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ZERO-GRAVITY TRANSIENT THERMAL MIXING SIMULATION

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I. ABSTRACT

The experimental program described in this paper is an outgrowth of independent investigations into alternate redesign concepts for the Apollo SM cryogenic oxygen storage system. The experiments were continued, after the redesign was established, to provide physical insight into transient thermal mixing in zero-gravity and to aid in the characterization of the system performance in flight.

Zero-gravity heat transfer and fluid mixing were simulated experimentally through an analogy between unsteady heat conduction and species diffusion. The forced convection and transient fluid mixing associated with initiation, reversal or termination of spacecraft passive thermal control (PTC) motions have been studied through geometric and Reynolds number similarity and by the use of a dye diffusing into water. Motion pictures of the simulation have been made and radial measurements of the time for the fluid to come to equilibrium with the tank motion were taken. The results indicate that there should be a negligible potential for pressure collapse in the oxygen tanks for a significant period of time after a change in PTC. These times vary with the mass of oxygen in the tank, however, they are on the order of from 3 to 10 hours. Unfortunately, experimental simulation of the heat transfer at the heater-fluid interface was not adequate for quantitative assessment of overall energy transport, however, in principle the potential for this simulation does exist.

To further support numerical analyses of the cryogenic oxygen storage system, the experimental investigation was extended to include a cubical tank geometry, representative of existing numerical models. In general, the transient flow patterns in the cubical tank are far more complex than those of the spherical tank and the extent of fluid mixing is significantly greater but less repeatable.

II. INTRODUCTION

The experimental program reported herein is an outgrowth of independent investigations into alternate redesign concepts for the Apollo SM cryogenic oxygen storage system. These experiments were continued, after the redesign was established, to aid in the characterization of the system performance in flight.

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The basic objective of these experiments has been to provide information on energy transport and fluid mixing in a zero-gravity environment. Since it is impossible to produce a zero-gravity environment on the earth for an extensive period of time, an analogy was drawn between thermal diffusion and constant density species diffusion. This enabled an experimental simulation of the transient flow and mixing associated with initiation, termination or reversal of spacecraft passive thermal control (PTC) roll motion. Following is a discussion of the analogy, experimental apparatus, tests conducted, and test results.

III. THEORETICAL BASIS

Consideration of energy addition and distribution processes in the Apollo cryogenic oxygen system involves a matrix of phenomena and motions as shown in figure 1. In the case of zero motion, and in the absence of gravity, energy transfer is accomplished through conduction and secondary flows created by thermal expansion. Although conduction is readily calculated secondary flow processes require a numerical flow description. When the spacecraft is undergoing PTC the oxygen tanks experience a radial acceleration which in turn allows for a dominant free convection heat transfer and associated fluid mixing. Although free convection heat transfer can be calculated readily through semi-empirical film heat transfer coefficients, the associated fluid mixing requires either numerical or experimental simulation.

After initiation or reversal of PTC, the extensive transient motion involves all of the phenomenon shown in figure 1. The transient motion associated with termination of PTC involves all but free convection heat transfer. The specification of all simultaneous phenomenon requires numerical computation or flight experimentation. The forced convection and mixing associated with the transient motion can be obtained by a Reynolds number simulation of PTC coupled with a concentration diffusion simulation of thermal conduction.

The first order behavior of both unsteady thermal conduction and the diffusion of a dye into water can both be described by the diffusion equation:

$$\frac{\partial \theta}{\partial t} = \alpha^2 \nabla^2 \theta \qquad 0 \leq \theta \leq 1$$

Where for thermal conduction,

$$\theta = \frac{T - T_\infty}{T_{source} - T_\infty}$$

$$\alpha^2 = D_T = \frac{k}{\rho C_v} = \text{mean thermal diffusivity}$$

T_∞ = bulk fluid temperature

T_{source} = effective source temperature

And for the diffusion of dye into water,

$$\theta = \frac{\text{dye concentration}}{\text{source dye concentration}}$$

α^2 = diffusion constant, dye/water, D_{12}

To compare absolute times for the two physical processes the:

$$\text{Characteristic time for thermal diffusion} = \frac{D_{12}}{D_T} \times \text{Characteristics time for dye diffusion}$$

The dye diffusion constant in these experiments was measured to be on the order of 10^{-1} of the calculated thermal diffusivity of the oxygen at significant conditions.

The flight oxygen tank Reynolds number based on tank radius and PTC rotation rate (Ω = 3 revolutions per hour) is shown in figure 2 as a function of the oxygen mass remaining in the tank. The circled points indicate the test simulation conditions with water at approximately 30 revolutions per hour (.5 RPM). The model flow times relative to the flight oxygen tank flow times can be scaled inversely with kinematic viscosity. Therefore, the model or test flow occurs ten times faster than in the flight case. In these tests the dye diffusion proceeded at a rate of 10^{-2} relative to the flight thermal conduction. Although this does not provide a good simulation, it does provide a conservative model for the extent of mixing in the tank. Due to this diffusion time difficulty and due to the difficulty associated with simulating the precise energy transport at the heater surface, the main results of these tests are characteristic motion times and the physical insight gained concerning zero-gravity phenomenon.

IV. EXPERIMENTAL APPARATUS

Two experimental investigations were conducted. The first was a simulation of the Apollo SM cryogenic oxygen storage system including the use of a simulated spherical tank. To support numerical analysis efforts the experimental investigation was extended to a second program which included a cubical tank having the same volume as the previous and actual tank.

Simulated Tank - As shown in figure 3, the first experimental apparatus consisted of the following: a counter-balanced, reversible rotating beam of sufficient length to represent the location of the inner O_2 tank of the SM, a plexiglas mock-up of the O_2 tank, a metal/wood mock-up of the heater and quantity probe assembly, a dye injection system, motion picture cameras, and a radial dye injection system. The radial dye injector was not used while motion pictures were being obtained. A cloth tent was fabricated to diffuse the available indoor lighting thereby reducing unwanted reflections which would degrade the motion pictures.

To obtain a condition representative of a "hot" heater, a high concentration of dye around the heater mock-up was desired. Through trial and error the following combination was found to give acceptable results. A 3/16-inch copper tube was spirally wrapped around the heater mock-up with a pitch of approximately 7/8 inches. At 90 degree intervals the tubing was perforated by a .010-inch drill at two locations, one directed upward and one downward. The tubing was not terminated at the lower end of the heater mock-up, but rather was routed vertically to the tank exterior. Such a configuration allowed dye to be injected at either the upper or lower end of the heater assembly.

The area representing the heater surface was wrapped with cheese cloth which was subsequently wrapped with a fiber napkin, similar to a paper dinner napkin. The upper and lower regions were taped and the lap joint was sealed with a silicon rubber compound. A series of cord bindings were then added at each tubing spiral for the purpose of attempting to create small dye sources. A beaker of concentrated methonal blue was elevated above the tank to provide the dye source to the simulated heater tubing.

After initial tests were conducted, a tube was extended along a tank radius in a horizontal plane as shown in figure 4. Small holes were drilled in the tube at one inch intervals to provide twelve radial locations at which flows could be observed. The tube was extended up the exterior of the capacity probe to the tank exterior and the dye reservoir. Holes in the radial tube were located to oppose the relative fluid (simulated O_2) motion. Therefore, when no stagnation and reverse flow of dye occurred, a station could safely be assumed at equilibrium conditions. Because of the small quantities of dye injected during the radial equilibrium experiments, no photographic equipment was used in these experiments.

Cubic Tank - The experimental apparatus was identical to that used in the spherical tank tests with the following exceptions: the test tank was a plexiglas cube (volume of approximately 4.75 ft^3), the simulated heater and quantity probe assembly was necessarily shorter, consisting of a wooden dowel of the proper diameter simulating the heater and a metal tube with a diameter equal to that of the center portion of the quantity probe. The simulated heater extended to within one-half inch of the top and bottom surfaces of the tank. For tests that would correspond to previous radial tube tests, two configurations were examined: in one, the tube was extended from the quantity probe to a corner with the heater positioned such that the flow just prior to the heater was measured. The second configuration consisted of a tube extending from the quantity probe to a wall so that the tube was perpendicular to the wall. Again, the heater was oriented so that the tube measured flow that would logically have contacted the heater surface.

For the motion pictures studies, the apparatus was identical with that used in the spherical tank tests except that the top view was changed to provide a view through the top surface of the tank, although not at a normal orientation. When motion pictures were obtained, the complete dye injection system used with the spherical tank was utilized.

V. SIMULATION CONDITIONS AND TEST PROCEDURES

Three S/M roll conditions were evaluated: the starting transient, the stopping transient, and the combination of these, the roll reversal.

