INDUCER PUMPS FOR LIQUID METAL REACTOR PLANTS

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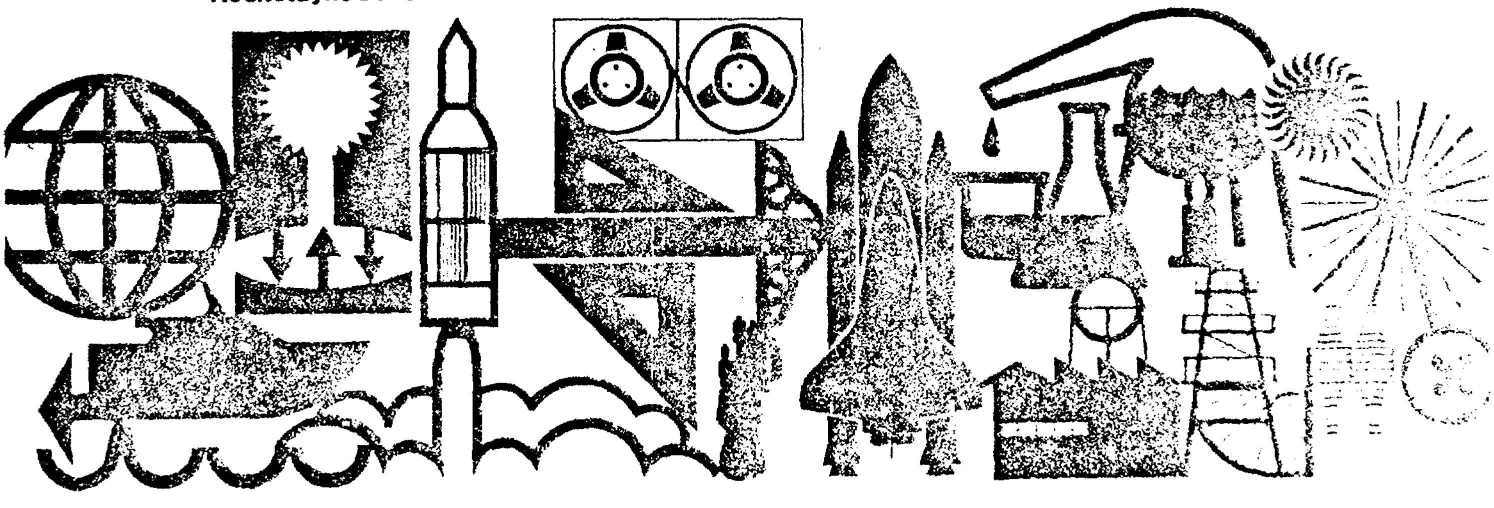
Rockwell International
Rocketdyne Division



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Introduction

Pumps proposed for liquid metal reactor plants typically use centrifugal impellers as the rotating element and are required to maintain a relatively low speed to keep the suction specific speed low enough to operate at the available net positive suction head (NPSH) and to avoid cavitation damage. These low speeds of operation require that the pump diameter increase and/or multiple stages be used to achieve the design head. This frequently results in a large, heavy, complex pump design. In addition, the low speed results in a larger drive motor size so that the resultant penalty to the plant designer is multiplied. The heavier pump can also result in further complications as, e.g., the difficulty in maintaining the first critical speed sufficiently above the pump operating range to provide margin for rotordvnamic stability. To overcome some of these disadvantages, Rockwell International has proposed the use of inducer pumps for Liquid Metal Fast Breeder Reactor (LMFBR) plants. This paper discusses some of the advantages of the inducer pump and the development history of designing and testing these pumps both in water and sodium. This paper was sponsored by DOE under Contract DE-AT-03-83SF11901.

Inducer Technology Development

Rockwell began developing inducers in the early 1950s to support the aerospace needs. For vehicles planned for space operation, the vehicle weight is critical and every pound saved provides an additional pound of payload. The development of inducers benefitted the program in two ways. First, by providing the capability to operate at lower NPSH values, required minimum tank pressures could be reduced significantly reducing the tankage weight, and secondly, the weight of the pump elements themselves could be reduced by using a higher speed, small lightweight pump. The historical development of Rockwell's high suction specific speed (NSS) capability is illustrated in Fig. 1, showing that in a period of less than 20 years, pump operation was successfully developed from an NSS value of 10,000 (rpm, gpm, feet units) without inducers to over 50,000 with inducers. To put this in perspective, with a fixed flow and NPSH, this would permit a five-fold increase in speed, and with a fixed head requirement and number of stages, this would reduce the required diameter by a factor of 5. Of course, all rocket engine pumps do not operate at 50,000 NSS, but inducers are consistently used to increase the suction capability and to significantly decrease the total weight of the vehicle.

