primary Pump Coastdown**

Westinghouse results. Rotor lock now occurs at 132 s with the homologous pump model, this compares favorably with the Westinghouse value of 130 s. Obviously a further modification to I_p could yield a more exact agreement between the two, curves, however the models flexibility is verified without further calculations. Additionally, this comparison produces the conclusion that the generalized Wylie and Streeter data at N_s = 1800 gpm is applicable to medium speed centrifugal pumps. The specific speed for the CRBR primary pump is ~2069 gpm, thus the generalized data is demonstrated to be appropriate given a ΔN_s of ~300. As mentioned in Section III.A, it was expected that a variation of $\Delta N_s = \pm 400$ would be acceptable; the results here tend to support this.

TABLE III. CRBR Primary Pump Model Parameters

Parameter	Rated Conditions
N_R (rpm)	1116
H_R (m)	139.6
Q_R (m^3/s)	2.1261
N_s (SI/gpm)	40.1/2069
I_p ($kg \cdot m^2$)	1182
T_R ($N \cdot m$)	26,981
$T_{f,R}$ ($N \cdot m$)	$0.0286T_R$ (771.65)

III.C Comparison with Experimental Coastdown Data

The next step in model validation was to compare the homologous pump model's response with actual experimental data. Two pumps were utilized: EBR-II and FFTF.

III.C.1 Comparison with EBR-II Coastdown Data

A comparison with with the EBR-II SHRT-17 test[13] data was performed with the SASSYS-1 code. Table IV gives the pump parameters used for the EBR-II simulation. EBR-II has two primary pumps. Pump 1 has higher frictional torque losses and stops sooner during a coastdown. The SASSYS-1 calculations were done for pump 2. Also, during a coast-down the pumps in EBR-II lock-up suddenly at a speed of about 3% of its rated value. This lock-up was modeled empirically in the SASSYS-I calculation.

For the SHRT-17 test, the power to the motor-generator sets driving the primary pumps was tailored to give a coast-down with an initial halving-time of 6 seconds. The ratio of the measured pump motor power to motor speed was used to obtain the pump motor torque (T_m) utilized in Equation 5 as a function of time. The pump inertia was adjusted to fit the early part of the coast-down. The loss torque of Equation 6, with a scale factor of 1.0, was found to be adequate for the later part of the coast-down. The impact of the scaling factor is lessened by the imposed rotor lock at 3% speed.

The coastdown data and homologous prediction is illustrated in Fig. 4. Excellent agreement is maintained over the entire coastdown range.

Table IV. EBR-II Primary Pump Parameters

Parameter	Rated Condition
NR (rpm)	870
H_R (m)	37.7
Q_R (m^3/s)	0.2946
N_s (SI/gpm)	31.01/1602
I_p ($kg.m^2$)	16.
T_R (N.m)	1300
$T_{f,R}$ (N.m)	.0286 T_R (37.2)

III.C.2 Comparison with FFTF Coastdown Data

A comparison of the homologous pump model versus FFTF acceptance testing data was performed within the environment of the COMMIX-1A code. Table V lists the various pump parameters which were available from the literature for the FFTF pump. It can be seen that critical data are missing: the rated hydraulic torque and the rated frictional torque. Given this problem, it is not possible to simply calculate a coastdown utilizing the recommended reference parameters from the literature and then to compare the homologous pump model response with the actual data.

The absence of data does not preclude a meaningful comparison; in fact, it alters the exercise such that a more rigorous testing of the model can be achieved. In a realistic situation, a pump manufacturer would nominally provide N_R, Q_R, H_R and probably I_p to its customer. The hydraulic and frictional torques would be furnished only through representative data ($\tau_{hydraulic}$) or through experimentation ($\tau_{hydraulic}$ and $\tau_{frictional}$). This situation matches the available data: recommended FFTF values for N_R, H_R, Q_R and I_p will be utilized by the homologous pump model while the rated hydraulic torque and the frictional torque will act as model variables to be adjusted until an acceptable comparison is attained with the experimental data. This is then analagous to determining the missing pump parameters via prototypic pump test data. The fitting procedure falls into two categories: (1) adjusting T_R until the beginning of the transient matches the data and (2) choosing acceptable frictional