Where the simulated heater-dye injector system was used the procedure was as follows. The heater probe assembly was inserted in the spherical tank of water and was undisturbed for two hours. Dye (at near the tank water temperature) was slowly fed into the upper and lower regions of the heater assembly. As the dye penetrated the cheesecloth/napkin wrapper, a reasonably uniform cylinder of dye could be formed. If the dye injection was successful at this time, motion picture cameras were activated and rotation of the tank begun. Filming was continued for approximately 45 minutes. At the end of this time, while fluid motion still existed, inadequate contrast between stream lines had greatly reduced the value of photography.

For the radial tube experiments during the starting transient essentially the same procedure was used until the initiation of rotation. At 7-1/2 minute intervals, dye was injected along the tube in a direction opposing the tank fluid flow. Visual observations were made of each location and recorded. When the dye no longer stagnated and returned beyond the tube, flow was considered to have ceased.

Stopping transients were similarly investigated. The wrapped heater assembly was inserted and the tank rotation begun. After rotating for two hours, an attempt was made to uniformly inject dye through the heater tubes to form a cylinder of dye around the heater assembly. If this condition was satisfactory, cameras were started and rotation terminated.

The radial tube tests were similar. After rotation was ceased, dye was injected at 7-1/2 minute intervals through the radial tube and observations were made.

Roll reversal tests were like the stopping transient tests except that the rotation was reversed rather than stopped.

VI. TEST RESULTS

Test results are presented in the form of motion pictures as tabulated in Tables I and II and plotted flow relaxation time data for starting, stopping, and roll reversal transient conditions. Note that motion pictures were obtained at approximately four frames per second, and, therefore, if viewed at 16 frames per second events are occurring 40 times faster than in the flight O_2 tank.

Simulated Tank - To illustrate the flow and mixing simulation obtained in the experiments figure 5 shows five time sequences of a starting transient flow. Motion was initiated immediately following the first view of essentially stagnant injected dye. Considerable mixing occurs with the initial motion as shown in the second view at one minute of model time. The mixing decays as shown until in the last view at nine minutes model time the dye distribution rate is governed primarily by diffusion.

With the radial tube injection device the radial distribution of flow relaxation times were measured as shown in figures 6 and 7. The repeatability of the relaxation times for the spherical tank are as illustrated in figure 6 for two independent tests of the starting transient. The character of the flow relaxation is significantly different for the starting, stopping, and roll reversal as shown in figure 7. The radial relaxation patterns are consistent with the observed mixing in that the starting and roll reversal provided significantly better mixing than the stopping transient. As shown in figure 7, the flow came to rest around the heater sooner for the stopping transient and thereby produces less mixing of the dye or simulated hot fluid.

Except for the stopping transient, some flow was noted for almost any test duration. This flow was not significant near the heater assembly, but was noted primarily near the tank wall. A flow reversal and oscillation was noted in the wall boundary layer in several starting transient tests. This occurred at approximately 20 SC hours and was most prolonged in the case of roll reversal.

All test observations indicate some small radial flow toward the capacity probe.

All tests also indicated, as would be expected, that longer flow durations are obtainable at a tank radius of five to six inches.

The observed test times for relaxation of the relative motion about the heater element have been transposed to real flight times as shown in figure 8. Again the stopping transient is a characteristically different flow from the starting or reversal and as such relaxes in less than half the time as shown in figure 8.

Cubic Tank - In the cubical tank tests the fluid was essentially stagnant in the tank corners with the primary flow resembling that which would be expected in a cylindrical tank. The tank geometry, however, does significantly effect the flow patterns as can be determined by comparing the spherical and cubical tank data for identical test conditions. In general, the cubical tank data were not as repeatable or as uniform as that obtainable with the spherical tank. Although there is a similarity of a portion of the data for the two tanks, the flow patterns were observed to be substantially different. For example, with the cubical tank flow at several "radial" stations ceased at essentially the same time rather than uniformly decaying as was generally observed in the spherical tank. With the spherical tank, the primary flow under investigation was dominant and secondary flows, while present, did not significantly alter the flow patterns. With the cubical tank, primary and secondary flows can equally influence the overall flow patterns and mixing. In the cubical tank, flows perpendicular to a "radius" were observed at times to be in three alternate directions, a condition which could later change to one or two directional flow. In tests, where secondary flows were less dominant, the cubical tank flow patterns more nearly resembled those observed in the spherical tank.

Figure 9 presents data from two starting transient tests of the same configuration. In one test, the flow uniformly relaxes, while in the other the flow abruptly ceased between 3 and 6 inches radius. Figure 10 presents data for the same configuration obtained in a simulated roll reversal. As with the spherical tank, relaxation times for roll termination with the cubical tank were extensive and were generally not recorded to their completion. The flow, while present, was observed to be very slow and at a location not under investigation. Figure 11 illustrates typical roll termination data obtained with the cubical tank. No abrupt ceasing of flow was observed during any of the roll termination tests. Figure 12 presents a summary of data obtained with the "radial" tube injector orientated perpendicular to a tank wall. The relaxation times are for a station at the outer heater surface. The cubical tank data does not define a distinct difference between the test conditions as was obtained with the spherical tank.

Figure 13 illustrates data obtained from three transient tests with the "radial" dye injector tube extending from the probe to a tank corner. Although not shown in this figure, fluid flow was also observed to abruptly cease at several radial stations at the same time with this configuration. The stopping and reversal transients provide the longest period of fluid motion past the heater surface.

Figure 14 is a summary of all data obtained for the probe-to-corner tube configuration. A comparison between figures 12 and 14 indicates that the heater orientation in the cubical tank does not significantly affect the relaxation times. However, neither figure indicates significantly different relaxation times for the stopping transient as obtained with the spherical tank.

Motion picture data provides a more complete illustration of the flow patterns and presents one case (S71-079) where secondary flows significantly influence the flow field. Under this condition, mixing is enhanced and exceeds that obtained with the spherical tank.

VII. CONCLUDING REMARKS

The forced convection and transient mixing associated with changes in spacecraft PTC provide a significant mode of energy distribution within the cryogenic oxygen tanks. The transient effects last for a period of up to six to nine hours from termination of PTC and up to fourteen to twenty-three hours from initiation or reversal of PTC. The associated mixing during these times should provide for negligible potential for pressure collapse. The transient motion from initiation or reversal of PTC should also provide a significant enhancement of the free convection and otherwise steady flow and mixing processes.

The forced convection and transient mixing in a cubical tank does not provide a good simulation of conditions to be expected with a spherical tank. In general, the overall flow in the cubical tank is far more complex, less repeatable, and can provide significantly greater mixing than in the spherical tank. Portions of the flow field in the cubical tank, particularly near the heater can at various times provide characteristics similar to the simulated tank flow.

The significant differences in the flow and mixing between the two tanks indicates that fluid mixing could be enhanced considerably through irregular geometry or protuberances.

MSC MOTION PICTURE FILE NUMBERS FOR O_2 MIXING STUDIES*

TABLE 1 - SIMULATED TANK

STARTING TRANSIENT	
Dye injected before initiation of rotation	S-70-310
Dye injected after rotating 1 hour (lab time)	S-70-337
STOPPING TRANSIENT	
Dye injected before termination of rotation	S-70-333 S-70-338
REVERSAL TRANSIENT	
Dye injected after rotating 2 lab hours and before reversing rotational direction	S-70-343

TABLE II - CUBICAL TANK

STARTING TRANSIENT	
Dye injected before initiation of rotation	S-71-075
Dye injected after rotating 1 hour (lab time)	S-71-106
STOPPING TRANSIENT	
Dye injected before termination of rotation	S-71-079
REVERSAL TRANSIENT	
Dye injected after rotating 2 lab hours and before reversing rotational direction	S-71-116

* Each film reel contains two camera views, one above, one below.

NASA-S-71-1429-X

ENERGY ADDITION AND DISTRIBUTION MECHANISMS

		RELATIVE MOTION			
PHENOMENON	CONTROLLING PARAMETERS	ZERO	STEADY ROLL (PTC)	TRANSIENT	
				START OR REVERSE PTC	STOP PTC
CONDUCTION	$D_T = \frac{k}{\rho C_v}$, ∇T	√ a,s,n	√ n	√ s	√ s
CONVECTION: FREE	ACCELERATION FIELD, $\nabla \rho$	--	√ n,a	√	
FORCED	VELOCITY FIELD, ∇T	--	--	√ s	√ s
MIXING: FLUID	VEOCITY, $\nabla \vec{v}$	--	√ n	√ s	√ s
THERMAL	$\frac{\partial \rho}{\partial t}$, ∇T	√	√	√	√

s - SIMULATION BY CURRENT EXPERIMENTS
a - READILY ANALYZED
n - NUMERICAL DESCRIPTION AVAILABLE

NOTE: THERMAL RADIATION IS SIGNIFICANT ONLY FOR ENERGY EXCHANGE BETWEEN SURFACES

Figure 1.