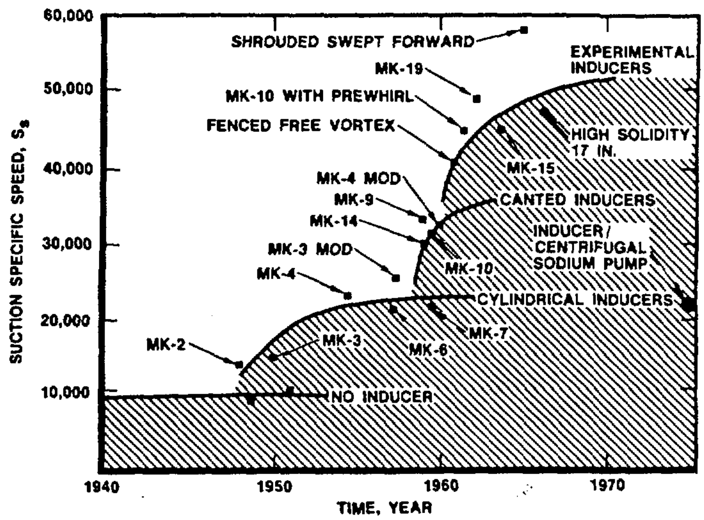

Fig. 1. Historical Development of Suction Specific Speed Capability

In the late 1960s, Rockwell began applying their successful inducer suction performance capability in other areas. The initial application was for pumps for waterjet propulsion systems. The most significant technical challenge for this application was the requirement for long life; whereas, rocket engine pumps were generally required to operate for periods measured in seconds. Rockwell was able to demonstrate to its customers that with proper design features, the long-life requirements could be successfully met, and inducer pump designs were introduced to high speed waterjet applications. For example, Rockwell's Powerjet 20 waterjet pumps were used on the Jetfoil boat. These pumps operate with suction specific speeds of 30,000 and tip speeds of 200 ft/sec during every startup until the boat achieves foil-borne operation. The Powerjet 20 inducer had a guaranteed life of 2500 hours, but the current projected service life is 30,000 hours based on observations of inducers with over 12,000 hours of field operation. These inducers show no signs of detrimental cavitation damage, and the projected service life could increase as more operating time is accumulated.

The next application for the inducer technology was for sodium plant operation. Rockwell recognized in the mid 1970s that an advancement of sodium pump design was necessary to achieve realistic component sizes and economic objectives for large LMR plants. The potential savings using an inducer pump is illustrated in Fig. 2 and becomes substantial at the higher flowrates proposed for new plants (e.g., 85,000 gpm). For the sodium pump application, the pump not only had to achieve the long life (40 to 60 years) but also achieve this life while potentially operating over a broad range of flow coefficient (ratio of pump flow divided by speed). This latter requirement was viewed as particularly critical in that inducers had gained the "reputation" of only being useful for long-life operation over a very narrow flow coefficient range due to cavitation-damage potential. However, Rockwell has demonstrated through a series of pump design/test programs that with the proper design, this requirement could be met by an inducer pump.