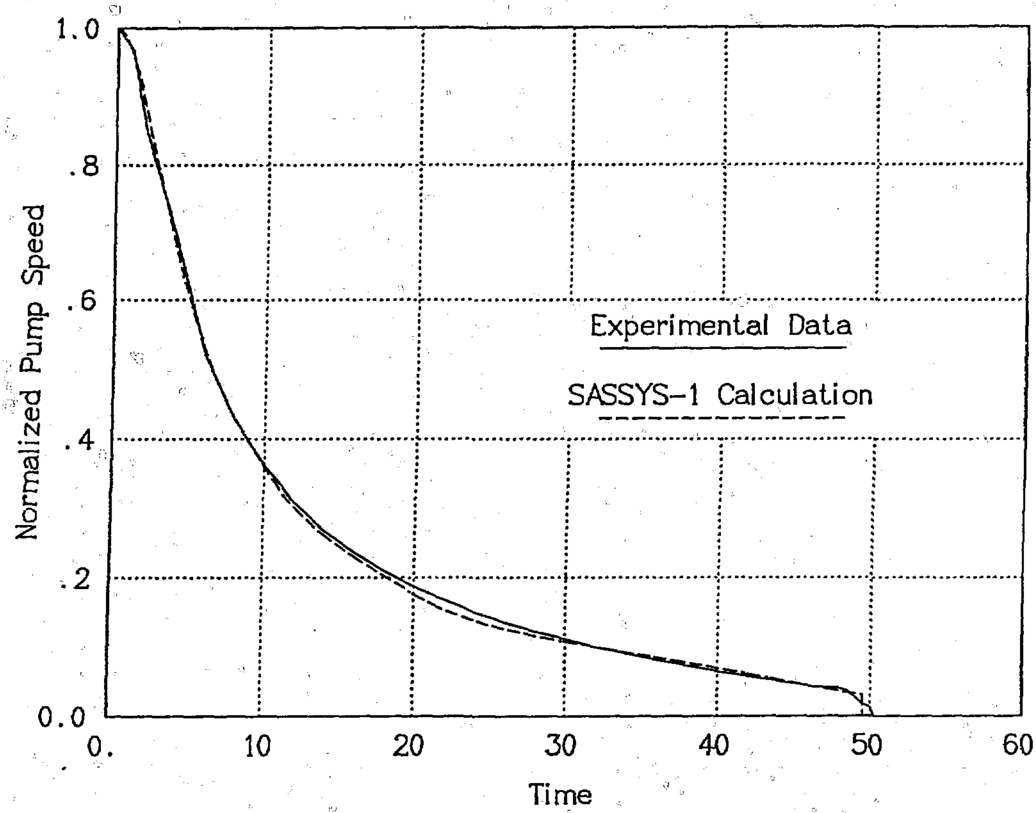

Fig. 4. EBR-II Pump Speed, SHRT-17 Test

torque expressions and adjusting $T_{f,R}$ until the tail of the coastdown matches the data. [Additionally, some iteration could be necessary as the two parameters do interact and influence the middle portion of the transient.]

The frictional torque expressions could either be created for these data or borrowed from a representative pump. Because this exercise concerns a calculational experiment rather than an actual prototypic pump, an expedient course was chosen: utilize the frictional torque expressions from the CRBR primary pump (Equation 6, see section II). Assuming that the expressions general dependencies upon N are appropriate to FFTF primary pumps, then the frictional torque term can be scaled directly. [This is referred to as the "Biased CRBR Frictional Torque" in subsequent figures]. The second modeling variable is the rated hydraulic torque, with which the normalized values from the Wylie and Streeter data are multiplied. This variable (T_R) was simply adjusted parametrically until an accurate fit was obtained. A comparison of the CRBR and FFTF pump parameters (Table III and V) shows that the FFTF pump is somewhat smaller with respect to both the moment of inertia and the rated flow. Specifically, the ratio of FFTF/CRBR values of I_p and Q_R is .60 and .43: a credible value for T_R should probably be within this range. The parametric, therefore, concentrated near this range of modification to the CRBR value: expected values

Table V. FFTF Primary Pump Parameters

Parameter	Rated Condition
N_R (rpm)	1110
H_R (m)	152.4
Q_R (m^3/s)	0.91481
N_s (SI/gpm)	24.48/1264
I_p ($kg.m^2$)	704.9
T_R (N.m)	not available
$T_{f,R}$ (N.m)	not available

of the FFTF T_R were thus between 10,800 (40%) and 16,200 (60%) N.m.

It should be noted that this empirical fitting procedure is not unlike the actual process of creating a pump model for a specific pump. For example, implementation of the prototype pump data from the CRBR tests resulted in substantial changes to the original estimated frictional torque representations. In fact, the estimated time of motor lock doubled when the improved frictional estimates were reflected in the pump model (e.g. compare Ref. 12 with Fig. 3). Thus, this parametric exercise with the FFTF pump data is not at variance with realistic procedures.