NASA-S-71-1439-X

REYNOLD'S NUMBER VS TANK QUANTITY

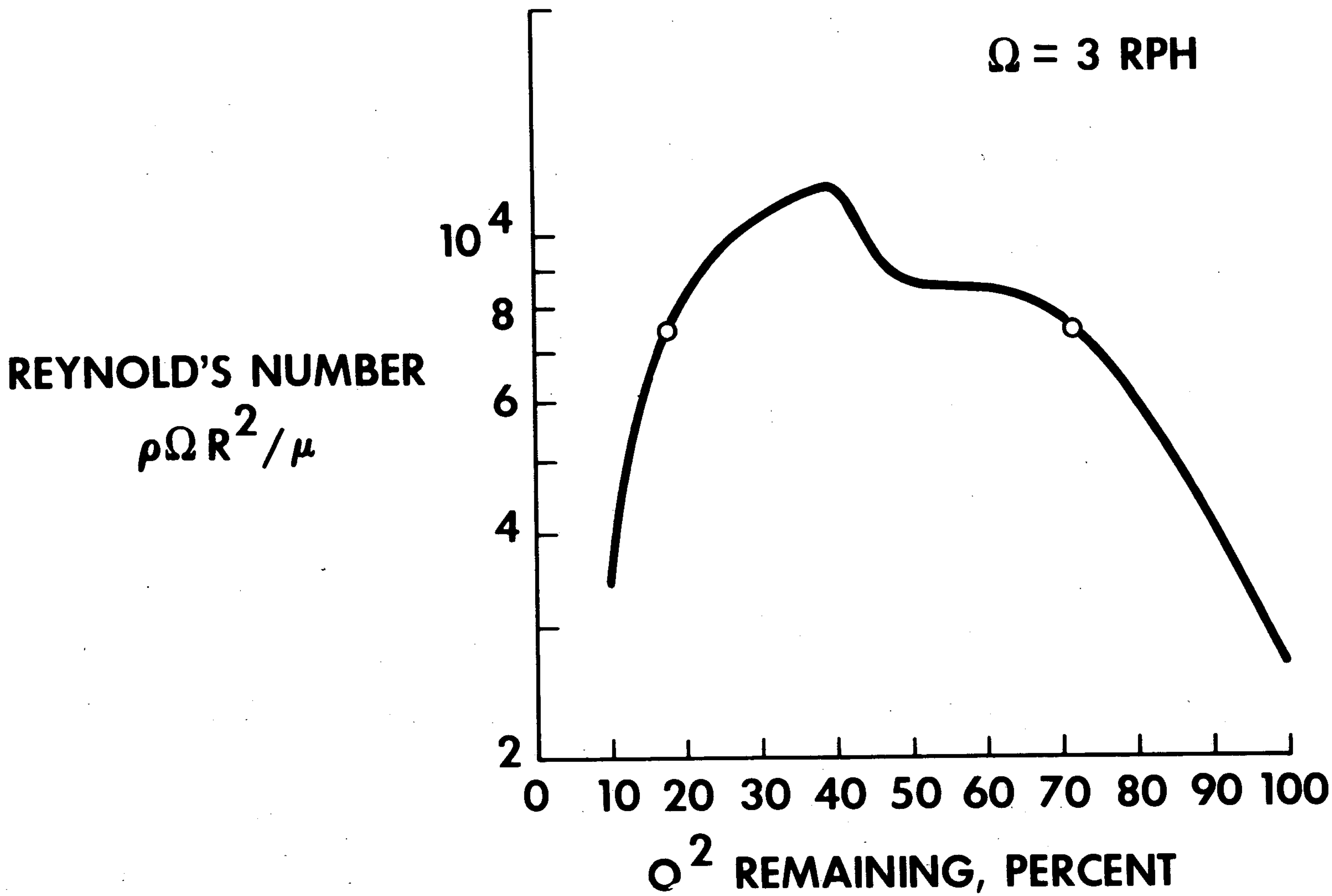


Figure 2.

NASA-S-71-1436-X

EXPERIMENTAL APPARATUS

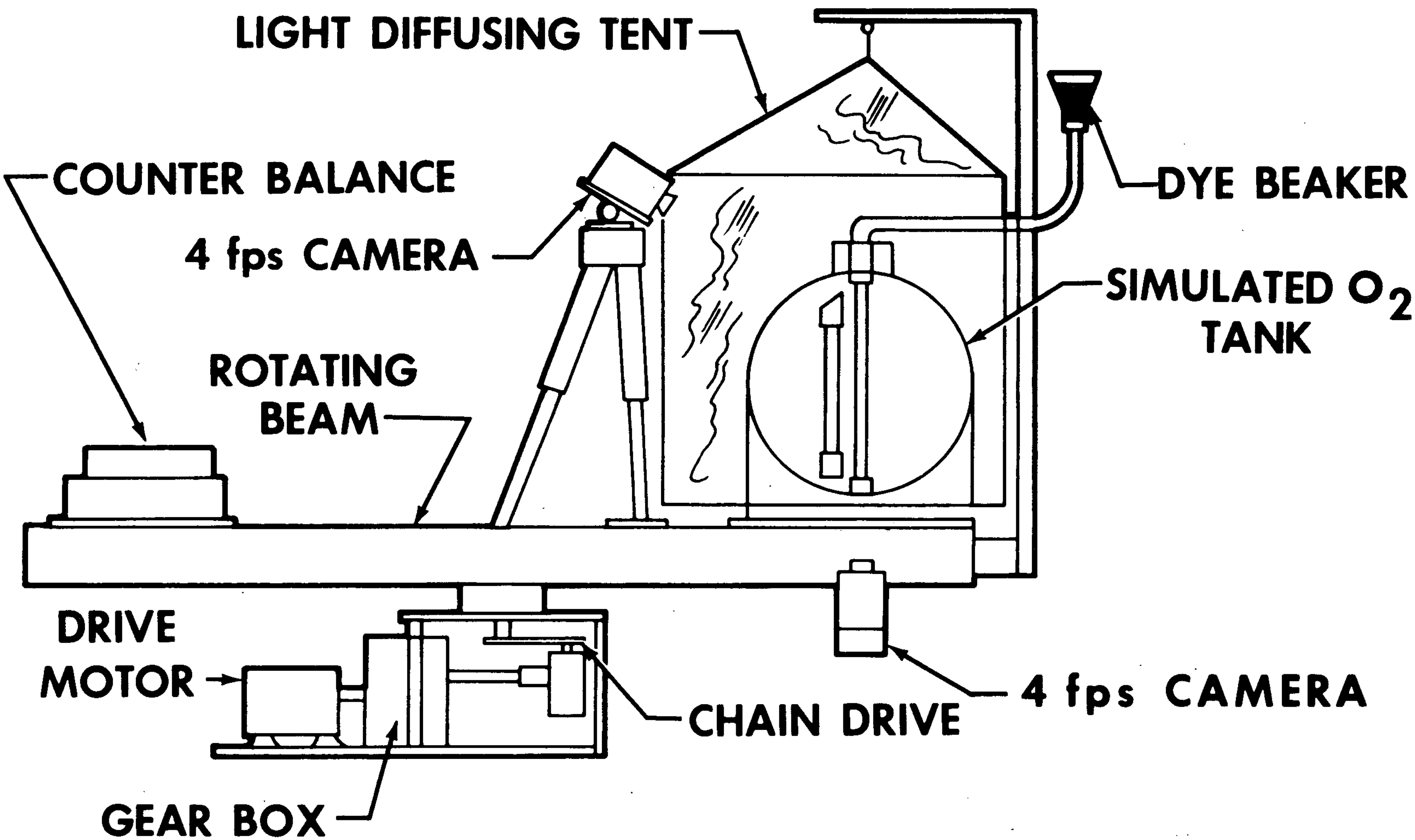


Figure 3.