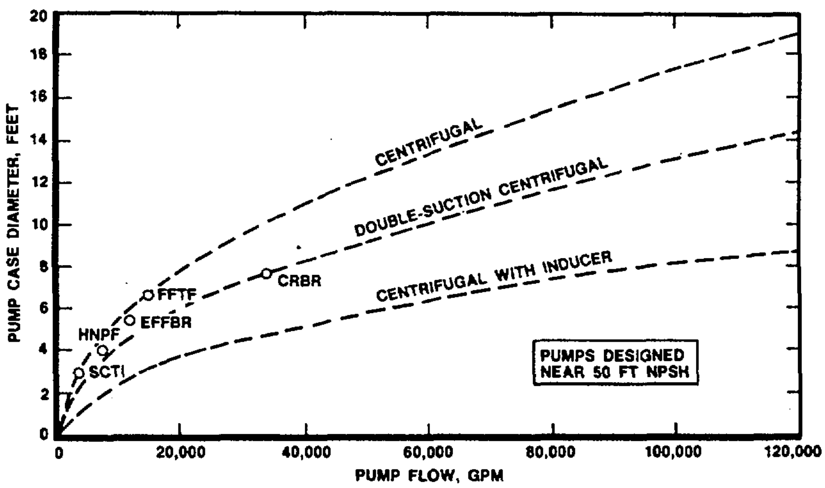

Fig. 2. Inducer Pump Offers Significant Size Advantage

Sodium Inducer Programs

Four inducer pump programs have been conducted at Rockwell under contract to the U.S. DOE consisting for the most part of subscale component test evaluations in both water and sodium. Of course, these programs have also been supported by numerous technology studies funded by company internal discretionary funds. In this section, these four programs will be briefly described, and in the next section, more details concerning the specific test evaluation methodology will be discussed.

Original Subscale Pump

This pump was the first inducer pump to be tested in sodium in 1977. To meet program schedules, and specifically test facility availability windows, this pump was designed, fabricated, and immediately tested in sodium as a scale-model pump without important life-capability tests being previously conducted in water. All of Rockwell's sodium pumps have a centrifugal impeller immediately downstream of the inducer. The design point flow was 2838 gpm, and the operating speed in sodium was 3329 rpm. The inducer was tested for 1800 hours in sodium. The inducer pump met all design requirements of headrise and suction performance, but examination of the inducer revealed some areas of cavitation damage along the tip due to the tip vortex. Model inducer water tests were then conducted and also demonstrated the potential for cavitation damage so that the damage was attributed to a design deficiency. However, this confirmation also demonstrated the feasibility of using inexpensive water tests to screen designs and verify the long-life potential before committing to sodium testing. Internal research had already identified some improved design features that were different from this original design, so a new inducer design was initiated for the Prototype Subscale Pump.

Prototype Subscale Pump

This pump had essentially the same design point, but a new improved inducer design. The new design was first demonstrated by water tests and shown to have long-life potential. The model pump was then submitted for sodium testing. The sodium data resulted in slightly more head and slightly better suction performance than estimated from the water tests (Fig. 3). The pump was tested for a total of 4700 hours covering a wide operating range that actually exceeded the required operating range that is typical for large loop-type LMR pumps. The test results were also totally successful with regard to showing no cavitation damage even though the pump had operated over such a wide range. (The techniques used to verify no damage are discussed in the next section.)

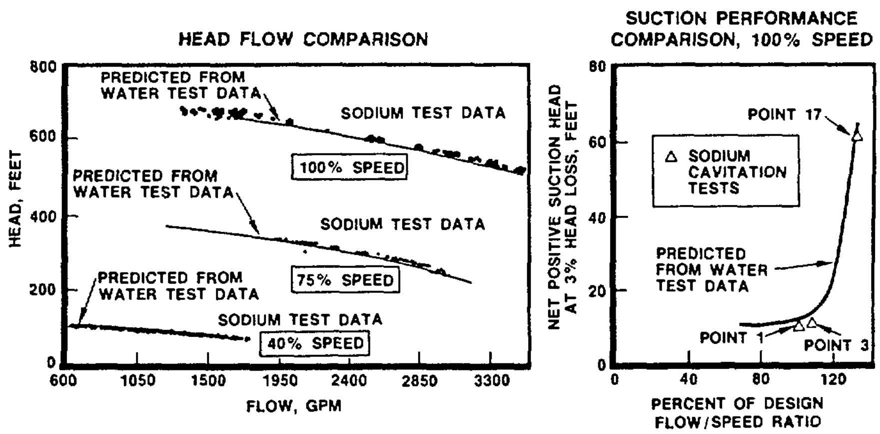

Fig. 3. Subscale Inducer Pump Water/Sodium Performance Data

Intermediate Size Inducer Pump

This inducer pump was designed to demonstrate the scalability of an inducer pump to a size more representative of large plant operation. The pump was designed based on using to the maximum extent possible the prototpye pump used in the Fast-Flux Test Facility (FFTF). Rockwell designed an inducer, impeller, and a diffuser to replace the FFTF impeller. The modified pump maintained the same discharge flow (14,500 gpm) and operated at the same speed (1110 rpm). The tests were performed in 1981 with a total of 2000 hours in sodium covering an operational range of 95 to 125 percent of design flow. Again, the tests were considered totally successful in that the pump not only met its performance goals but also resulted in no cavitation damage. In addition, the inducer required only one-half the suction pressure and provided 12 percent more head at the same flow and speed even though it had an 8-percent smaller impeller diameter.