The parametric adjustments to T_R indicated that a value of 13,500 N.m produced an excellent fit of the data during the first portion of the transient. This value corresponds to 50% of the CRBR value and is therefore quite credible with respect to the expected range of values. The adjustment of the frictional torque expressions achieved a similar agreement with the data: the application of a bias factor of 2.5 was seen to yield good results over the last portion of the transient. Figures 5a and 5b compare the data with this calculation over two scales. It can be seen that there are slight differences in the transition range, however, the magnitude is such that they are irrelevant from a practical viewpoint.

These comparisons illustrate several points. First, as verified by Figs. 4 and 5a, the homologous pump model can be made to match experimental coastdown data via some rather simple parameter adjustments. The homologous models applicability to an actual pump is again confirmed. Second, the results here indicate that the Wylie and Streeter data are applicable to a pump with a specific speed differential of >500. The previously discussed range of applicability (i.e. ±400) is again verified and also demonstrated to be possibly conservative. With respect to Fig. 5b, a third conclusion is that the exact point of rotor lock shows a several second variance among the FFTF loops. Clearly the loop 3 pump has substantially higher frictional torque values than the loop 1 or 2 pumps. This physical example demonstrates the magnitude of variances one can expect in "identical" pumps. Given this, the precise achievement of a certain calculated rotor lock time with any particular calculational model has less significance.

The fourth conclusion concerns the transition period. The figures illustrate that the frictional torque expressions borrowed from the CRBR pump produced a very good fit of the data. This shows that one does not necessarily need specially fit expressions for different pumps. The inherent quadratic dependencies upon $\bar{N}$ are shown to be adequate by example in these cases. However, the frictional torque is composed of

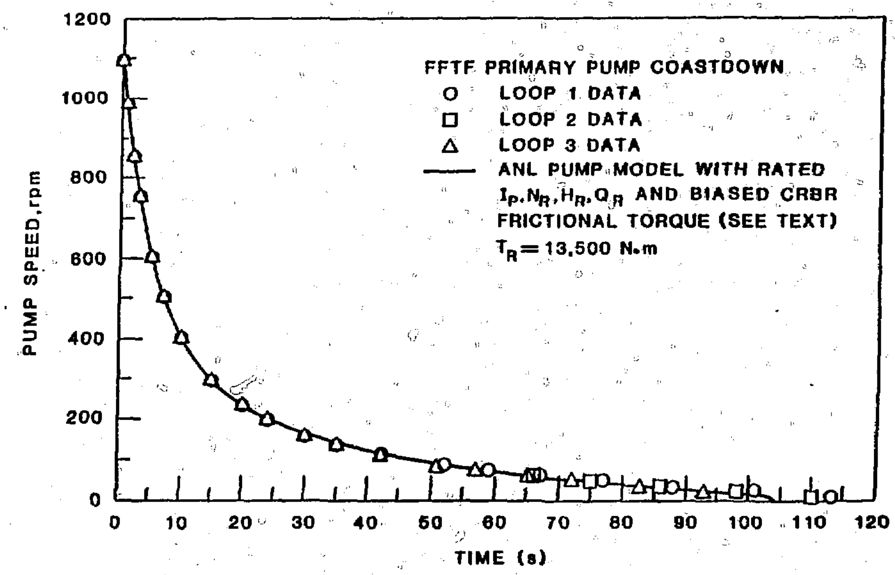

Fig. 5a. Comparison of Homologous Pump Model Calculation with FFTF Primary Pump Coastdown Data