NASA-S-71-1441-X

EXPERIMENTAL APPARATUS

RADIAL TUBE TEST

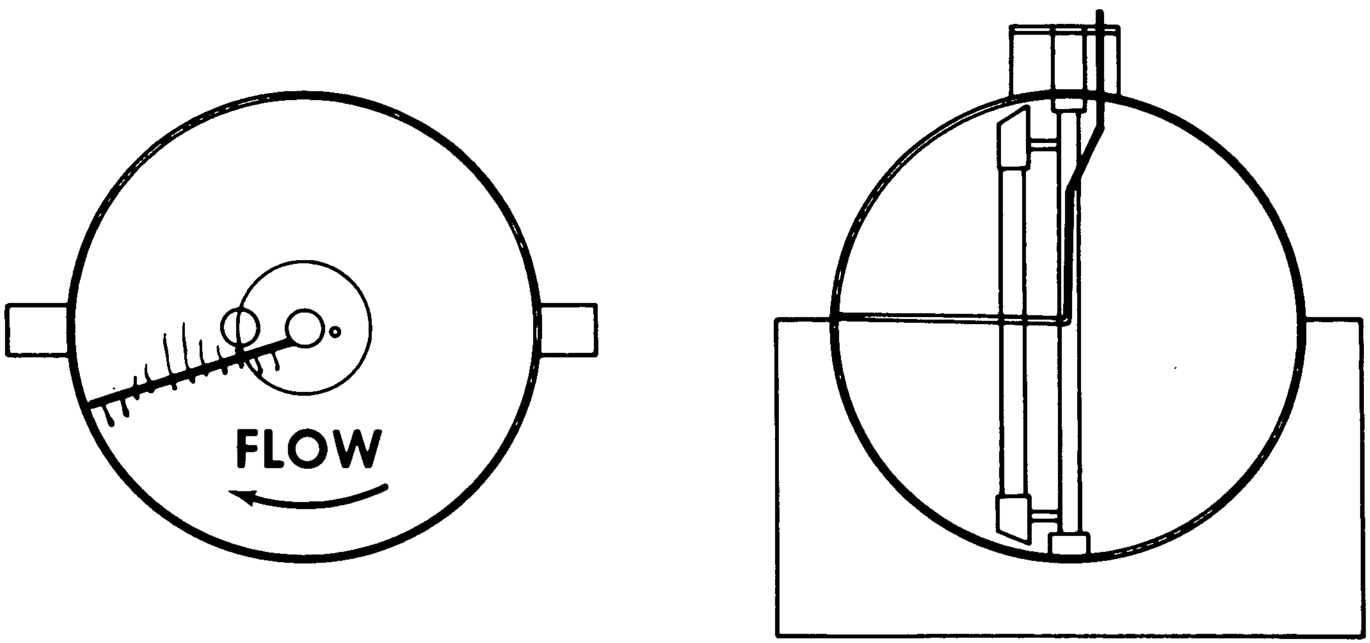
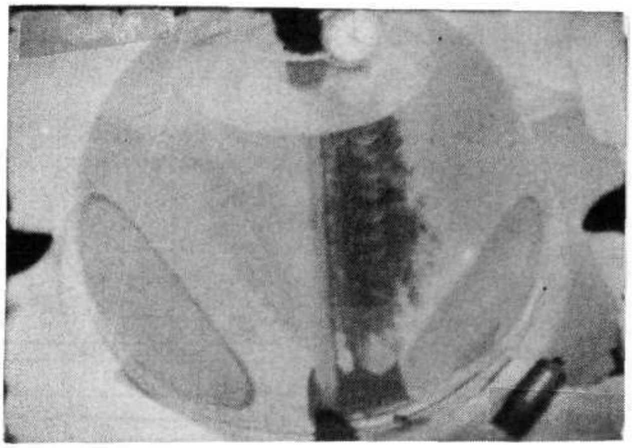
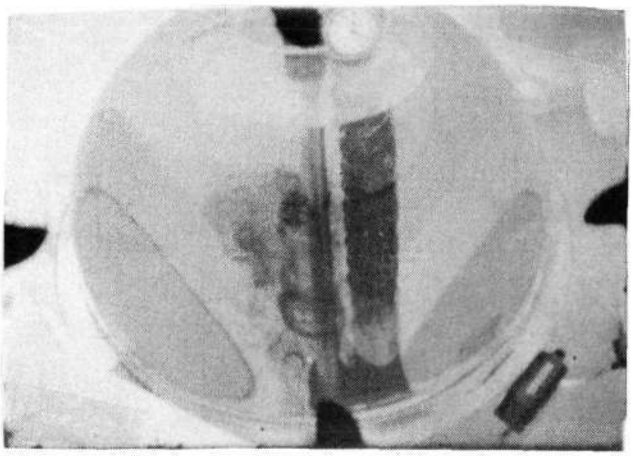


Figure 4.



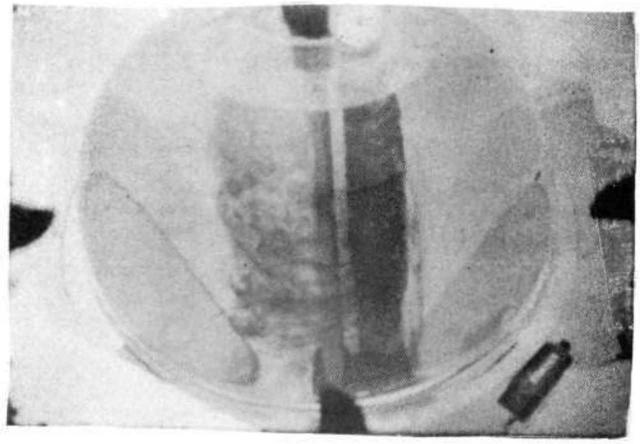
t = 0



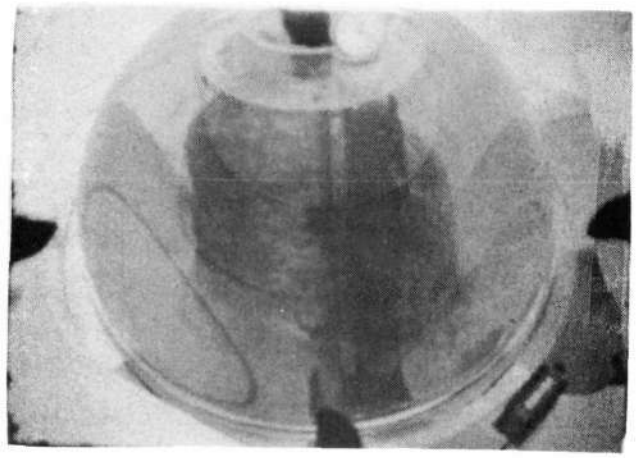
t = 1 min.

FIGURE 5 - STARTING TRANSIENT TIME SEQUENCE
(MODEL TIMES)

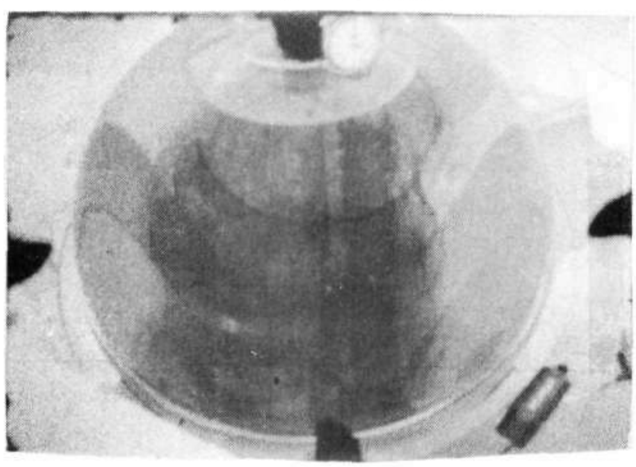
NOT REPRODUCIBLE



t = 3 min.



t = 6 min.



t = 9 min.