One-Fifth Scale Pump

The most expensive testing of an inducer pump designed for sodium operation was performed on a one-fifth scale model of an 85,000-gpm pump for application in the primary sodium system of a large loop-type LMFBR. Two scale model pumps were fabricated (Fig. 4), and one was tested in water for over 600 hours while the second was tested in sodium for 5100 hours. Reference 1* discusses this pump design and the test results in some detail, and only the highlights are presented here. The 1/5-scale models operated at a design flow of 3400 gpm at a speed of 3295 rpm. Design performance exceeded predictions achieving 23,500 suction specific speed and an overall pump efficiency of 82 percent.

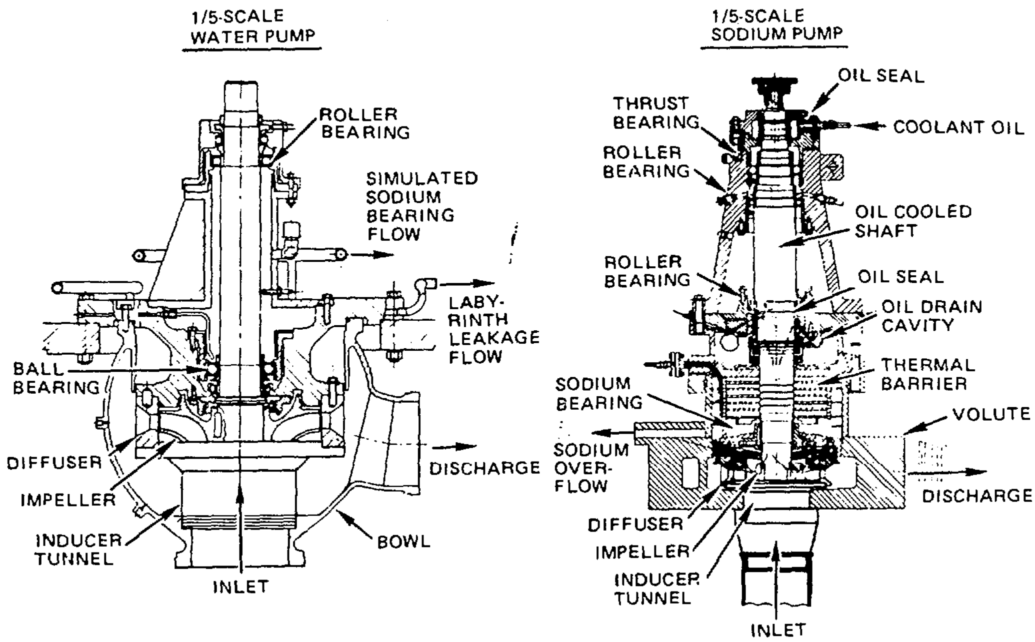

Fig. 4. One-Fifth Scale Pumps for Water and Sodium Testing

Four water test series were conducted, the first two being designed to establish hydrodynamic characteristics of the pump, and the latter two determined bearing loads on the shaft assembly using instrumented bearing carriers. The tests covered a wide flow and speed range and included special tests such as dye tests to verify no cavitation damage and velocity surveys to define inlet flow fields. The dye tests demonstrated that no cavitation damage potential existed throughout the steady-state operating range and even beyond.

The sodium tests were then performed to verify both the performance and long-life capability of the design. Table 1 (from Ref. 1) presents the sodium test program. The performance in sodium was essentially identical to that in water, and the life characteristics were again verified by showing no cavitation damage after 5100 hours of sodium operation, including extensive off-design operation.