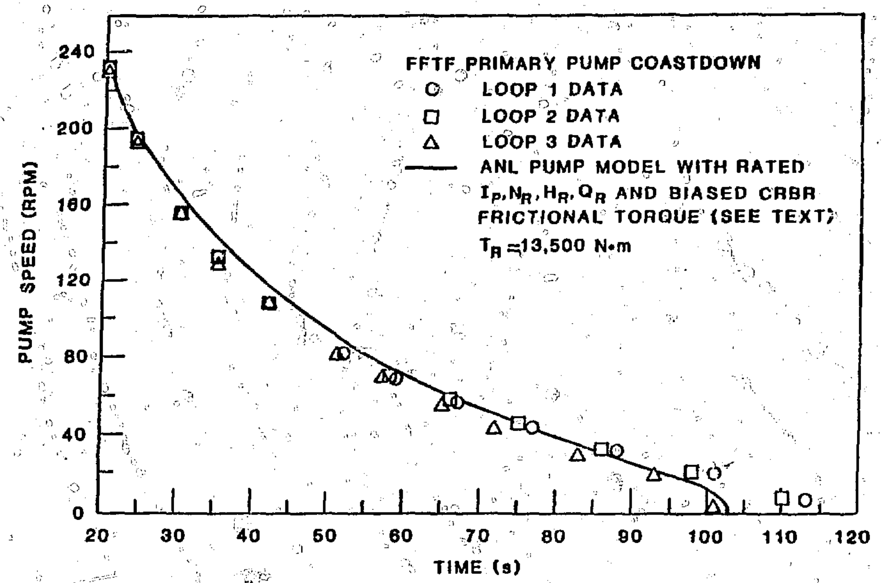

Fig. 5b. Comparison of Homologous Pump Model Calculatiaon with FFTF Primary Pump Coastdown Data: Expanded Scale

two calculational components, the functional dependencies themselves and the scaling factor of the rated frictional torque. This latter quantity is not transferable between pumps, even of the same size. The point here is that the fitting procedure for the FFTF data was made uncomplicated by utilizing the available CRBR expressions and simply scaling them uniformly upward to achieve the desired fit. A corollary to this is that if one were concerned with the differences exhibited within the transition region, two straightforward yet tedious solutions exist. One is to bias the expressions in a nonuniform manner, i.e. a different bias factor within each pump speed range. A second solution is to create a new set of frictional torque expressions, unique to the FFTF data. Both procedures complicate the fitting process, particularly the latter approach.

IV. SUMMARY AND CONCLUSIONS

A homologous pump model has been assembled which is applicable to standard centrifugal pumps as utilized in LMR analyses. This model is based upon the dimensionless-homologous pump theory of Wylie and Streeter[3,4] with modifications to include the improved homologous formulations of Marchal, Flesch and Suter.[5] Briefly, homologous pump theory states that geometrically similar pumps will have similar dynamic conditions. In particular, the pump head vs. discharge flowrate and the head vs. pump speed data for pumps of similar specific speeds will be identical. The specific speed is given as:

$$N_s \equiv \frac{N\sqrt{Q}}{H^{0.5}} \cdot$$

The specific speed thus provides a similarity condition which ensures that pump response is essentially identical among pumps with similar specific speeds. Given this, the homologous data can predict the response of any centrifugal pump as long as the desired pump's specific speed is near the specific speed of the pump which produced the homologous data.

The validity of utilizing medium specific speed (i.e. N_s = 1800 gpm) homologous data for current sized LMR pumps was demonstrated both by inference and by direct calculation. First, a comparison among several actual LMR pumps illustrated that the individual specific speeds bracketed 1800 gpm, these values ranged from ~1200 to ~2100 (gpm). Subsequent benchmark calculations illustrated that the chosen homologous data were equally applicable to the CHBR pump at N_s = 2069, to EBR-II with N_s = 1602, and to the FFTF pump with N_s = 1264. Specific speed variations of at least about +300 and −500 around the chosen value of 1800 were thus demonstrated to be allowable. If in the future much larger sized pumps are utilized, homologous data are readily available at N_s = 7600 and 13,500 (gpm).

The homologous pump model was implemented into both the SASSYS-1 one-dimensional and the COMMIX-1A three-dimensional thermal hydraulics codes for testing. Validation was achieved by comparing calculational results with both those obtained from alternate pump models and also against actual pump coastdown data. With respect to CRBR primary pump coastdown calculations, the homologous pump model (via COMMIX-1A) compared well against the Westinghouse model. Given equivalent parameters, both pump models produced essentially identical results despite the fact that the Westinghouse model used prototypic test data while the homologous model utilized representative homologous data.

Comparisons with actual pump coastdowns were made against the EBR-II and FFTF data, with SASSYS-1 and COMMIX-1A, respectively. In each case, the homologous pump model provided excellent agreement with the data. Several conclusions can be made at this time. First, it has been demonstrated that the homologous data at N_s = 1800 (gpm) is applicable to current medium sized LMR centrifugal pumps. This is both from investigation of the data and application to a wide range of pumps. Second, the homologous pump model has been shown to be an accurate representation of the homologous data as shown via comparison with calculations from alternate homologous pump models. Third, the comparison versus the EBR-II and FFTF coastdown data illustrated that the pump model can accurately reproduce the characteristics of actual pumps. Therefore, the current homologous pump model is deemed to be both validated and representative of typical LMR centrifugal pumps.

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