NASA-S-71-1433-X

TIME TO STEADY STATE STARTING TRANSIENT

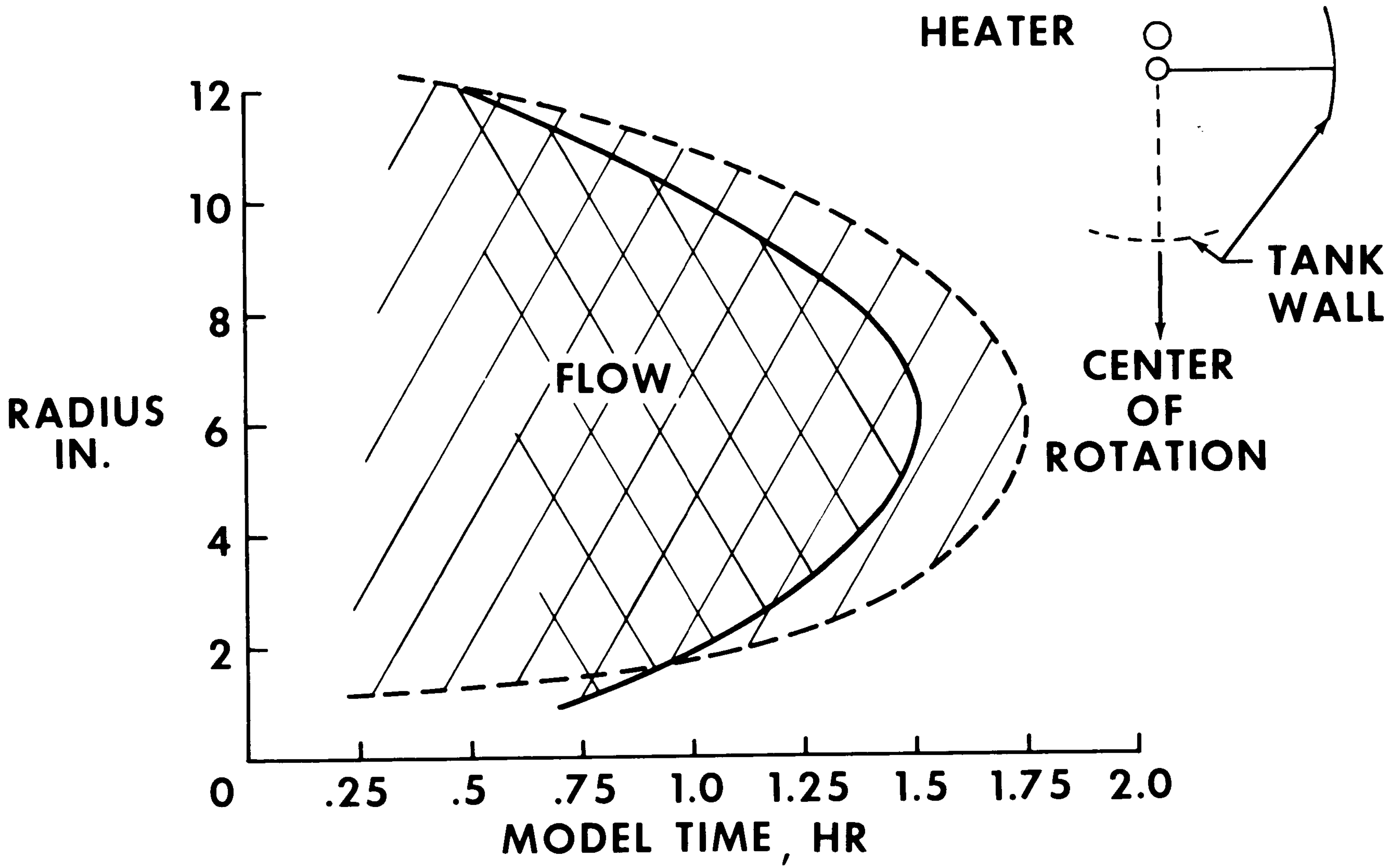


Figure 6.

NASA-S-71-1434-X

TIME TO STEADY STATE

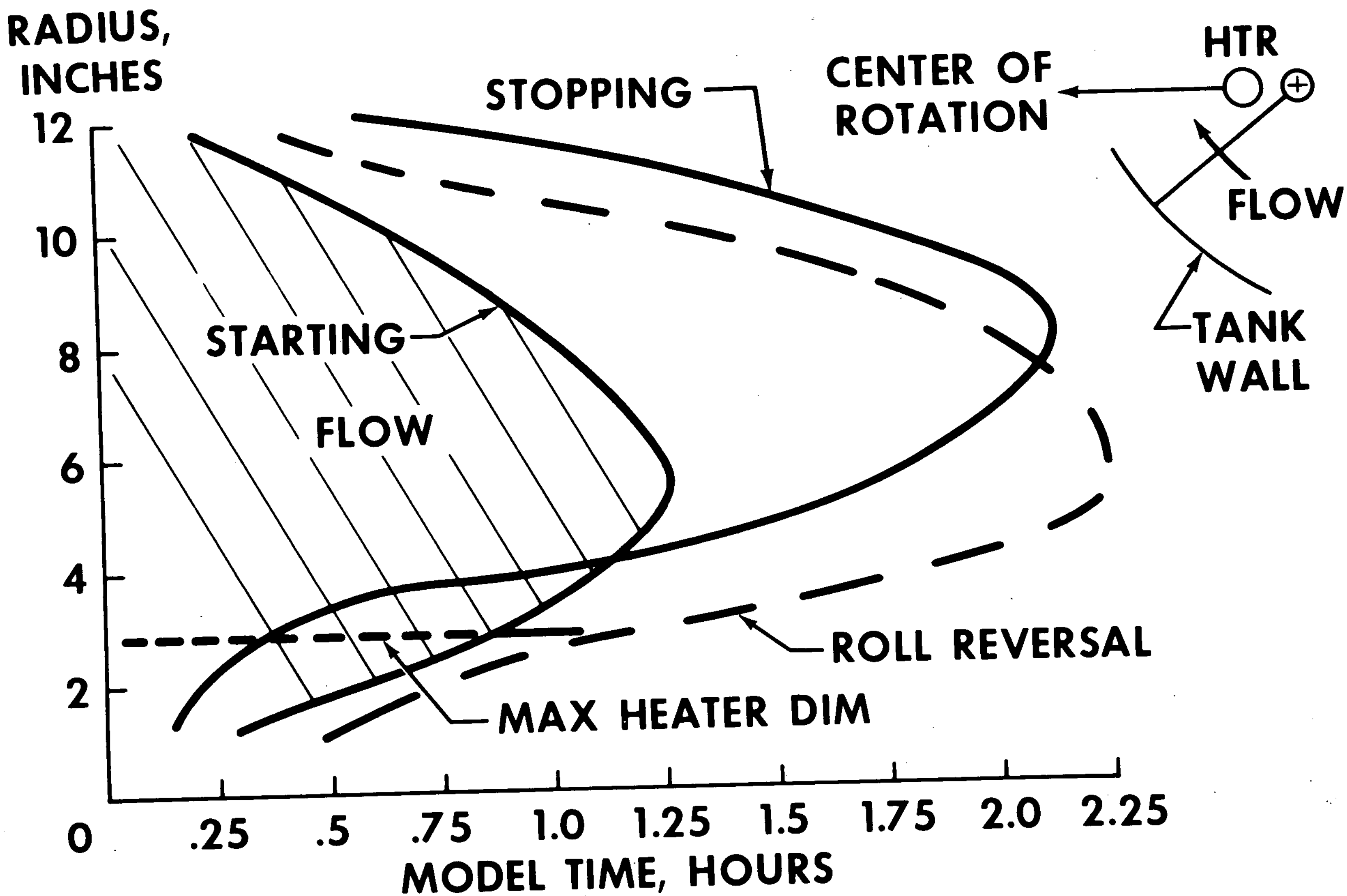


Figure 7.