*Ref. 1: Dunn, C. and M. J. Gabler, "Development of an 85,000 Gal/Min Inducer Pump for LMFBR Application," Liquid Metal Engineering and Technology, Vol. 2, Proceedings of the Third International Conference held in Oxford, April 1984

Table 1. 1/5-Scale Sodium Pump Test Program

	% SPEED	% DESIGN FLOW/SPEED RATIO	NPSH (FT)
ENDURANCE TEST			
2000-h DESIGN POINT ENDURANCE TEST	100	100–104	44.8–46.8
PERFORMANCE TESTS			
HEAD-FLOW TESTS	40	70–140	MAXIMUM
	60	70–140	MAXIMUM
	80	70–130	MAXIMUM
	100	70–115	MAXIMUM
CAVITATION TESTS	80	128	MAXIMUM-27
	105	100	MAXIMUM-19
OFF-DESIGN TESTS			
50-h POINT 2 ENDURANCE TEST	105	100–104	43.4–45.4
250-h POINT 17 ENDURANCE TEST	80	123–128	44–46
SHUTOFF TESTS	40	60–0	MAXIMUM
	60	60–0	MAXIMUM
SPEED-FLOW SCAN POINT 2 - POINT 24	105–60	100–0	44–60
REPEAT PERFORMANCE TESTS			
HEAD-FLOW TEST	100	70–115	MAXIMUM
CAVITATION TEST	105	100	MAXIMUM-19

Following an initial test series on a first inducer sodium pump, three very successful inducer pump programs have been conducted including design, fabrication, and extensive testing in both water and sodium. These programs have established design conditions to avoid cavitation damage with an inducer. Therefore, inducer pumps can be safely designed for long-life operation in sodium.

Testing Techniques

The inducer pump has the advantage of offering a smaller lightweight design such that questions concerning rotordynamic performance and bearing capability are of less concern, and full-size pump testing can be entered with increased confidence. The critical element of the inducer pump is the inducer itself, but this component is also the easiest to test and can typically be tested at a very early point in the program schedule and with minimal cost. In addition, the inducer is readily tested in a scale model size and with water as the test fluid as demonstrated in previous programs where both the success and failure of inducers in sodium was demonstrated by model water tests. These features provide decided programmatic advantages.

Water Tests

Water tests conducted on model inducers invariably include defining the head-flow characteristic and the suction performance characteristic over a flow range that is at least as wide and generally wider than the inducer is expected to operate. These results are generally directly scalable to the larger size with the full-size component generally showing some improvement due to scale-size effects. The other test type always conducted in water is the dye test in which all of the hydrodynamic surfaces of the inducer and, frequently, the inducer tunnel are coated with an insoluble dye. Through experience, Rockwell has determined a dye capable of withstanding the high velocities (up to 200 ft/sec) without erosion and yet sensitive to any cavitation collapse occurring on the solid surface. Tests have also demonstrated that operation at a fixed point for 20 minutes is sufficient to fully describe any regions of dye removal due to cavitation. (Dye removal, when it occurs, generally occurs within 1 minute and has covered the extent of the damage region within 5 to 10 minutes. Tests both with and without dye removal have been extended to as long as 1 hour without any further dye removal.) Thus, each test point of interest is tested for 20 minutes with both visual and photographic coverage of the results. Figure 5 shows a typical result with dye removal obtained by operating the inducer at 70 percent of its design flow coefficient (steady-state operation would be from 100 percent to approximately 130 percent). A successful test would, of course, result in no dye removal throughout the required long-life operating range.

The low cost of these scale model water tests also offers the opportunity of exploring other flow features. For example, velocity survey tests have been performed, and tests of various inlet and inducer tunnel characteristics have been conducted. A velocity survey at the inducer exit can be used to add confidence in the design of the centrifugal impeller before submitting that component to fabrication.

Sodium Tests

Dye coatings cannot be applied for sodium operation; therefore, demonstration of the long-life capability of the part requires verifying by other techniques that no damage has occurred on the surface . This necessarily involves longer test times and more sophisticated verification techniques. Four inspection techniques have been used for the pump operating in sodium.

Fig. 5. Dye Removal on Inducer Due to Operation at 70% of Design Flow (No Dye Removal from 95 to 130% of Design)

1. Macrotracking - basically similar to dye testing in that it involves unaided visual inspection and macrophotographs. This technique is, of course, used only for any more obvious damage, but testing for 2000 or more hours should show any significant problem area.

2. Weight - parts are weighed to within 0.01 grams pretest and posttest. The part is first ultrasonically cleaned, weighed, and then micropolished for stain and oxide coating removal and reweighed. Because the micropolishing can also remove a small amount of metal, the true weight is believed to be between the two weights measured posttest. Figure 6 shows such a time-weight map obtained for the prototypic subscale pump. The weight loss rate experienced is typical of rates experienced by static components (e.g., ducts) subjected to sodium flow.

3. Dimensional Measurement - Key parts like the inducer are also measured to define the three-

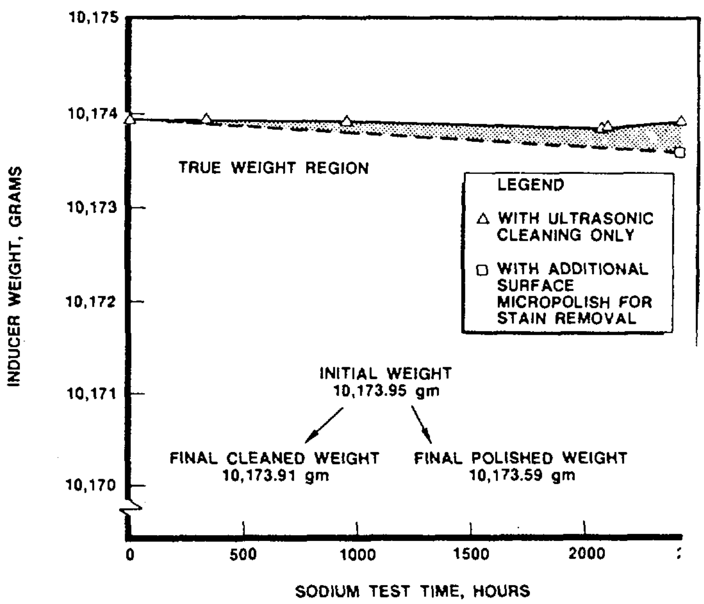

Fig. 6. Time-Tracking the Inducer Weight

dimensional blade surface coordinates. This technique will identify any movement of the blade surface even if a weight loss has not occurred. Figure 7 shows some typical results obtained at three different points of operation for the blade centerline location at the tip. (The tip is the region most likely to experience movement in an unshrouded inducer.) The measurements are typically made of both the suction surface and pressure surface at each of 5 radii and for every 10 degrees of circumferential angle on all of the blades. The accuracy of the measurement is approximately 0.003 inch, and as Fig. 7 shows, all results fall within that band demonstrating the structural stability of the blades.

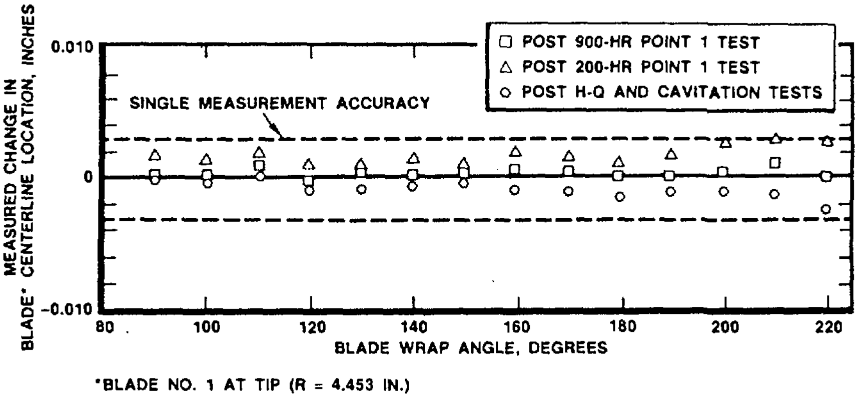

Fig. 7. Typical Inducer Three-Dimensional Blade Measurement History

4. Microtracking - This is a topographical technique involving the use of two-stage, chromium-carbon, cellulose-acetate replicas. This is a long-established technique that is routinely able to resolve surface features on the order of 50 nanometers. However, to our knowledge, this is the first use of this technique for detecting cavitation damage from sodium testing. Specific surface locations are selected for tracking; these being selected based on experience with cavitation damage locations from other inducer testing. Any surface effects caused by the operating environment manifest themselves as subtle highlighting of the material's microstructure, which can easily be visually observed within normal surface roughness of a fabricated component. The cellulose-acetate technique allows these effects to be recorded and observed under high magnification. Figure 8 shows some typical results again obtained for the prototypic subscale pump. No evidence of cavitation damage initiation or progression was found at any of the locations throughout the test history.