NASA-S-X-71-1430-X

TIME FOR O_2 TO COME TO REST ABOUT THE HEATER VS MASS FRACTION OF OXYGEN REMAINING IN TANK

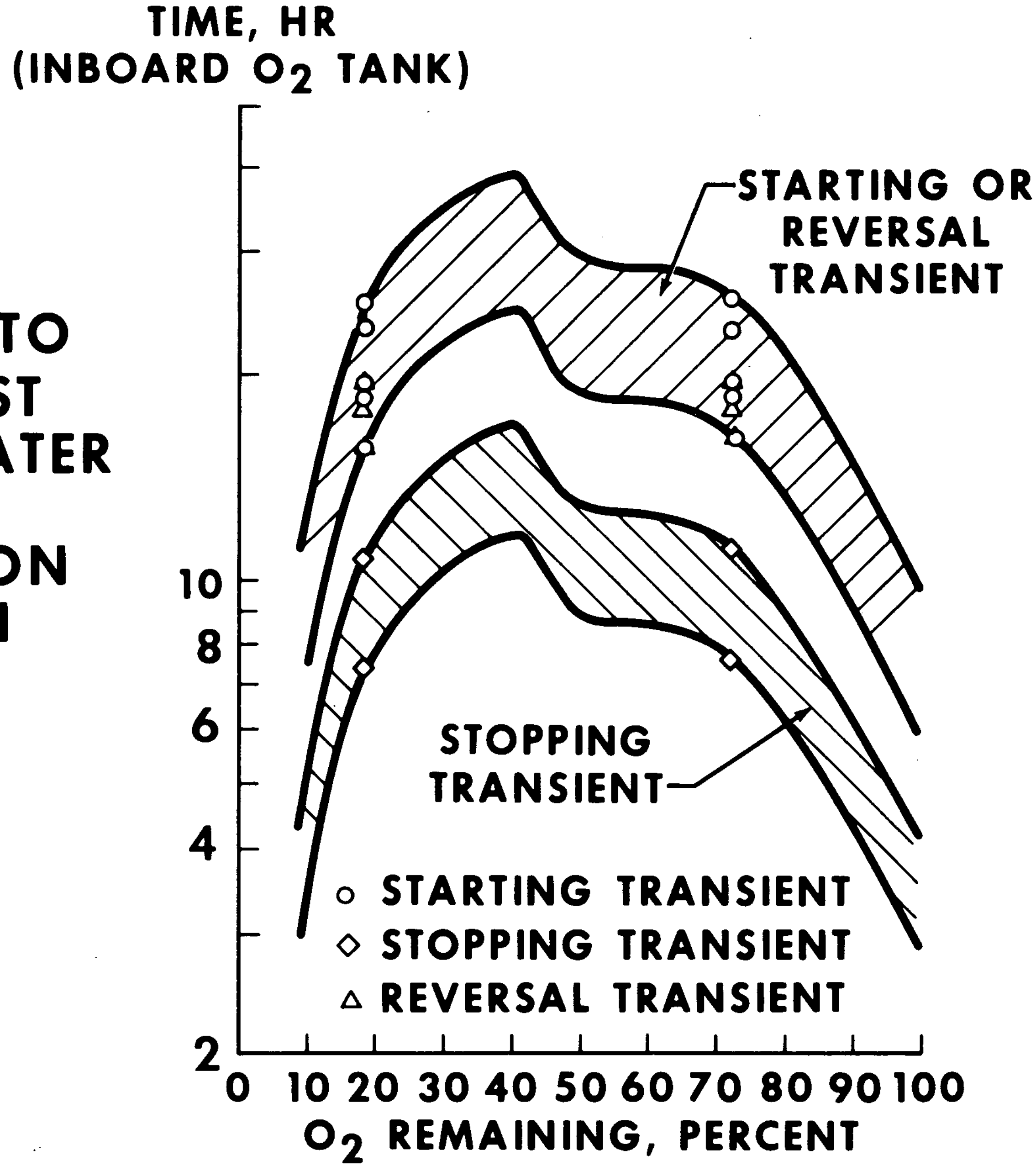


Figure 8.

NASA-S-71-1443-X

TIME TO STEADY STATE
STARTING TRANSIENT

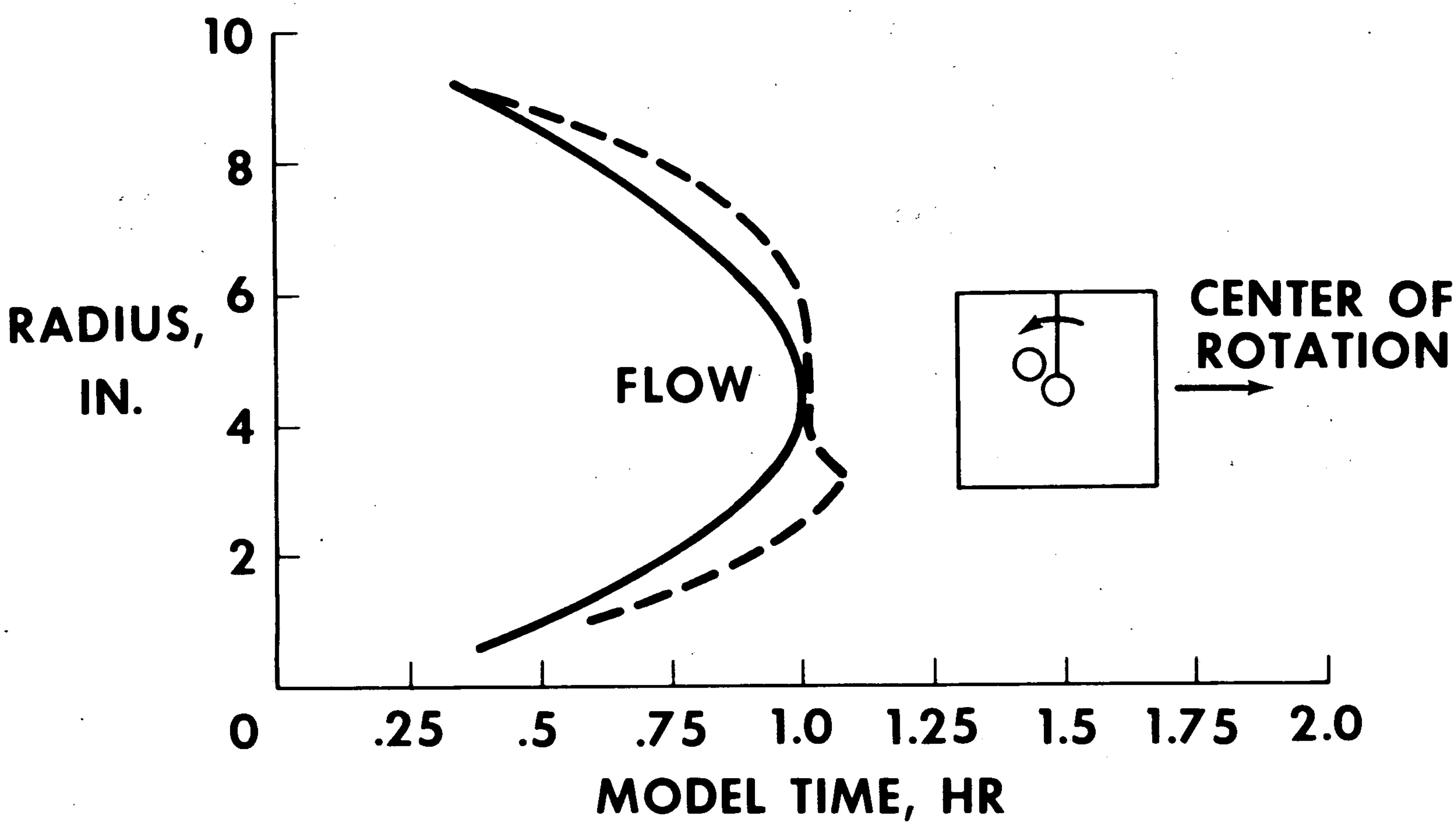


Figure 9.

NASA-S-71-1442-X

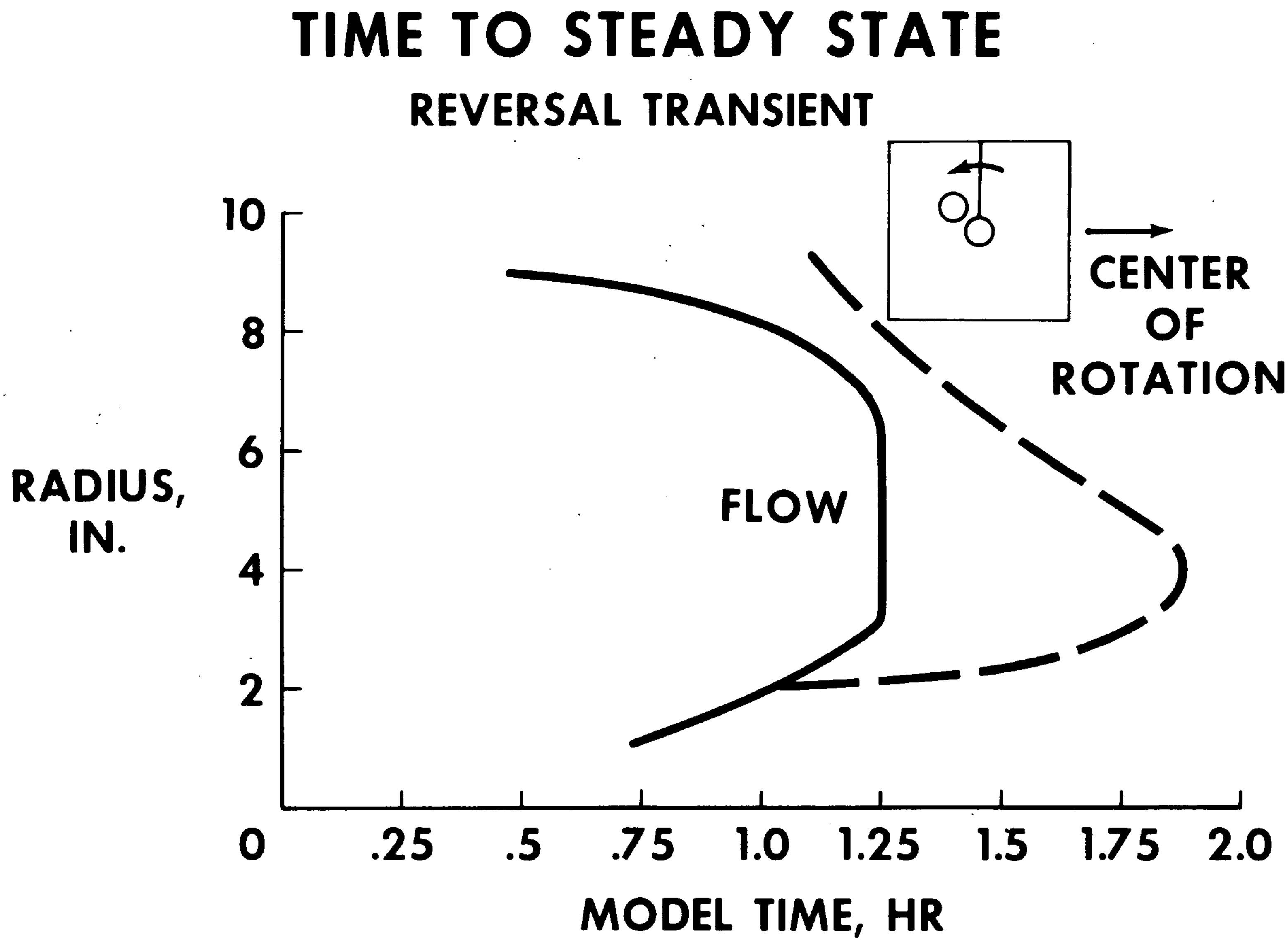


Figure 10.