Other measurements are made and tracked through the test history to verify that no change in performance is experienced. These include not only the normal pressure measurements but accelerometer measurements and in some special cases bearing loads. Acoustic measurements have not been used extensively, partially because the inducer does experience cavitation but is designed to prevent the cavitation from collapsing on the blade surface. Acoustic measurements were made on the FFTF stand with the Intermediate Size Inducer Pump (ISIP). This inducer pump replaced an existing centrifugal pump and operated at the same speed and flow. While different instruments were used and certain of the test conditions were varied, it was generally observed that the acoustic noise was significantly less (up to 10 db) with the ISIP pump as compared with the original FFTF pump.

Advanced Pump Concepts

Rockwell is continuing to investigate other pump concepts to further improve the operating range of the inducer pump. One concept currently being evaluated as part of the DOE Base Technology Program consists of a shrouded inducer. For the unshrouded inducers, the key cavitation experienced in the Rockwell designs is the tip vortex cavitation due to the flow between the tip of the blade and the stationary tunnel. The inducer is designed to cause this cavity to collapse between the blades in the

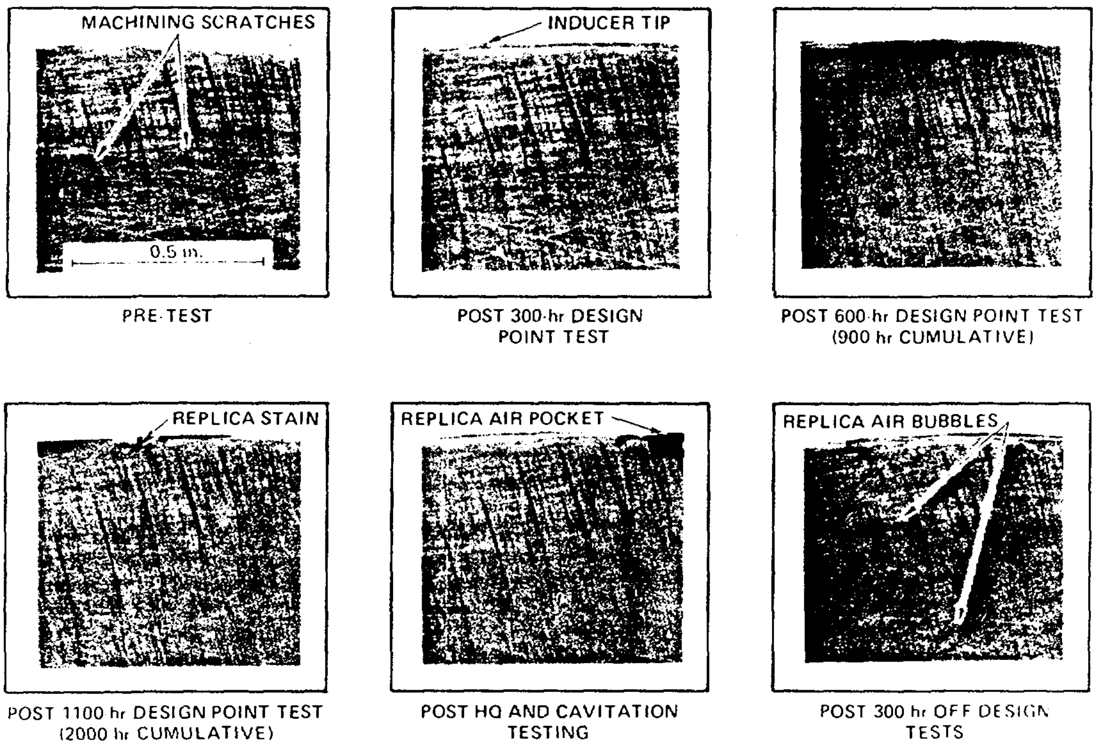

Fig. 8. Time-Tracked Replicas Show No Cavitation Damage (Inducer Blade No. 1 Suction Side Tip)

flow field and not on any metal surface. This design objective can be achieved over a limited flow range that is adequate to cover many plant steady-state operating ranges. However, wider flow ranges and even higher suction specific speed capability can potentially be achieved by the shrouded inducer because it does not have a typical blade-tip vortex. This can be illustrated by Fig. 9, which shows the typical "bucket curve" characterizing the required NPSH as a function of flow/speed ratio. For the unshrouded inducer, a lower flow boundary is encountered due to tip vortex cavitation. A high flow boundary is encountered due to tip vortex cavitation. A high flow boundary is encountered due to suction performance. These boundaries define the resulting limits of operation. Test results have demonstrated the capability for operating the shrouded inducer at an even lower flow/speed ratio permitting the design to operate over a wider flow range and to achieve even better suction performance by optimizing the operating range. Four shrouded inducers (Fig. 10) for sodium application have been tested in the past 2 years with variations in design conditions and covering a suction specific speed range of 21,000 to 34,000. The results have been very promising, and the potential for operating inducer pumps over an extremely wide flow range is very real.