NASA-S-71-1437-X

TIME TO STEADY STATE

STOPPING TRANSIENT

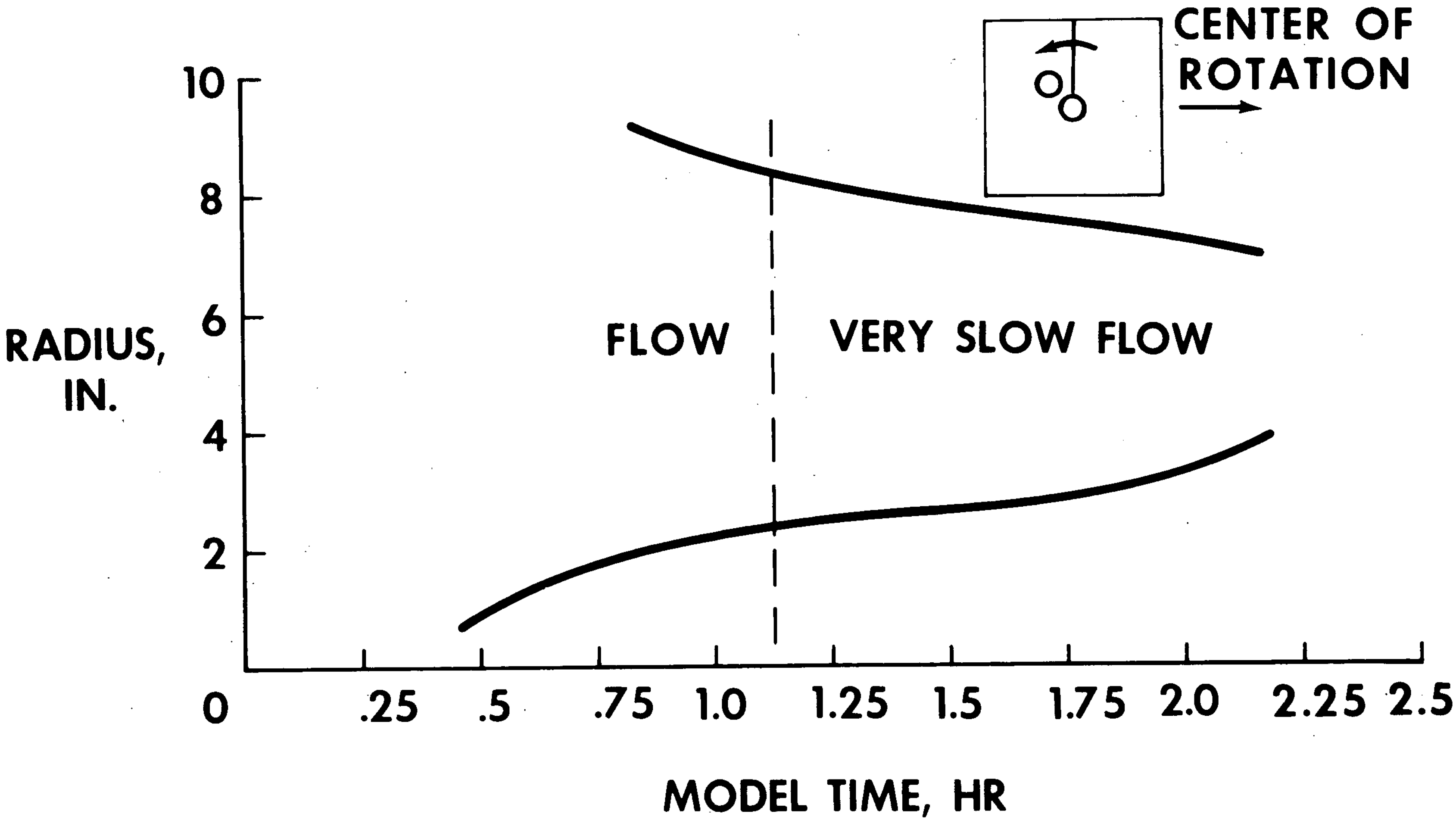


Figure 11.

NASA-S-71-1432-X

TIME FOR O_2 TO COME TO REST ABOUT THE HEATER VS MASS FRACTION OF OXYGEN REMAINING IN TANK

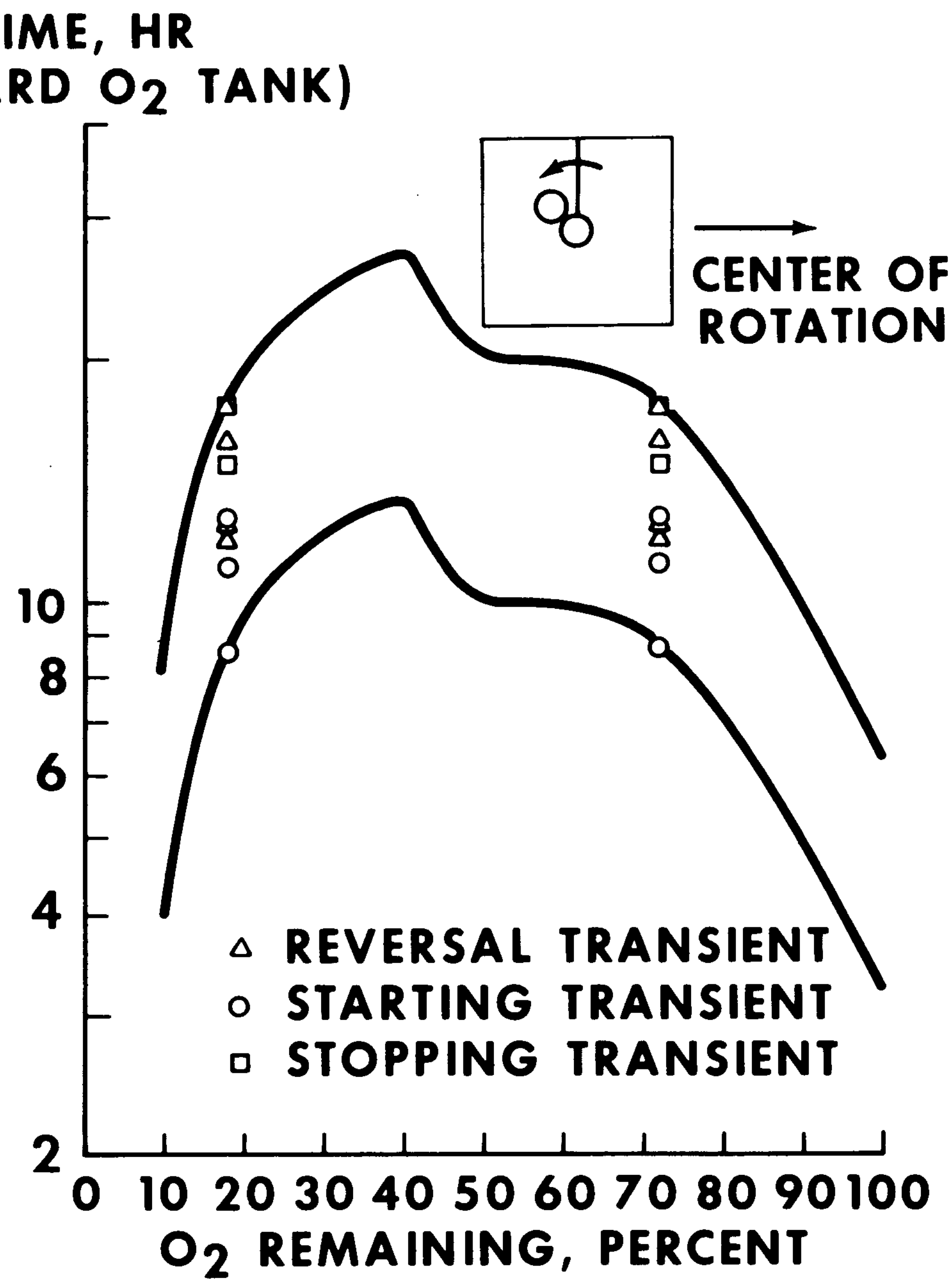


Figure 12.

430

NASA-S-71-1431-X

TIME TO STEADY STATE

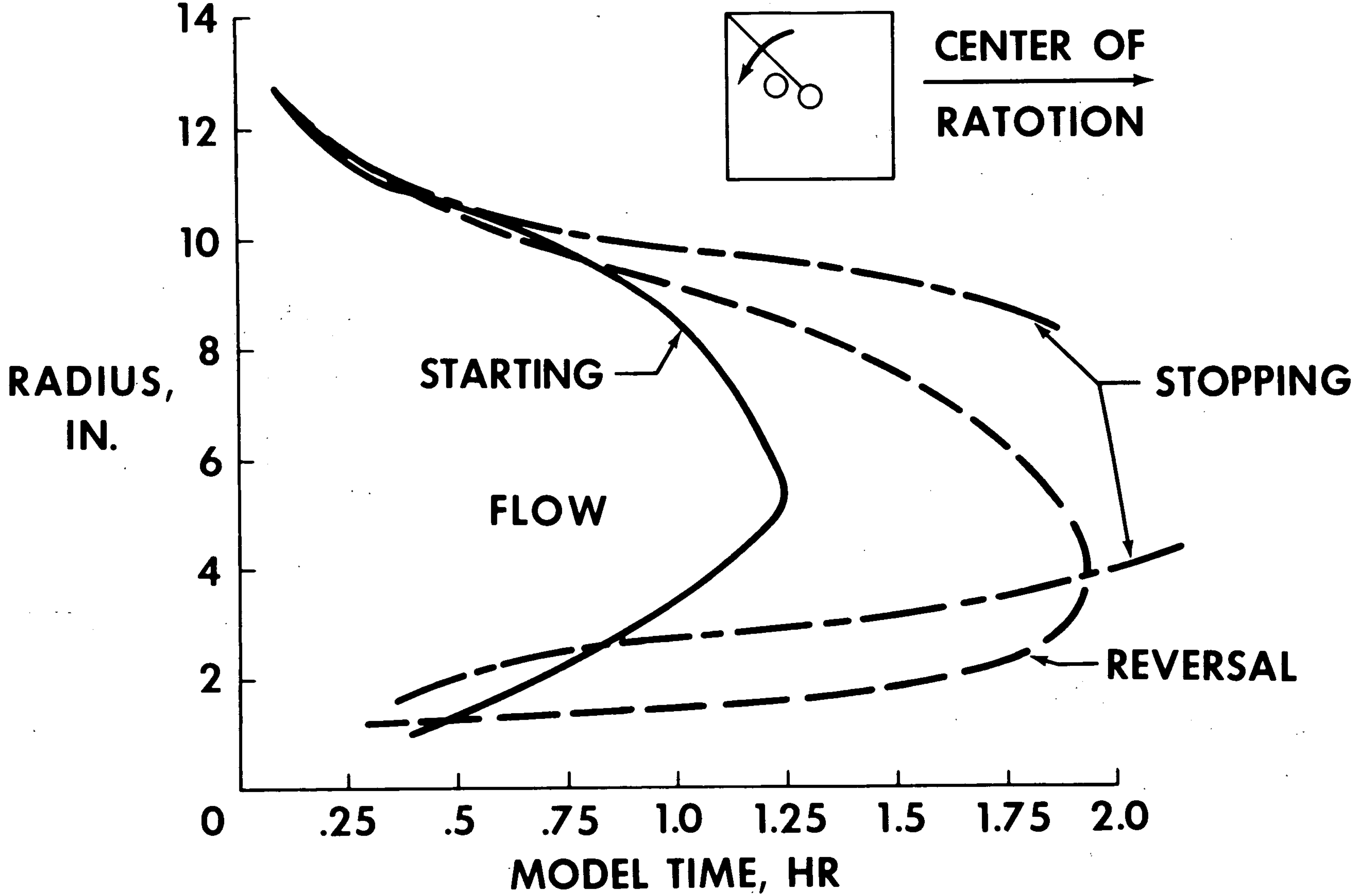


Figure 13.

NASA-S-71-1435-X

TIME FOR O_2 TO COME TO REST ABOUT THE HEATER VS MASS FRACTION OF OXYGEN REMAINING IN TANK

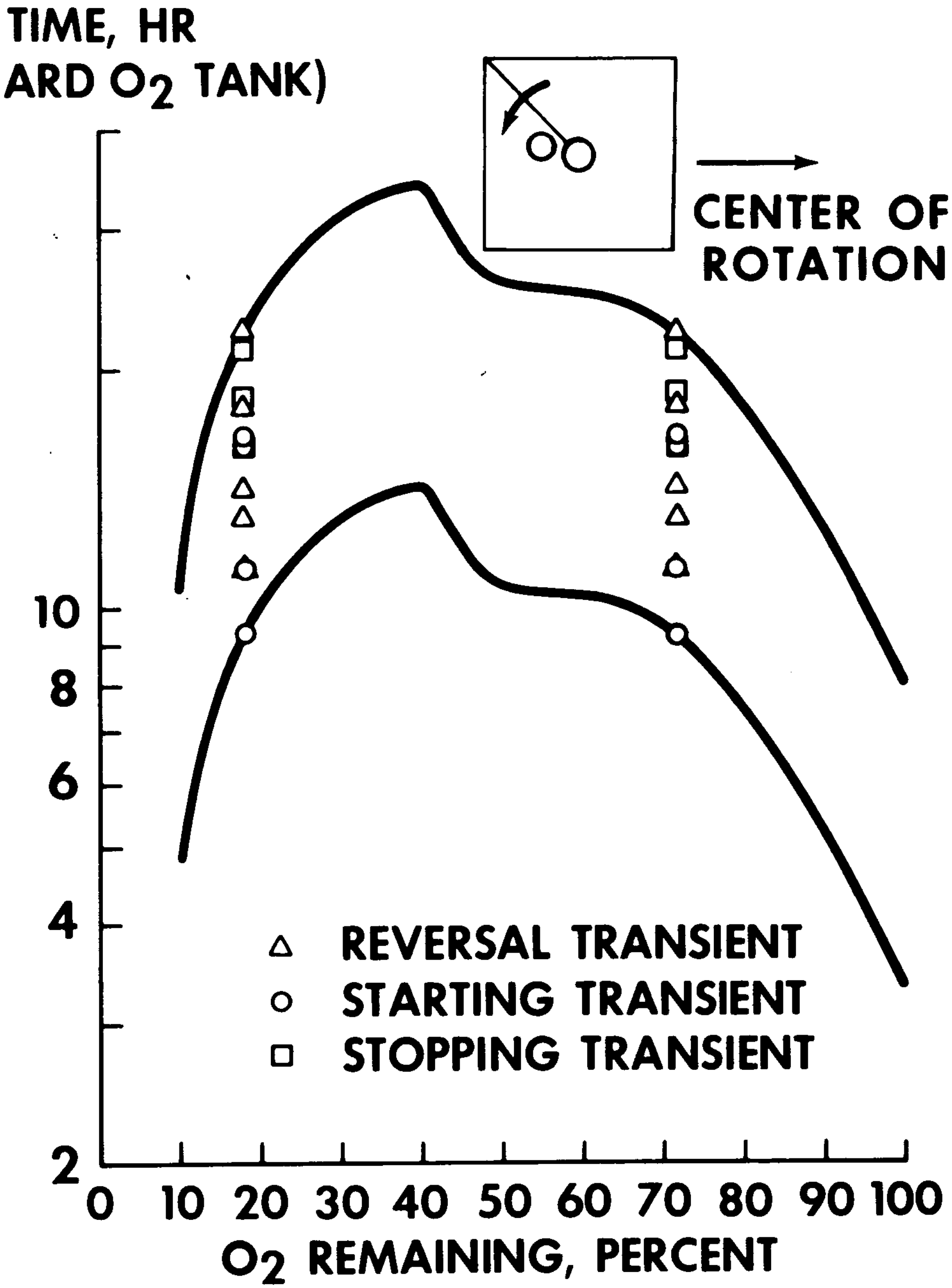


Figure 14.