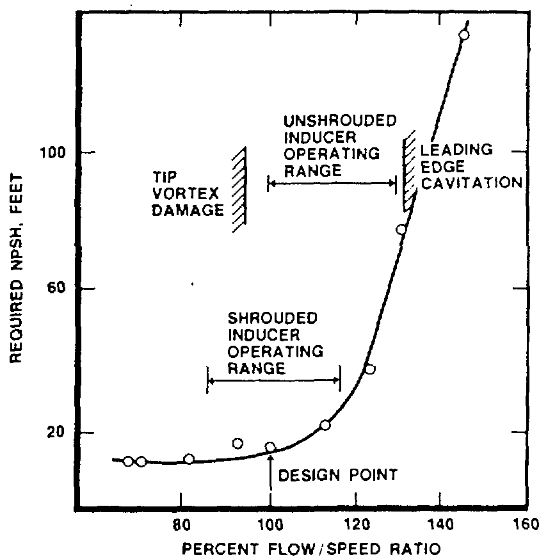

Fig. 9. Shrouded Inducer Operates on Flat Portion of "Bucket Curve"

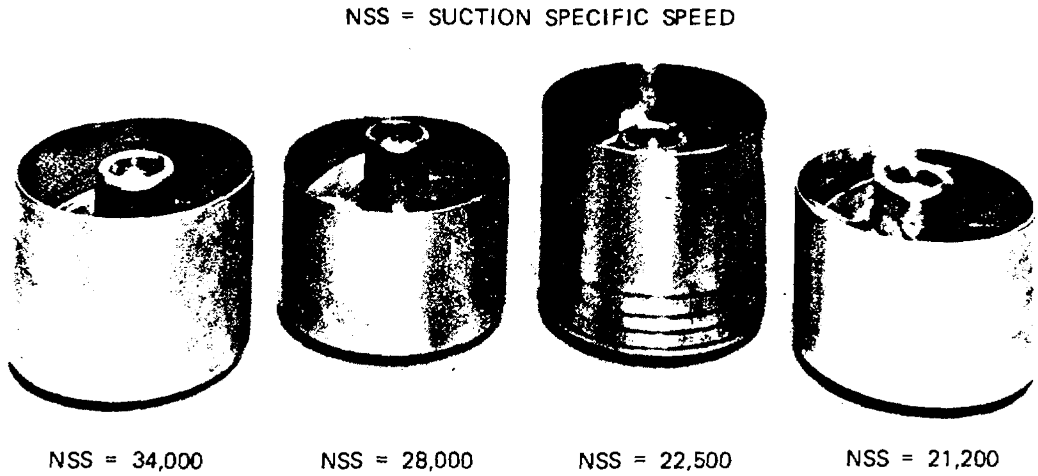

Fig. 10. Four Shrouded Inducers Tested by Rockwell in Past 2 Years

Conclusions

In conclusion, the inducer pump is seen to be a sound concept with a strong technology base derived from the aerospace and ship propulsion industries. The superior suction performance capability of the inducer offers significant system design advantages, primarily a smaller, lighter weight, less complex pump design with resulting saving in cost. Extensive testing of these pumps has been conducted in both sodium and water to demonstrate the long-life capability with no cavitation damage occurring in those designs based on Rockwell's current design criteria. These tests have utilized multiple inspection and measurement approaches to accurately assess and identify any potential for cavitation damage, and these approaches have all concluded that no damage is occurring. Therefore, it is concluded that inducer pumps can be safely designed for long-life operation in sodium with significant economic advantages over alternative pumps. Furthermore, the technology is continuing to grow with advanced concepts into test in both water and sodium that can offer the designer the capability to operate over even wider flow ranges with higher suction specific speed.